1

1 micron minimum:
A local minimum in the continuum spectrum of most AGN occurring around a wavelength of 1 micron (1 μm). It is thought to represent the minimum between a hot thermal spectrum (the big blue bump) possibly due to emission from an accretion disc, and a cool thermal spectrum due to emission in the infrared by warm dust grains.

2

2dF:
The 2 degree field multi-object spectrometer on the Anglo Australian Telescope. Used to conduct the 2dF galaxy redshift survey and the 2dF quasar survey.

2MASS:
The 2 Micron All Sky Survey. A survey of the complete sky using two telescopes (one at Mount Hopkins, Arizona and one at Cerro-Tololo, Chile) in three infrared wavebands: J-band (1.25 μm), H-band (1.65 μm) and K-band (2.17 μm).

3

3C273:
One of the closest quasars to us (redshift = 0.158), the optically brightest (magnitude = 12.9) and the first quasar to be identified, in the 3C radio source catalogue.

4

4000 angstrom break:
A break, or absorption feature, at a wavelength of 4000Å in the spectra of galaxies caused by Balmer continuum absorption in the atmospheres of stars.

A

aberration of light:

The phenomenon whereby the observed direction of a *star* changes with time, due to the combined effect of the motion of the observer and the finite speed of light. If the relative speed of the observer and star is small compared to the speed of light, the aberration is small: $\tan \alpha = (v/c)\sin\theta$, where α is the aberration angle, v is the speed of motion, c is the speed of light and θ is the angle between the direction of motion and the direction of the star. The aberration due to the Earth's motion around the Sun is no more than 20.5 arc seconds. If the relative speeds are a significant fraction of the speed of light, the effects of special relativity become significant and the Lorentz transformations must be used to calculate the aberration angle.

ablation:
The process whereby material is lost from a body as a result of gas or fluid flow past it. The gas carries away (ablates) material from the body's surface.

absolute magnitude:

A numerical quantity used to describe the luminosity of a body. The relationship between absolute magnitude and luminosity is given by:

$M = -2.5 \log_{10} L + K$

where K is a constant that depends on the units of L and the waveband being considered. The absolute magnitude of an astronomical body is equal to the apparent magnitude the body would have if it were located at a distance of 10 parsecs from the observer, ignoring any effects due to obscuration.

absolute temperature:
Any temperature measured on the thermodynamic temperature scale.

absolute temperature scale:
See thermodynamic temperature scale.

absolute visual magnitude:
An absolute magnitude, measured in the visual (V) band (at wavelengths around 550 nm).

absorption (and emission) of radiation:
General processes whereby energy carried by electromagnetic radiation may be added to, or taken from, the total energy of the system responsible for the emission or absorption. A particular case is that in which an electron makes a radiative transition between two energy levels in an atom. When an electron makes a transition from a lower energy level E_1 to a higher energy level E_2, the atom increases its total energy by an amount $E_2 - E_1$. In the case of a radiative transition, the atom obtains this energy by absorbing a single photon of energy $E_2 - E_1$. Similarly, an atom can emit a photon of energy $E_2 - E_1$ in a radiative transition when one of its electrons makes a transition from a higher energy level E_2 to a lower energy level E_1.

absorption distance:

The quantity X in the expression

$$\frac{\mathrm{d}X(z)}{\mathrm{d}z} = (1+z)^2 \frac{H_0}{H(z)}$$

If absorbers have a constant comoving space density and constant proper sizes and cross sections, then the number of absorbers per unit absorption distance is constant.

absorption edge:
A jump in absorption cross-section at a particular wavelength or energy corresponding to an ionisation state of the absorbing atom or ion.

absorption line:
See absorption line spectrum.

absorption line spectrum:
A spectrum of the kind observed when continuum radiation (e.g. from a black body) passes through matter. Radiation is absorbed at specific energies (wavelengths) corresponding to atomic or molecular transitions in the absorbing material, giving rise to absorption lines in the spectrum (see, for example, hydrogen spectrum). The absorption spectrum gives information on the atomic or molecular species present and their physical state.

accelerating model:
A model of the universe in which the rate of expansion increases. The acceleration is a result of the changing densities of matter, radiation and dark energy with time.

acceleration:

The (instantaneous) rate of change of velocity of a body. For a particle moving in one-dimension along the x-axis, the acceleration a_x at any time is the instantaneous rate of change of the particle's velocity v_x, and is given by the gradient of the particle's velocity–time graph at the relevant time. This gradient is equal to the derivative of the velocity with respect to time at the relevant time, so the acceleration at time t may be written

$$a_x(t) = \frac{\mathrm{d}v_x(t)}{\mathrm{d}t}$$

Acceleration is a vector quantity, characterized by a direction as well as a magnitude. In one dimension the sign of a_x suffices to indicate the direction, but in two or three dimensions some other method must be used to indicate direction. This is often achieved by expressing the acceleration vector in terms of its (Cartesian) components, as in $\boldsymbol{a} = (a_x, a_y, a_z)$, where

$$\boldsymbol{a}(t) = \frac{\mathrm{d}\boldsymbol{v}(t)}{\mathrm{d}t}$$

and $\boldsymbol{v}(t)$ is the velocity vector.

acceleration due to gravity:
The acceleration towards the centre of a massive body (such as a star or planet) of a freely falling object. The magnitude of the acceleration for a spherically symmetrical body is GM/r^2, where M is the mass of the body inside the radius r, r is the distance from the centre of mass and G is the universal gravitational constant. The acceleration is independent of the mass of the falling object, and so is the same for all bodies in the same gravitational field. At the surface of the Earth the magnitude of the acceleration due to the Earth's gravity is about 9.81 m s^{-2}. This quantity varies slightly from place to place, but is generally represented by the symbol g.

accretion:
The process whereby the mass of an astronomical body grows as a result of the accumulation of matter. Accretion is most important in systems where matter is falling in under the influence of gravity; it allows a massive body to gain more mass from other matter in its surroundings. If the infalling matter has significant angular momentum, an accretion disc is formed. The luminosity of various types of astronomical object, including X-ray binaries and active galactic nuclei, is ultimately the result of accretion.

accretion column:
A form of accretion flow where the width in any direction perpendicular to the direction of the flow is small compared to the geometrical extent along the flow direction. The magnetically controlled accretion in polars is thought to occur via an accretion column.

accretion curtain:
A form of accretion flow between the inner edge of a magnetically disrupted accretion disc and the surface of the accretor. The magnetically controlled accretion in intermediate polars is thought to occur via accretion curtains.

accretion disc:
A flow of matter that is largely confined to a plane and that is spiralling in towards a central object. The azimuthal component of the flow velocity is close to the Keplerian value, while the radial component is much smaller. See also mass transfer.

accretion disc luminosity:

The energy an accretion disc radiates per unit time. For a steady-state, geometrically thin, optically thick, infinite disc with a non-rotating central accretor with mass M and radius R_* and accretion rate $\dot{M}$, the accretion disc luminosity is

$$L_{\text{acc}} = GM\dot{M}/2R_*$$

(G is the gravitational constant). This is just half the accretion luminosity.

accretion disc spectrum:

The continuum spectrum of a geometrically thin, optically thick, Keplerian, steady state accretion disc is a 'stretched-out' black body spectrum, with a characteristic flat region where $F_\nu \propto \nu^{1/3}$

accretion disc structure:
See accretion disc.

accretion efficiency:

The accretion luminosity, expressed in units of the rate of accreted mass energy. If L_{acc} denotes the accretion luminosity, $\dot{M}$ the mass accretion rate, and c the speed of light, then the accretion efficiency is $\eta = L_{\text{acc}}/\dot{M}c^2$.

accretion luminosity:

The gravitational energy liberated by accretion per unit time. If an object with mass M and radius R_* accretes matter at a rate $\dot{M}$ the accretion luminosity is

$$L_{\text{acc}} = \frac{GM\dot{M}}{R_*}$$

(G is the gravitational constant).

accretion powered compact binaries:
See X-ray binary, cataclysmic variable.

accretion powered compact binary:
See X-ray binary; cataclysmic variable.

accretion powered pulsar:
A pulsar whose emission is powered by accretion from a companion star. See X-ray pulsar.

accretion rate:

The mass accumulated per unit time through accretion. Usually denoted by $\dot{M}$ and measured in kg s^{-1} or g s^{-1} or $M_\odot$ yr^{-1} (sometimes also called mass accretion rate). Also used in a more general sense to denote the rate of mass transported by accretion through a given surface per unit time, e.g. the rate of mass flowing through a disc annulus in an accretion disc.

accretor:
An object that accretes matter (often a star in an interacting binary system where mass is being exchanged).

achromatic:
Referring to a phenomenon which is independent of wavelength (or colour).

achromatic break:
A change of slope in a light curve, whose position is independent of the frequency of radiation in which the light curve is constructed.

acoustic peaks:
Peaks in the angular power spectrum of the cosmic microwave background radiation.

acoustic wave:
Also known as sound wave. Periodic modulations in pressure and density that occur (for instance) inside stars. The amplitudes and periods of such waves depend on the detailed structure and composition of the star.

action:
The integral, over time, of the Lagrangian of a system. Particles in classical mechanics follow a path that minimizes the action.

active galactic nuclei:
The central regions of active galaxies: often abbreviated AGN. The active nucleus is the region in which an active galaxy differs most strongly from a normal galaxy; they often exhibit strong optical and X-ray emission and show bright emission lines. The activity in the active nucleus is thought to be powered by accretion of matter from within the galaxy on to a black hole with a mass 10^6–10^9 times that of the Sun. The active nucleus is sometimes called the central engine.

active galaxies:
See active galaxy.

active galaxy:
A galaxy which emits electromagnetic radiation (in the radio, optical, and/or X-ray wavebands) that cannot be attributed to the normal constituents of a galaxy, such as stars, gas and dust. In some types of active galaxy, such as Seyfert galaxies and radio-quiet quasars (QSOs) the unusual activity is confined to the active galactic nucleus, the central region of the active galaxy. In others, such as radio galaxies, radio-loud quasars and BL Lac objects, the results of the activity can be detected on much larger scales as well. Only a small fraction of galaxies are active.

active star:
A type of star demonstrating one or more of a range of characteristics including flares, emission-line spectra, variability due to starspots, and non-thermal radio emission, believed to be due to strong magnetic fields, and often associated with youth.

ADAF:
Advection-dominated accretion flow, see advection.

adaptive optics:
An approach to correct for turbulence in the Earth's atmosphere, and so improve seeing, by measuring the distortion and correcting telescopes in real time.

adiabatic condition:

The condition PV^{γ} = constant (or equivalently $P \propto \rho^{\gamma}$) that may be used to specify a particular reversible adiabatic process in a given quantity of ideal gas where the ratio of heat capacities is γ.

adiabatic index:

The numerical quantity γ that appears in the adiabatic condition PV^{γ} = constant; also known as the ratio of heat capacities.

adiabatic process:
A process in which no heat is transferred. See also adiabatic condition.

advanced Eddington-Finkelstein coordinates:

A coordinate system used to describe spacetime in the vicinity of a non-rotating black hole which avoids the coordinate-related problems encountered when using Schwarzschild coordinates and gets rid of the coordinate singularity at the Schwarzschild radius. A new coordinate t' is related to the Schwarzschild coordinates t and r by

$ct' = ct + R_S \ln (r/R_S - 1)$

where R_S is the Schwarzschild radius.

advection:
A process whereby energy is transported without significant loss as a result of bulk motion of material. An advection dominated accretion flow will occur if the cooling time of the material exceeds the time to fall onto the compact object. If the compact object is a black hole, the thermal energy carried by the flow will therefore be lost as the material disappears within the event horizon.

advection-dominated accretion flow:
(ADAF) See advection.

aether:
See ether.

afterglow:
A long-lasting, fading emission that follows a gamma-ray burst, in X-rays.

AGN:
See active galactic nuclei.

AGN continua:

The continuum spectra produced by active galaxies. Features present in many AGN continua include the big blue bump, the 1μm minimum, the small blue bump, and the submillimetre break.

AKARI:
A Japanese space telescope operating in the infrared part of the spectrum.

albedo:
The fraction of incident radiation falling on a planetary body that is radiated by it. When integrated over all wavelengths, this is known as the Bond albedo.

Alfven radius:
In the context of plasma that accretes spherically symmetrically onto a magnetic

accretor, the Alfven radius is the distance from the accretor at which the magnetic pressure just equals the ram pressure of the infalling material.

Algol:

A bright binary star in the constellation Perseus (β Persei). It has been known to be a variable star, with a period of around 68 hours, since historic times, and was the first eclipsing binary to be discovered. It is famous for the Algol paradox in the study of stellar evolution. The two stars in a binary system must have formed at the same time, and the more massive star should evolve more quickly, but in Algol the more massive star of the binary is still on the main sequence, while the less massive star is in the more highly evolved subgiant phase. The explanation of the paradox is that the more evolved star began as the more massive, but transferred a large fraction of its mass (up to 85%) to the other star as it evolved and expanded. See mass transfer, Roche lobe overflow.

Algol paradox:
See Algol.

Algol phenomenon:
Also known as the Algol paradox. See Algol.

allowed transition:
See permitted transition.

ALMA:
The Atacama Large Millimetre Array. An interferometer being built in Chile.

alpha-decay:
A type of radioactive decay in which a nucleus spontaneously emits an alpha-particle.

alpha-particle:

A positively charged sub-atomic particle with about four times the mass of a hydrogen atom. Alpha-particles are composite particles consisting of two protons bound to two neutrons; they are identical to the nuclei of helium-4 atoms. Each α-particle has a mass of 4.0026u and carries a positive charge of 2e.

alpha-prescription:
See alpha-viscosity.

alpha-viscosity:

A viscosity in accretion discs described by a kinematic viscosity of the form $v = \alpha c_s H$ (where c_s is the sound speed and H the disc thickness). The parameter α is dimensionless and less than unity.

AM Her star:
A star which is a member of a class of magnetic cataclysmic variables (named after the prototype system, AM Herculis) in which the white dwarf has such a strong magnetic field that the formation of an accretion disc is completely prevented. Instead, the accretion takes place via an accretion column. AM Her systems are also known as polars because the light they emit is strongly polarized.

amplitude:
In the context of a wave; the amplitude is the maximum magnitude of the disturbance that constitutes the wave (e.g. the displacement of a string from its equilibrium position). In the particular case of a simple travelling wave described by the equation $y(x, t) = A \sin(kx - \omega t + \phi)$, the amplitude is represented by the parameter A.

Andromeda galaxy:
Along with the Milky Way, one of two large spiral galaxies in the Local Group.

angle of inclination:
The angle between the plane of an orbit and the plane perpendicular to the line of sight. Consequently, an orbit seen 'face-on' has an angle of inclination of 0° and an orbit seen 'edge-on' has an angle of inclination of 90°.

angular acceleration:

The (instantaneous) rate of change of angular velocity, $d\boldsymbol{\omega}/dt$. It is a vector quantity, sometimes represented by the symbol $\boldsymbol{\alpha}$, and its SI unit is the rad s^{-2}.

angular coordinate:
A coordinate (usually denoted θ) that determines the angular position of a point in a (plane) polar coordinate system.

angular correlation function:
In cosmology, the probability that a galaxy will have a neighbour at a certain angular separation from it. It is a function which expresses the excess of clustering over what is expected in a non-clustered case.

angular diameter distance:

The size of an object divided by its angular diameter in radians:

$$d_{\mathrm{A}} = D/\theta$$

angular displacement:
A change in angular position in a specified sense, measured from a specified point.

angular frequency:
A characteristic property of an oscillating system, defined by the relation $\omega = 2\pi/T$, where T is the period of oscillation of the system. Since the frequency of an oscillator is defined by $f = 1/T$, it follows that $\omega = 2\pi f$. In the context of a simple harmonic oscillator, described by the equation $x = A \sin(\omega t + \phi)$, the angular frequency is represented by the parameter ω. The concept of angular frequency may be extended to the case of a wave, simply by taking T to be the period of the wave. Angular frequency is a positive scalar quantity with the SI unit s^{-1}.

angular momentum:

The momentum associated with the rotational motion of a body. For a particle, the angular momentum $\boldsymbol{j}$ (or $\boldsymbol{l}$), about a point O, is defined by the vector product

$\boldsymbol{j} = \boldsymbol{r} \times \boldsymbol{p}$

where $\boldsymbol{r}$ is the displacement of the particle from the point O, and $\boldsymbol{p}$ is the linear momentum of the particle. This implies that if the angle between $\boldsymbol{r}$ and $\boldsymbol{p}$ is θ, then $\boldsymbol{j}$ has magnitude $rp \sin \theta$, and points in a direction that is perpendicular to $\boldsymbol{r}$ and $\boldsymbol{p}$, as specified by the right-hand rule. The SI unit of angular momentum is the kg m^2 s^{-1}.

For an extended body, the angular momentum $\boldsymbol{J}$ (or $\boldsymbol{L}$) about a given point depends on the way the body's mass is distributed, and on the components of its angular velocity $\boldsymbol{\omega}$. There are a number of important special cases in which the body is in uni-axial rotation about an axis of symmetry and $\boldsymbol{J} = I\boldsymbol{\omega}$, where I is the moment of inerita about that axis. However, $\boldsymbol{J} = I\boldsymbol{\omega}$ is *not* a general relation that will be true in all circumstances. See conservation of angular momentum.

angular position:
Expressed relative to a point O and an arbitrarily chosen straight line through O, the angular position θ of a point P is the angle (measured in the anticlockwise direction) from the chosen straight line to the line linking O to P.

angular separation:
The angle subtended by the position vectors to two objects as seen by a distant observer situated at the origin of the coordinate system. Under the small angle approximation, the angular separation (in radians) is equal to the actual distance between the two objects divided by the distance from the observer to the objects.

angular speed:

The modulus of the rate of change of angular position of a particle or body:

$$\omega = \left|\frac{\mathrm{d}\theta}{\mathrm{d}t}\right|$$

The angular speed of a body, about a point O represents the magnitude of its angular velocity about O. Angular speed is a positive scalar quantity with the SI unit rad s^{-1}.

angular velocity:

The angular velocity of a particle or body about a point O, is a *vector* quantity $\boldsymbol{\omega}$, with magnitude equal to the angular speed about O and directed along the (instantaneous) axis of rotation through O.

If the displacement of a particle from O is $\boldsymbol{r}$, and if the velocity of that particle relative to O is $\boldsymbol{v}$, then the angular velocity $\boldsymbol{\omega}$ of that particle about the point O is related to $\boldsymbol{r}$ and $\boldsymbol{v}$ by the vector product

$\boldsymbol{v} = \boldsymbol{\omega} \times \boldsymbol{r}$

(Note that this result is *not* restricted to circular motion.)

In the case of a rotating *rigid body*, the angular velocity about every point fixed within the body has the same value at any given time.

annihilation:
A process in which the interaction of a particle and its antiparticle (such as an electron and a positron) results in both particles being destroyed and a pair of high-energy photons being produced. See also electron–positron pair production.

anomalous X-ray pulsar:
An X-ray pulsar which appears to have no optical counterpart, and hence no mass donor providing a source of accretion. Unlike accretion powered pulsars (X-ray pulsars) they are believed to be magnetars, powered by the decay of the very strong magnetic field. They typically have pulse periods of 5s - 12s. See also soft gamma-ray repeaters.

anthropic principle:
A line of reasoning which attempts to constrain cosmological parameters based on the fact that the universe contains intelligent life.

antielectron:

See positron.

antilepton:
One of six antiparticles to the six leptons. They comprise the antielectron (or positron), antimuon, antitauon, electron antineutrino, muon antineutrion, and tauon antineutrino.

antimuon:
The antiparticle of a muon. It has positive charge.

antineutrino:
One of three antiparticles to the three flavours of neutrino, namely the electron antineutrino, the muon antineutrino and the tauon antineutrino.

antiparticle:

Elementary particles that have the same mass and spin as certain known particles, but the opposite signs for certain other attributes, such as electric charge. For example, the electron and positron have the same mass and both have spin 1/2, but the former has a negative charge $-e$, while the latter has positive charge $+e$.

antiquark:
One of the six antiparticles to the six flavours of quark.

antitauon:
The antiparticle of a tauon. It has positive charge.

apastron:
The point in the orbit of a binary star (or, more generally, any orbit about a star other than the Sun) at which the orbiting bodies have their maximum separation. Contrast with periastron, at which the bodies have their minimum separation.

aphelion:
The point in the orbit of a body around the Sun at which the orbiting body has its maximum separation from the Sun. Contrast with perihelion, at which the orbiting body has its minimum separation from the Sun.

apoapsis:
See apocentre.

apocentre:

The point in an orbit that lies furthest from the centre of mass of the system. In the case of binary stars, the point of maximum separation is called the apastron; in the case of orbits around the sun, this is referred to as the aphelion.

Contrast with pericentre, which is the point in an orbit that lies closest to the centre of mass of the system.

apparent magnitude:

A numerical quantity used to describe the observed brightness of a body as determined by the flux received from that body. The relationship between magnitude and flux is given by:

$m = -2.5 \log_{10} F + K$

where K is a constant that depends on the units of F and the waveband being considered. The scale of apparent magnitude is defined, for historical reasons, to increase as the brightness of an object decreases. Thus the brightest *stars* in the sky have magnitudes around 1 and the faintest visible to the naked eye have magnitudes around 6. In astrophysics magnitudes are usually measured through a set of standard filters, which pass light only in well-defined regions of the spectrum. These include U (ultraviolet, around 365 nm), B (blue, around 440 nm), V (visual, around 550 nm), R (red, 700 nm) and I (infrared, around 900 nm).

apparent transverse velocity:
In the context of the apparent motion of a star or other object in the plane of the sky; the apparent transverse velocity is equal to the angular velocity of the object (i.e. its proper motion) multiplied by the distance to the object.

apside:
One of two points in an orbit that lie closest to (periapsis) and furthest from (apoapsis) the centre of mass of the system. The line joining the two apsides is the major axis of an elliptical orbit.

arbitrary constant:
A constant that arises in the general solution of a differential equation that is not present in the equation itself. The number of arbitrary constants in the general solution is equal to the order of the differential equation, and the values of the arbitrary constants are determined by the initial conditions that determine the details of the solution.

arc minute:
A unit of angle, equal to 1/60 of a *degree*. The Moon, as seen from Earth, is about 30 arc minutes, or 0.5 degrees, across.

arc second:
A unit of angle, equal to 1/60 of an arc minute or 1/3600 of a degree. The arc second is comparable to the resolution of many ground-based optical telescopes, and is a convenient unit for measuring the size of extended objects. It is therefore frequently used in astronomy.

argument:
The independent variable that actually determines the value of a function, e.g. θ is the argument of sin θ, and 2θ is the argument of $\sin(2\theta)$.

ASCA:
A Japanese X-ray astronomy satellite, which was a follow-up to Ginga, that operated from 1993 to 2000. Its high spectral resolution in the 1-10 keV band allowed the first detection of broadening in the 6.4 keV line discovered by Ginga, proving that the line originated in an accretion disc.

associated Legendre polynomials:

Functions of the form:

$$P_l^m(x) = \frac{(-1)^m}{2^l l!}(1-x^2)^{m/2}\ \frac{\mathrm{d}^{l+m}(x^2-1)^l}{\mathrm{d}x^{l+m}}$$

where *m* and *l* are integers.

asteroseismology:
The process of observing and measuring oscillations in stars to infer the stellar structure. The oscillations are generated by sound waves in the interiors of stars, and revealed by subtle photometric variability with amplitudes of a few parts per million. When applied to the Sun this is known as helioseismology.

astrobiology:
The study of the Universe's potential for life.

astrocentric frame:
The rest frame of reference of a star within which planets execute orbits around the star.

astrometry:
The branch of science concerned with the accurate measurement of the position on the sky of astronomical objects. Accurate measurements of the positions of stars are essential to determine their parallaxes, proper motions and (in the case of visual binaries) the orbital parameters of binary stars.

astronomical unit:
A precisely defined unit of distance that is roughly equal to the mean distance between the Sun and the Earth, $1.495\,97 \times 10^{11}$ m.

astrophysics:
The study of the physical processes occurring in the constituent bodies of the Universe.

asymptotically flat:
In the Schwarzschild solution to the Einstein field equations, referring to idea that gravitational effects become weaker as the distance from their source increases, leading to an approximately flat spacetime.

asymptotic giant branch:
(Known as the AGB.) The region of the H–R diagram occupied by stars that are powered by a mixture of hydrogen and helium shell burning, with a carbon and oxygen core. Shell helium burning causes the outer envelope of the star to expand and cool further, so that stars lie above and to the right of the red giant stars in the H–R diagram in this phase. In the early AGB (E-AGB) the energy generation is dominated by the helium shell. Later the helium is depleted, and hydrogen burning dominates: this generates fresh supplies of helium that may ignite again, producing thermal pulses (the TP-AGB).

ATIC:
The Advanced Thin Ionization Calorimeter balloon-borne experiment to study cosmic rays.

atmospheric extinction:
The absorption and scattering of light in the Earth's atmosphere causing a reduction in the measured brightness of an astronomical object.

atmospheric scale height:
A typical height of an atmosphere (of a planet).

atom:
The smallest electrically neutral sample of an element that retains the fundamental chemical and physical identity of that element.

atomic energy level:

An allowed energy of an atom.

atomic mass unit:
A non-SI unit of mass, defined as one-twelfth of the mass of one atom (including the electrons) of carbon-12 (^{12}C), the most common isotope of carbon. The atomic mass unit is represented by the abbreviation amu and has the symbol u, where 1u = 1.661 × 10^{-27}kg.

atomic number:
The number of protons in a specified nucleus. The atomic number is usually represented by the symbol Z, and is equal to the difference between the mass number *A* and the neutron number *N*, so $Z = A - N$. All atoms of the same element have the same atomic number. The positive charge on the nucleus is Ze. For a neutral atom, *Z* is also equal to the number of electrons in the atom.

auto correlation:
A technique of searching for correlations between one part of a light curve, or other time varying signal, and another part which is shifted by a certain time delay.

auto correlation function:

A function of time delay τ that describes the result of performing an auto correlation on a time varying signal $c(t)$:

$$F_{\mathrm{ACF}}(\tau) = \int_{-\infty}^{\infty} C(t)C(t-\tau)\,\mathrm{d}t$$

axion:
A hypothetical particle which may be a component of dark matter. It is proposed in quantum chromodynamics.

B

backward shock:
The shock that propagates backwards (in the direction opposite to that of the flow) from an event such as a gamma-ray burst.

Baldwin effect:

The effect that causes the equivalent width of the CIV emission line in AGN to be inversely correlated with the continuum luminosity. It may be parameterized as $L(\mathrm{CIV}) \propto L_\lambda^\gamma$ where $\gamma \sim 0.8$.

Baldwin Phillips Terlevich diagram:

A diagram which plots the [OIII] λ5007/Hβ λ4861 line ratio against the [NII] λ6583/Hα λ6563 line ratio to enable narrow line AGN to be discriminated from HII regions and LINERs.

ballistic trajectory:
The path taken by a test particle subject only to the gravitational force.

Balmer continuum absorption edge:
See Balmer jump.

Balmer decrement:
The ratio of the intensities of the Balmer lines.

Balmer jump:
The threshold at which a photon can cause ionization from the n = 2 level of hydrogen, at 3646 Å. Also known as the Balmer continuum absorption edge.

Balmer limit:
The wavelength of 3646 Å which corresponds to transitions between the n = 2 energy level of hydrogen and unbound states. See hydrogen spectrum.

Balmer series:
A series of lines in the spectrum of atomic hydrogen, the visible members of which have wavelengths 6562.1 Å, 4860.7 Å, 4340.1 Å and 4101.2Å. These lines correspond to transitions between the n = 2 energy level and energy levels with n = 3, 4, 5 and 6, respectively. Transitions from energy levels with higher values of n correspond to lines that are in the ultraviolet part of the spectrum. See hydrogen spectrum, Lyman series, Brackett series, Paschen series.

bandpass:
The wavelength range to which a particular detector is sensistive.

BAOs:
See baryon acoustic oscillations.

barn:
A unit of *cross-section* for particle collisions. It is represented by the symbol b and is defined by the relation 1 b = 10^{-28} m^2.

barrier penetration:
See quantum tunnelling.

barycentre:
The centre of mass of a system of stars and planets.

baryon:
A term used to describe strongly interacting particles that have half odd-integer spin (i.e. spin 1/2, 3/2, etc.). Each baryon is a combination of three quarks. The lowest mass baryons are the proton and the neutron.

baryon acoustic oscillations:
Wiggles in the galaxy spatial distribution power spectrum arising from the acoustic peaks in the matter spatial distribution power spectrum of the Universe before recombination.

baryon number:
The number of baryons (protons, neutrons, and other particles composed of three quarks) minus the number of anti-baryons in a given reaction. In the standard model of particle physics, baryon number is conserved in any process.

baryon wiggles:
See baryon acoustic oscillations.

basis vector:
See coordinate basis vectors.

B-band filter:
A broad band photometric filter used in astronomy spanning the wavelength range from about 400 to 500nm.

BCG:
Brightest Cluster Galaxy. The brightest galaxy in a cluster of galaxies, usually in the centre of the cluster.

beam:
A term adopted from radio astronomy used to refer to the area on the sky occupied by a point source when observed with a given telescope.

beaming:
An effect arising in the special theory of relativity whereby electromagnetic radiation emitted isotropically by material which is travelling towards an observer at a speed close to the speed of light, is observed as being concentrated into a narrow emission cone centred on the direction of motion.

beat frequency:
The frequency of a periodic oscillation that arises from the superposition of two other oscillations with different frequencies. The beat frequency is the sum or difference of these two frequencies. The corresponding period is the beat period, where $f_{beat} = 1/P_{beat}$.

beat period:
See beat frequency.

bell curve:
See Gaussian distribution.

BeppoSAX:
An Italian-Dutch X-ray astronomy satellite which operated from 1996 to 2003.

Be star:
A star of spectral type B (see spectral classification) which is irregularly variable and shows strong emission lines in its spectrum. The emission from a Be star is often polarized and the star's infrared emission is often stronger than that of other B stars, that is their spectra exhibit an infrared excess. These unusual properties are a result of a strong stellar wind, which often forms a circumstellar disc. Be stars with accreting neutron star companions are often observed as high mass X-ray binaries.

beta-decay:
A type of radioactive decay process. There are three distinct kinds of decay processes that are classed as β-decay. In beta minus decay (β^- decay) the nucleus spontaneously emits an electron and an antineutrino. In beta plus decay (β^+ decay), also called inverse beta decay or positron decay, the nucleus spontaneously emits a positron and a neutrino. In electron capture the nucleus spontaneously captures an orbiting electron and emits a neutrino; an X-ray is also emitted as an electron in an outer shell falls into the vacancy left by the capture.

beta minus decay:
A weak interaction process involving the emission of an electron and an anti-neutrino from a neutron, to leave a proton: $n \rightarrow p + e^- + \bar{\nu}_e$

beta-particle:
Another name for an energetic electron emitted by a nucleus in beta minus decay.

Beta Pictoris:

The second brightest star in the constellation Pictor. It shows an excess of infrared emission compared to normal stars of its class, and detailed observations reveal a large circumstellar disc, which may be a region where planets could form (see protoplanetary disc).

A planetary companion (β Pic b) has been imaged within the disc.

beta plus decay:
See inverse beta decay.

bias parameter:

The linking constant, *b*, in the empirical relationship between the measurement of quasar clustering and dark matter clustering:

$$\left(\frac{\delta\rho}{\rho}\right)_{\rm QSOs} = b\left(\frac{\delta\rho}{\rho}\right)_{\rm dark\ matter}$$

Big Bang:
The name given to the current standard cosmological model (see cosmology), in which the Universe began in a very hot, dense state and has been expanding and cooling ever since. The Big Bang model successfully explains the observed recession of distant galaxies (see Hubble's law), the properties of the cosmic microwave background radiation, and the abundances of the light elements in the Universe (see nucleosynthesis). As a result of the cosmological principle, the expansion of the Universe can be described in terms of the evolution of a single quantity, the scale factor, which describes the changing physical distance between typical points in the Universe. At the present time the scale factor is increasing with time, giving rise to the observed expansion. The behaviour of the scale factor depends on the amount of matter (and energy) in the Universe, and the ultimate fate of the Universe is determined by whether the gravitational effects of matter are strong enough to overcome the expansion (see big crunch, open universe, closed universe).

big blue bump:
A feature in the spectral energy distribution of some AGN that is probably due to thermal emission from an accretion disc.

big crunch:
A hypothetical end to the Universe, in which the density of the Universe is high enough that gravitational attraction overcomes the currently observed expansion (see Hubble's law) and the Universe recollapses. Currently it is not thought that this will happen. See also closed Universe.

bimodal:
Statistical term referring to a distribution with two distinct modes, possibly indicating two distinct sub-samples.

binary fraction:
The incidence of binarity. Fraction of stars residing in a binary or multiple stellar system.

binary pulsar:
A binary star consisting of two neutron stars, at least one of which a pulsar. The first example, and the most well studied, is PSR B1913+16 discovered by Hulse & Taylor, which has proved to be an excellent test-bed of general relativity.

binary star:
A stellar system consisting of two stars that orbit around their common centre of mass. A large fraction (up to 50%) of stars are in binary systems. Binaries can be classified according to their observational properties: visual binaries are identified by the direct detection of the two stars, eclipsing binaries by the fact that one star passes in front of the other as seen from the Earth, and spectroscopic binaries from periodic shifts in the spectral lines (emission or absorption) from the stars' atmospheres. They can also be classified by the degree of interaction between the two stars; detached binaries have no interaction while semidetached and contact binaries have increasing degrees of mass exchange between the two stars. If one of the two bodies in an interacting binary system is a white dwarf or neutron star, then phenomena powered by accretion, such as cataclysmic variables and X-ray binaries, may be observed. Observations of the orbits of binaries provide almost the only way of measuring the mass of stars other than the Sun.

binary system:
See binary star.

binding energy:
The least amount of energy which must be provided to disrupt a body formed of two (or more) parts. For example, in the case of a nucleus, the binding energy is the energy required to separate the nucleus into its individual protons and neutrons. (The binding energy is also equal to the energy that would be released if the nucleus were to be assembled from its separated constituents.) The binding energy of most nuclei is ≈8 MeV per nucleon.

binding energy per nucleon:
The amount of energy, obtained by dividing the binding energy *B* of a specified nucleus by the mass number *A* of that nucleus. The binding energy per nucleon provides a measure of the stability of a nucleus relative to other nuclei. A large value of *B*/*A* indicates a more stable nucleus.

biomarker:
A spectral signature of possible life on a planet.

bipolar outflow:
A flow of matter away from a central object (such as a star) in which the flow travels along an axis, in two opposite directions. Bipolar outflows from stars appear to be common in the early states of star formation, and are often seen, for example, coming from T Tauri stars.

Birkhoff's theorem:
States that even if a source of gravitation is not static (and therefore not necessarily stationary), as long as its effect is isotropic, the vacuum solution of the Einstein field equations in the region exterior to the source is still stationary and is still the Schwarzschild solution.

birth function:
With regard to a population of extragalactic sources, it is the number of sources of a given jet-power born per unit cosmic time per unit comoving volume in the redshift interval from z to $z + dz$. It is distinct from the more traditionally studied luminosity function. The birth function gives the triggering rate of these phenomena while the luminosity function includes only objects above survey flux-limits at redshifted finding-frequencies. (The luminosity function does not decouple the individual luminosity evolution of sources from the birth rate, hence it is not a direct measure of the triggering rate.)

black body:
An ideal absorber of electromagnetic radiation that would absorb all the radiation that was incident upon it. Such a body would also be an ideal emitter, and would emit electromagnetic radiation with a spectrum that depended only on the temperature of the body. See black body radiation.

black body radiation:
Electromagnetic radiation that is in thermal equilibrium with matter at a fixed temperature. Its name derives from the fact that its spectrum is identical to that which would be emitted by a black body at an appropriate temperature. Black body radiation is also called thermal radiation or cavity radiation.

black body spectrum:
The spectrum (intensity of radiation in a small wavelength range $\Delta\lambda$ at each wavelength λ) emitted by a black body.

black body temperature:
The temperature a luminous source would have if it were to radiate its power as a black body spectrum. For a star this is the effective temperature.

black hole:

In the general theory of relativity, an object whose density is so high that nothing that comes within a certain distance of it, crossing a boundary called the event horizon, can subsequently emerge. This includes light (photons) and other massless particles, giving the black hole its name.

To be a black hole a (non-rotating) system of mass M must lie within its Schwarzschild radius, $R_S = 2GM/c^2$, which is also the size of the event horizon (of a Schwarzschild black hole).

The results are more complicated for a rotating black hole (known as a Kerr black hole), which is more realistic, but the Schwarzschild radius still defines a useful characteristic radius.

Black holes are the expected endpoints of the evolution of very massive stars (after a type II supernova explosion) and supermassive black holes lie at the centres of many galaxies, including the Milky Way. Accretion onto stellar-mass black holes gives rise to some X-ray binaries, while accretion onto galactic-centre black holes powers active galaxies.

black smokers:
Deep sea hydrothermal vents.

BLAST:
The Balloon-borne Large Area Submillimetre Telescope.

blazar:
A galaxy which is a member of the class of active galaxies which encompasses the BL Lac objects and the OVV quasars. The common property that unites blazars is strongly variable radio and optical emission, which is thought to be due to a relativistically moving jet seen at a small angle to the line of sight. (See Doppler boosting.)

blend:
In an astronomical image where more than one point source of light is merged together to form an apparent single object.

BL Lac object:
A galaxy that is a member of a class of active galaxy (named after the prototype object, BL Lacertae, that was originally thought to be a variable star) that is characterized by strong, violently variable, polarized optical emission, together with strong nuclear radio and X-ray emission and in some cases extended radio lobes. No

or very weak emission lines are seen, and the redshift must usually be determined from absorption lines in the spectrum of the underlying galaxy. In unified models for active galaxies, BL Lacs are thought to be low-power radio galaxies seen at a small viewing angle. See blazar.

BLR:
See broad-line region

blue cloud:
Part of the distribution of galaxies in the colour-magnitude plane. The blue cloud comprises galaxies undergoing active star formation. See red sequence, green valley.

blue loop:

A track in the Hertzsprung-Russell diagram made by massive stars ($M_{ms} > 8M_\odot$) as they undergo advanced stages of nuclear fusion beyond He-burning. They begin with an excursion to higher effective temperature (blueward) when fusion ignites, and then return (redward) towards the giant branch when core burning is exhausted and shell burning continues. Thus they make a blueward loop away from the giant branch.

blueshift:
A shift of a spectral line to bluer (shorter) wavelengths. See redshift.

bolometric correction:
The correction in magnitudes which is applied to a magnitude measured at a given wavelength to convert it to a bolometric magnitude, i.e. the difference $m - m_{bol}$.

bolometric magnitude:
A magnitude (either an absolute magnitude or an apparent magnitude) measured over all wavelengths rather than being restricted to any particular waveband. See also bolometric correction.

Boltzmann constant:
The constant that relates temperature to energy. It has a value of $k = 1.381 \times 10^{-23}$ J K^{-1}. In classical physics, the average translational energy of a molecule in a gas that is in thermal equilibrium at (absolute) temperature T is given by $3kT/2$.

Boltzmann distribution law:
A law stating that, for a (classical) gas in thermal equilibrium at absolute temperature T, the probability of finding a given molecule in a given phase cell of energy E is $p = Ae^{-E/kT}$, where A has the same value for all phase cells, no matter what their energy.

Boltzmann equation:

An equation that gives the relative population of two different energy levels in a system in thermodynamic equilibrium at absolute temperature T. If the two levels are separated by an energy E, and the degeneracies of the two levels (i.e. the number of states at each level with the same energy) are g_1 and g_2, then

$N_2/N_1 = (g_2/g_1) \exp(-E/kT)$

where k is the Boltzmann constant.

Boltzmann factor:
An exponential factor of the form $\exp(-E/kT)$, such as appears in the Boltzmann equation, which involves the ratio of some energy E to the thermal energy kT of the system.

Boltzmann occupation factor:
The factor $NAe^{-E/kT}$ that determines the average number of particles occupying a quantum state of energy E in a system of N distinguishable particles in thermal equilibrium at absolute temperature T. The parameter A is a normalization factor, and k is the Boltzmann constant.

Bond albedo:
The fraction of light reflected by a planetary body, integrated over all wavelengths.

bottom quark:
A quark with electric charge $-e/3$. Along with the top quark, a member of the heaviest generation of quarks.

bottom-up:
See hierarchical formation.

boundary layer:
The transition region from a Keplerian accretion disc to the surface of the accreting (non-magnetic) star.

bound-bound:
A term used to describe a transition in which an electron goes from one bound state to another resulting in the emission or absorption of a photon. Contrast with free-free, bound-free and free-bound transitions.

bound-free:
A term used to describe a transition in which an electron goes from being bound to an atom to being unbound ('free'). Most commonly this occurs when the atom absorbs a photon with sufficient energy to eject the electron (see photoionization). If the photon has insufficient energy to eject the electron then a bound-bound transition may occur.

bound particle:
A particle that is trapped in a potential well because its total energy is less than its potential energy at every point on the boundary of the well. In classical physics, a bound particle is rigorously confined to the region in which the potential energy is less than the total energy. In quantum mechanics, tunnelling can occur, and the particle can stray beyond the classically allowed region; nevertheless, the wave function of the particle usually decreases rapidly beyond the classically allowed region, so the probability of tunnelling is generally quite small. In quantum mechanics, the energy levels of a bound particle are discrete.

bowshock:
A shock that forms in advance of the leading edge of a body moving or expanding supersonically through a fluid medium. Bow shocks have a characteristic shape and are observed in a number of astrophysical situations, including around rapidly moving X-ray binaries and the lobes of radio galaxies.

Boyer-Lindquist coordinates:

The coordinates used to describe the Kerr metric. ϕ is a standard spherical coordinate, but θ and r are related to standard Cartesian coordinates by

$x = (r^2 + a^2)^{1/2} \sin\theta \cos\phi$

$y = (r^2 + a^2)^{1/2} \sin\theta \sin\phi$

where $a = J/Mc$ and J and M are the mass and angular momentum of the black hole.

BPT diagram:
See Baldwin Phillips Terlevich diagram.

Brackett series:
The series of hydrogen spectral lines arising in atomic transitions whose lowest energy level is that with $n = 4$. Contrast with Balmer series, Lyman series, Paschen series.

branching point:

The lifetimes of some unstable nuclei before they β-decay depends on whether the nucleus is in its ground state or is excited. Consequently, in the s-process some such nuclei will β-decay to the next element, whereas others will survive long enough to capture another neutron and become a heavier isotope of the same element. These separating paths in the chart of nuclides are called branchings, and the isotopes for which it can occur are called branching points.

bremsstrahlung:
See free-free emission.

brightest cluster galaxy:
The brightest galaxy in a cluster of galaxies (usually lying at its centre), often a giant elliptical galaxy.

brightness temperature:

A temperature defined such that the flux at any wavelength, λ, emitted per unit surface area by a body is given by the Planck function at this temperature $B_\lambda(T_{\mathrm{bright}})$. The relationship between the effective temperature of a star and its brightness temperature depends on the spectral type of the star and on ithe wavelength being considered. However, it is generally within a factor of order unity.

The brightness temperature is also commonly used in radio astronomy, where the frequencies are in the Rayleigh-Jeans tail of the black body spectrum. In this case the brightness temperature is given by $T_{\mathrm{bright}} = B_\nu c^2/2k\nu^2$, where B_ν is the surface brightness (flux density per unit solid angle) of the source at frequency ν, k is the Boltzmann constant, and c is the speed of light.

bright spot:
The location on an accretion disc in a semidetached binary star where the accretion stream from the inner Lagrangian point impacts the disc. As its name suggests, the bright spot is more luminous than other parts of the disc.

broadband noise:
Variability in a light curve across a broad range of frequencies, in excess of Poisson noise.

broadening:
The phenomenon whereby spectral lines exhibit a line profile that is broader than their natural line-width would dictate. Causes of broadening are associated with the environment in which the line is formed and include pressure broadening and thermal broadening.

broad infrared lines:
Broad emission lines (widths ~2000 km s^{-1}) seen in the infrared spectra of galaxies

that are proposed to be obscured Seyfert 1 galaxies.

broad-line clouds:
Clouds of material responsible for the broad emission lines seen in the spectra of AGN. Broad-line clouds are believed to be closer to the central engine of AGN than are narrow-line clouds. See broad-line region.

broad-line radio galaxy:
See radio galaxy.

broad-line region:
The region responsible for producing the broad emission lines seen in the spectra of some classes of active galaxy. See also quasar and Seyfert galaxy.

broad-line region structure:
The structure of the broad-line region of an active galaxy; the distribution of the broad-line clouds.

brown dwarf:
Objects similar to stars, but with a temperature too low for hydrogen burning to begin. Brown dwarfs contract from protostars in the same way as stars, but their low mass means that electron degeneracy sets in before the temperature required for thermonuclear reactions is attained. Degeneracy pressure then supports the brown dwarf, and its small radiative output is powered by slow gravitational contraction (see Kelvin-Helmholtz contraction time). Brown dwarfs are cool, faint objects and inherently difficult to observe, but a number of possible brown dwarf candidates have been discovered.

bulk viscosity:
The viscosity which arises when the flow velocity varies along the flow.

Butcher-Oemler effect:
The observation that at higher redshifts (z ~ 0.4) there is a larger fraction of blue galaxies in the cores of clusters than are seen in the cores of clusters in the local Universe. It suggests more star formation at higher redshifts in cluster core galaxies.

BzK galaxies:
A population of galaxies selected in the (B-z) versus (z-K) colour-colour plane which satisfy (z-K)-(B-z) > -0.2. They are star forming galaxies at redshift >1.

C

cadence:
The time between individual measurements.

calculus:
The branch of mathematics concerned with the way in which small changes in one quantity determine, or are determined by, changes in related quantities.

carbon burning:

A nuclear fusion process in which carbon nuclei react with one another to produce neon, sodium and magnesium. The process can, for a time, become the dominant means of core energy production in the post-main-sequence life of initially massive stars ($M_{ms} > 8M_{\odot}$).

carbon-nitrogen cycle:
A nuclear fusion process involving isotopes of carbon, nitrogen and oxygen that are used as catalysts in the conversion of H to He. The CN cycle is the more common part of the CNO cycle. It operates at lower temperatures than the oxygen-nitrogen cycle.

Cartesian components:
The scalar quantities required to specify a vector relative to a Cartesian coordinate system. For example, a vector $\boldsymbol{v}$ may be specified relative to a three-dimensional Cartesian coordinate system, with axes x, y and z, by determining the projection of $\boldsymbol{v}$ in the x-, y- and z-directions. These projections are the Cartesian components v_x, v_y and v_z, and we can write $\boldsymbol{v} = (v_x, v_y, v_z)$. The term 'Cartesian components' is often abbreviated to 'components'.

Cartesian coordinates:
See Cartesian coordinate system

Cartesian coordinate system:
A system of mutually perpendicular axes, meeting at a single point called the origin, and calibrated in a common way (usually in metres, starting from zero at the origin), that allows the position of any point to be uniquely specified by an ordered set of values. In three-dimensional space, three axes are required; these are conventionally labelled x, y and z; and the coordinates of a point P are represented by the ordered triplet of position coordinates (x_P, y_P, z_P). Three-dimensional Cartesian coordinate systems may be right-handed or left-handed. It is conventional to use right-handed systems for most purposes.

case A mass transfer:

Mass transfer in a binary star system driven by a star's slow expansion whilst on the main sequence undergoing hydrogen-burning.

case A recombination:
Recombination (electrons recombining with ions) occurring in a nebula under conditions such that each radiative transition produces a photon which escapes from the nebula. Under such conditions, the recombination lines are all optically thin.

case B mass transfer:
Mass transfer in a binary star system driven by a star's rapid expansion towards the giant branch and along the red giant branch, but before the ignition of core helium burning.

case B recombination:

Recombination occurring in a nebula under conditions such that the Lyman series lines are optically thick, so Lyman series photons are degraded to lines of other series plus Lyα. See recombination lines.

case C mass transfer:
Mass transfer in a binary star system driven by a star's rapid expansion along the asymptotic giant branch, after the termination of core helium burning.

cataclysmic variable:
A compact binary system, consisting of a white dwarf and a low-mass main-sequence star, in which much of the optical emission comes from an accretion disc around the white dwarf primary. Many cataclysmic variables (CVs) show regular increases and decreases in luminosity, known as dwarf nova outbursts, which are due to accretion disc instabilities. Others have much more powerful classical nova outbursts that occur when enough hydrogen has accumulated to allow a temporary phase of thermonuclear burning on the surface of the white dwarf. CVs with high magnetic fields behave differently: see magnetic cataclysmic variable.

causality:
The principle that all observers must agree that any effect is preceded by its cause.

causally related:
Events which mighty be linked by a light signal, or any signal that travels at less than the speed of light, are said to be causally related.

caustic:
In gravitational lensing, the critical positions in the source plane (i.e. the plane of the background lensed source) where the images become merged.

CCD photometer:
An electronic imaging device (Charge Coupled Device) containing a light-sensitive silicon chip which is able to detect individual photons. CCDs are composed of a regular array of pixels, typically 1024 x 1024 or 2048 x 2048 in size.

CDM:
See cold dark matter.

central engine:

A term used to refer to the central source of energy in an AGN, namely a supermassive black hole.

Alternatively, a term used to refer to the site of a gamma-ray burst, thought to be either a hypernova or a coalescence of two compact objects.

centre of mass:
The unique point associated with any given rigid body (which does not necessarily lie within the body) with the property that if any unbalanced force acting on the body has a line of action that passes through the centre of mass, then the only effect of that force will be to cause translational *acceleration* of the body. If the total external *force* acting on a body is $\boldsymbol{F}$, the acceleration of the centre of mass is $\boldsymbol{a} = \boldsymbol{F}/m$, where m is the total mass of the body. So, if the body experiences no net external force (e.g. if it is isolated), its centre of mass moves with constant velocity. The centre of mass can therefore be regarded as the point at which Newton's laws for particle motion can most easily be applied to rigid bodies.

centre of momentum (frame):
A frame of reference such that the total momentum of the system with respect to the frame is zero.

centrifugal force:
A fictitious force that may be used to account for certain aspects of the motion of bodies observed from a rotating (non-inertial) frame of reference. The effect of the centrifugal force is to cause bodies to accelerate radially outwards from the axis of rotation. By introducing such fictitious forces, the motion of the bodies may be made to conform with the predictions of Newton's laws, which do not, strictly speaking, apply in such frames. See also Coriolis force.

centripetal acceleration:

The acceleration of a particle moving in a circle. The acceleration is directed towards the centre of the circle and has magnitude $\omega^2 r$, where ω is the angular speed of the particle about the centre of the circle, and r is the radius of the circle.

centripetal force:
The unbalanced *force* (whatever its origin) required to keep a body in uniform circular motion about a fixed point. When a *particle* of mass m moves around a circle of radius r with uniform angular speed ω (and therefore uniform speed $v = r\omega$), its acceleration is always directed towards the centre of the circle and has magnitude $a = r\omega^2 = v^2/r$. It follows from Newton's second law of motion that such a particle must be subject to an unbalanced force, directed towards the centre of the circle, with magnitude $F = mr\omega^2 = mv^2/r$; this is the centripetal force.

Cepheid variable:
A type of variable star with a well defined relationship between period and luminosity, named after the prototype delta Cephei. Two types exist, following different period-luminosity relationships. Type I Cepheids are massive young stars, whilst type II Cepheids are low mass stars. They may be used as a standard candle.

Cerenkov imaging:
The process of making an image of astronomical Cerenkov radiation. High-energy gamma-ray telescopes rely on this process to distinguish between the radiation due to cosmic rays (high-energy particles originating in space) and the radiation produced by the gamma rays themselves, both of which produce Cerenkov radiation because they generate a shower of high-energy particles when they interact with the atmosphere. Imaging (mapping the distribution of) the Cerenkov radiation observed on the ground allows the telescope to select only the gamma rays and ignore the cosmic ray background.

Cerenkov radiation:
Radiation produced when a particle travelling through a medium moves faster than the speed of light in that medium. For a medium with a refractive index n the speed of light in the medium is c/n, so Čerenkov radiation is produced when the speed of the particle v is greater than c/n. Cerenkov radiation is important as a means of detecting energetic particles. In astronomical contexts, these include cosmic rays and solar neutrinos. Ground-based high-energy gamma-ray telescopes rely on Cerenkov radiation to detect gamma rays, using the Earth's atmosphere as a detector.

chain galaxy:
A type of very distant, irregular galaxy first observed in the Hubble deep field.

chain rule:
The statement that derivatives may be combined in the manner $\mathrm{d}y/\mathrm{d}x = \mathrm{d}y/\mathrm{d}u \times \mathrm{d}u/\mathrm{d}x$. This can help to simplify finding the derivatives of certain functions by substitution of variables.

Chandra:
A NASA X-ray Astronomy Satellite launched in 1999 and still currently active. It was omptimised for imaging, and has unprecedented spatial resolution of order 1 arcsec or better. The sharp focus and extremely low background noise level enable detection of an X-ray source with as few as 5 X-ray photons. However, this was only achieved by sacrificing sensitivity, as the quality of the mirrors was chosen over quantity.

Chandrasekhar limit:
The theoretical upper limit to the mass of a white dwarf, about $1.4\mathrm{M}_{\odot}$, also called the Chandrasekhar mass. Contrast with Oppenheimer-Volkoff limit.

Chandrasekhar mass:
The maximum stellar mass that can be supported by electron degeneracy pressure: hence an upper limit on the mass of a white dwarf. The limit arises when the electrons at the centre of the star become fully relativistic. The value of the Chandrasekhar mass depends on the model used for the internal structure of the white dwarf and on its composition, but is around 1.4 solar masses. A stellar remnant with a higher mass, or a white dwarf whose mass exceeds the Chandrasekhar mass as a result of accretion, will collapse further, perhaps in a supernova explosion, to become a neutron star or black hole.

charm quark:
A quark with electric charge $+2e/3$. Along with the strange quark, a member of the second generation of quarks.

chart of nuclides:

An arrangement of all possible isotopes according to the number of neutrons N and protons Z they contain. N increases from left to right, and Z increases from bottom to top. Thus ${}^{1}_{1}\mathrm{H}$ occupies the lower-left position, while isotopes like ${}^{238}_{92}\mathrm{U}$ are found towards the upper-right.

chemical potential:

A quantity, usually denoted μ (or μ') used to describe the energy that each particle in an ensemble brings to the total. The chemical potential, temperature and pressure fully describe the thermodynamic state of a gas. The SI unit of chemical potential is the joule (J).

chemolithotrophic:
Refering to bacteria which obtain their energy from the oxidation of inorganic (non-carbon) compounds.

chi-squared:
A statistical measure of the goodness of fit between a model and data. Chi-squared is the sum of the squared differences between model and data, weighted by the corresponding uncertainties. If a given measurement of the *N* data points results in a chi-squared value close to *N*, then the this indicates that the model is a sensible representation of the data. A higher value of the chi-squared indicates that the model does not fit the data well, whilst a lower value indicates that the assumed uncertainties are probably over-estimated.

chi-squared minimisation:
The process of adjusting the parameters of a model such that a minimum value of the chi-squared statistic is achieved.

chromatic aberration:
Distortions introduced into an image as a result of optical elements that cause light of different colours to be focussed to different points.

circularization radius:
The radius of a circular orbit centred on the accretor in an interacting binary system, where the orbital angular momentum per unit mass is the same as for material leaving the donor at the inner Lagrangian point. Hence, the radius from the accreting star at which material will first settle, before spreading via viscous diffusion into an accretion disc.

circular polarization:
Electromagnetic radiation is said to be circularly polarized if it is polarized in such a way that its electric field vector at any point maintains constant magnitude while rotating uniformly about the direction in which the radiation is travelling.

circumstellar dust:
Dust that exists around a star.

cirrus:
Wispy-looking interstellar dust.

cirrus-confusion noise:
If the limit of source-confusion in deep-field images is due to the presence of foreground cirrus structure, this is known as cirrus-confusion noise.

citation:
A reference to another piece of work, such as a journal article.

cite:
The act of referring to another (usually prior) piece of work. Most research papers will cite a dozen or more previous works.

classical narrow line region:
Another name for the narrow line region of active galaxies.

classical nova:
A member of a particular subclass of cataclysmic variables which shows an extreme brightening due to runaway thermonuclear burning on the surface of the accreting white dwarf. Classical nova outbursts may recur on timescales of tens of thousands of years.

classical physics:
One of the major subdivisions of physics that should be compared and contrasted with quantum physics. Classical physics is often taken to consist of those subjects, such as mechanics, electromagnetism and thermodynamics, that were already well-defined by the year 1900, along with their direct developments in the twentieth century.

Class I habitat:
A planetary body on which the stellar and geophysical conditions lead to Earth-analogue planets.

Class II habitat:
A planetary body where life may evolve, but with stellar and/or geophysical conditions which differ from those of a Class I habitat. Mars and Venus are members of this class.

Class III habitat:
A planetary body which harbours sub-surface water in direct contact with a silicate-rich core. The Jovian moon Europa may be such a body.

Class IV habitat:
A planetary body with sub-surface water which does not interact with a silicate-rich core. Saturn's moons Titan and Enceladus may be examples of this class.

closed-box model:

A model linking the observed high redshift neutral hydrogen matter density to the current comoving stellar density. It is a 'closed-box' model because it assumes that damped Lyman alpha systems (which dominate the high redshift neutral hydrogen matter density) do not interact much with their environment. Such models give rise to the G-dwarf problem.

closed hypersurface:
A hypersurface with curvature parameter $k=+1$.

closed neutron shell:
The neutrons in a nucleus can be thought of as arranged into shells. Fully populated (closed) shells have greater stability. This is analogous to the concept of electron shells in atomic structure, though the numbers of particles in a closed shell differ in the two cases. Closed-shell nuclei have a much lower neutron-capture cross-section than neighbouring nuclei in the chart of nuclides. This greater stability leads to peaks in the abundance distribution at these isotopes. Neutron numbers corresponding to closed shells are called neutron magic numbers.

closed universe:
A universe, in the Big Bang cosmological model, in which the mean density is high enough to halt the expansion of the universe, leading to a recontraction and eventually a big crunch. Compare with open universe.

cloud-in-cloud problem:
The expression of the question: could an object that's a virialised clump on one mass scale also be later contained in another larger clump on a bigger mass scale?

clump red giant star:
A star which has already started helium burning at the helium flash and is burning the helium in the core. As evolution slows during core helium burning, such stars pile up in the Hertzsprung-Russell diagram, forming a small clump just to the left of the red giant branch.

CMB:
See cosmic microwave background radiation.

CN cycle:
See carbon-nitrogen cycle.

CNO cycle:
The collective name for two cycles (the CN cycle and ON cycle) in the nuclear fusion processes that dominate the energy production in the hydrogen burning phase of stars more massive than the Sun. In both cycles, existing heavy elements (carbon and nitrogen) act as catalysts for the production of helium from hydrogen, without being consumed themselves. Neutrinos and high-energy photons are byproducts of the process. See also proton-proton chain.

COBE:
The COsmic Background Explorer satellite which mapped the cosmic microwave background radiation across the whole sky.

CODEX:
The COsmical Dynamics EXperiment, a very high resolution spectrograph that is planned for the E-ELT.

cold dark matter:
Dark matter whose particles move slowly. See hot dark matter, warm dark matter.

collapsar:
See hypernova.

collisional de-excitation:
A process whereby an atom in an excited state drops to a lower energy level as a result of a collision with another atom, ion or free electron.

collisional excitation rate:
The constant of proportionality, q, in the expression relating the number of atoms per second which are raised into excited quantum states (i.e. above the ground state) as a result of energy transfer due to collisions with other particles (not photons) and the product of the number densities of the two species involved in the collision, i.e. rate = qn_An_B. See also radiative transition.

collisionally excited:
Atoms or ions which are raised to energy levels above the ground state by collisions with energetic particles.

collisionally suppressed:
The phenomenon whereby forbidden lines are prevented from forming in a relativiely high density gas. Collisions between the atoms or ions give rise to collisional de-excitation.

colour:
See colour index.

colour-colour diagram:
A graph on which each of the two axes represents a different colour index of a set of astronomical objects.

colour excess:

A numerical quantity used to describe how much a star has been reddened by wavelength-dependent extinction. It is defined to be the difference in magnitudes between the measured colour index of a star and its expected intrinsic value:

$E = (B - V) - (B - V)_0$

colour index:
A numerical quantity used to give an approximate description of the colour of a star. It is defined to be the difference between the magnitudes of a given star measured at two different standard wavelengths. Because of the (approximately) black body spectrum of stars, the colour index is an indication of a star's temperature, and so is often plotted as part of an observational Hertzsprung-Russell diagram. The colour index is most often calculated from the difference between the magnitudes in the blue (*B*, 440 nm) and visual (*V*, 550 nm) bands, but other indices are in use. A given spectral class of star has an expected intrinsic colour index (corresponding to an expected surface temperature) which can be used to calculate the colour excess.

colour-magnitude diagram:
A graph of the magnitude of a sample of astronomical objects against the colour index. The Hertzsprung-Russell diagram is an example of a colour-magnitude diagram.

column density:
A quantity used to describe the amount of absorption due to a specified species along a given line of sight. It is defined to be the integral of the number density of particles of the specified species along the line of sight. Units are m^{-2} (SI) or cm^{-2} (cgs).

Coma cluster:
A large cluster of galaxies about 100 Mpc away.

COMBO-17:
(Classifying Objects by Medium-Band Observations in 17 filters) A photometric galaxy redshift survey.

common envelope:

A situation that can occur in the evolution of close binary stars. When a star expands beyond its Roche lobe radius, it will start rapid mass transfer onto the other star. As a result of losing mass in this way, the envelope of the donor star may expand even more rapidly, so causing an even higher mass transfer rate and an even faster expansion. The result of this run-away process is a rapidly expanding envelope that engulfs both stars.

The common envelope therefore contains the cores of both stars orbitting within it. Frictional forces convert energy from the binary orbit into heat, which causes the orbital separation between the two stars to decrease and the envelope to expand. The common envelope phase ends when sufficient orbital energy has been lost to unbind the envelope from the binary and expel it. As a result the orbital period reduces greatly resulting in a compact binary composed of the core of the evolved star and the other star. Numerical simulations indicate that a common envelope phase lasts less than 1000 years.

comoving coordinate:
Coordinates defined such that the worldline of a fundamental observer is assigned the same values of the three spatial coordinates on every space-like hypersurface. In an expanding (or contracting) universe, the grid of comoving coordinates must expand (or contract) with the space-like hypersurfaces.

comoving distance:
The comoving distance is equal to the scale factor at the present time R_0 multiplied by the comoving coordinate separation.

comoving volume:
A volume defined using comoving coordinates. Any particular comoving volume will grow at a rate described by the scale factor.

compactness parameter:

A parameter that determines the importance of pair production at a distance R from an astrophysical object, such as an AGN. The compactness parameter is given by

$$l = 2\pi \left(\frac{L_\gamma}{L_\mathrm{E}}\right) \left(\frac{R_\mathrm{S}}{R}\right) \left(\frac{m_\mathrm{p}}{m_\mathrm{e}}\right)$$

where L_γ is the gamma-ray luminosity of the source, L_E is its Eddington luminosity, R_S the Schwarzschild radius of the central black hole, and m_p and m_e are the masses of the proton and electron. If $l \geq 4\pi$ then pair production reactions will be important.

compact object:
A white dwarf, neutron star or black hole.

complete sample:
A sample or survey which contains no biases or selection effects.

components:
A set of scalar quantities that can be used to specify a vector. See Cartesian components.

Comptonization:
The effect of inverse Compton scattering on an initial spectrum of electromagnetic radiation.

Compton scattering:
The process whereby energetic photons transfer energy and momentum to charged particles, typically electrons. Compton scattering differs from Thomson scattering in that the energies of the incoming photons are typically much higher, so that the energy transferred to the electrons and the change in energy of the photons are not negligible, as they are in Thomson scattering. Compare inverse Compton scattering.

Compton upscattered:
Radiation which has undergone inverse Compton scattering is said to be Compton upscattered.

Compton y parameter:

The quantity

$$\int n_e \frac{kT}{m_e c^2} \sigma_{\mathrm{T}} \mathrm{d}l$$

in the evaluation of the Sunyaev-Zel'dovich effect.

concordance cosmology:
Used to describe the level of agreement between cosmological parameters derived from the cosmic microwave background radiation and cosmological parameters derived from other measurements, such as distant supernovae.

confinement mechanism:
With relation to the broad line region of active galaxies, a means of maintaining the integrity of clouds against processes such as evaporation.

conformal time:
A variable used in cosmological models such that the past lightcone takes on the form it would have in the flat spacetime of special relativity.

confusion limit:
The limit beyond which individual objects cannot be separated using a particular telescope.

conjunction:
The two points in an orbit where the two bodies involved are most closely aligned with each other, as viewed from Earth. See inferior conjunction and superior conjunction.

connection coefficients:

In an n-dimensional Riemannian space there are n^3 connection coefficients, usually denoted by $\Gamma^i{}_{jk}$ (where i, j, k = 1, 2, ..., n), though due to symmetry they are not all independent. $\Gamma^i{}_{jk}$ represents the component in the direction of basis vector $\mathbf{e}_i$ of the rate of change of basis vector $\mathbf{e}_j$ with respect to the coordinate x^k, i.e.

$$\frac{\partial e_j}{\partial x^k} = \sum_i \Gamma^i{}_{jk} e_i$$

In terms of the metric coefficients, the connection coefficients are:

$$\Gamma^i{}_{jk} = \frac{1}{2} \sum_l g^{il} \left(\frac{\partial g_{lk}}{\partial x^j} + \frac{\partial g_{jl}}{\partial x^k} - \frac{\partial g_{jk}}{\partial x^l} \right)$$

conservation law:
Any law that expresses the fact that a certain physical quantity (such as energy or momentum) remains constant in time under specified circumstances. Such laws are often referred to as conservation principles.

conservation of angular momentum:
The principle that, in any system, the total angular momentum about any point remains constant as long as no net external torque about that point acts on the system.

conservation of electric charge:
A fundamental law of electromagnetism that electric charge can neither be created nor destroyed.

conservation of energy:
The principle that the total energy of any isolated system is constant. A more informal statement of this principle is that energy may neither be created nor destroyed.

conservation of linear momentum:
The principle that the total linear momentum of any isolated system is constant.

conservation of mass:
The principle, in classical Newtonian mechanics, that the mass of any system remains constant, provided no matter enters or leaves the system. A more informal statement of this principle is that mass cannot be created or destroyed. (The development of special relativity has shown that this principle is not generally true, though it is still of considerable value and is widely used within Newtonian mechanics.)

conservative force:
A force with the characteristic that the *work* it does when its point of application moves from one position to another, is independent of the route followed between those two points. (This is equivalent to the requirement that the work done by the force when its point of application moves around a closed loop is zero.) The gravitational force on a body of fixed mass is an example of such a force.

conservative mass transfer:
A form of mass transfer in a binary system, where the total mass and total angular momentum of the system remains constant. If during the mass transfer process the system loses mass or angular momentum into space, the mass transfer is said to be non-conservative.

constant acceleration equations:

A set of equations relating the displacement, velocity and acceleration of a uniformly accelerating particle. For a particle accelerating along the x-axis, the equations are

$$s_x = u_x t + \tfrac{1}{2} a_x t^2$$
$$v_x = u_x + a_x t$$
$$v_x^2 = u_x^2 + 2 a_x s_x$$

where s_x is the displacement of the particle at time t from its initial position at time t = 0; the initial velocity (at time t = 0) is u_x, and v_x is the final velocity at time t. The acceleration is a_x and must be constant for the equations to apply.

If the (constant) acceleration is specified by the vector $\boldsymbol{a}$ = constant, then

$$\mathbf{s} = \mathbf{u}t + \tfrac{1}{2}\mathbf{a}t^2$$
$$\mathbf{v} = \mathbf{u} + \mathbf{a}t$$

where $\boldsymbol{u}$ is the initial velocity, $\boldsymbol{v}$ is the velocity at time t, and $\boldsymbol{s}$ is the displacement from the initial position (not necessarily the origin) at time t.

constant of proportionality:
See proportionality.

constants of the motion:

A set of conserved quantities in the geodesic equations that describe motion in Schwarzschild spacetime. The conserved total orbital energy per unit mass energy (i.e. the specific energy) is

$$\frac{E}{mc^2} = \left(1 - \frac{2GM}{c^2 r}\right)\frac{\mathrm{d}t}{\mathrm{d}\tau}$$

When defined in this way, the specific energy is dimensionless.

The conserved orbital angular momentum magnitude per unit mass (i.e. the specific angular momentum) is

$$\frac{J}{m} = r^2 \sin^2\theta \ \frac{\mathrm{d}\phi}{\mathrm{d}\tau}$$

where $\mathrm{d}\tau$ is the proper time. When defined in this way, the specific angular momentum has dimensions of length^2 time^{-1}. (Nb. the specific angular momentum may alternatively be defined as $\frac{J}{mc}$ and so have dimensions of length.)

contact:

With reference to an eclipse or transit by a star or planet across the face of another star:

First contact is when the limb of the disc of the planet (or eclipsing star) first coincides with the limb of the disc of the eclipsed star, as seen by the observer.

Second contact is when entire disc of the planet (or eclipsing star) is just within the disc of the eclipsed star, as seen by the observer.

Third contact is when the limb of the disc of the planet (or eclipsing star) just coincides with the limb of the disc of the eclipsed star at the last instant when the entire disc of the planet (or eclipsing star) is just within the disc of the eclipsed star, as seen by the observer.

Fourth contact is when the trailing limb of the disc of the planet (or eclipsing star) crosses the limb of the disc of the eclipsed star at the last instant of the eclipse or transit, as seen by the observer.

contact binaries:
See contact binary.

contact binary:
A binary system in which the two stars both fill their Roche lobes, and so are effectively sharing gas. Contrast with detached binary and semi-detached binary.

continuously habitable zone:
The region of the habitable zone around a star which has the right conditions for life throughout a star's evolution (as its temperature and luminosity changes).

continuous spectrum:
A spectrum that extends without a break over a wide range of frequencies, and in which no emission lines are visible. Black body radiation, thermal bremsstrahlung and synchrotron radiation are examples of radiation processes that produce continuous spectra.

continuum:
The flux level of the continuous spectrum in a system that emits both a continuous spectrum and emission lines.

continuum emission:
See continuous spectra, continuum.

contraction (of a tensor):
The process of summing a tensor over one raised index and one lowered index to form a tensor of lesser rank. The process may be used to form invariants.

contravariant:

A contravariant tensor is a tensor whose indices are in the 'up' position and which transforms in the same way as a four-displacement. For example, under a Lorenz transformation, $[A'^{\mu}] = [\Lambda^{\mu}{}_{\nu}]\ [A^{\nu}]$ where $[\Lambda^{\mu}{}_{\nu}]$ is the Lorentz transformation matrix.

See covariant.

convection:
A mechanism of heat transfer involving a fluid in a gravitational field. Energy deposited into the fluid causes the fluid to expand and decrease in density so that it rises through overlying denser fluid, thus carrying the transferred energy away from the source of the original heating.

convection zone:
A region of a star in which convection is important as a method of energy transport as a result of a relatively high opacity. For protostars on the Hayashi track convection is important throughout the whole star, but in low-mass main-sequence stars like the Sun convection takes place only in a region near the star's surface. More massive stars, burning hydrogen by the CNO cycle, have convective cores. Convection allows material from inside the star to be circulated to the star's outer layers.

convective eddies:
Packets, bubbles or blobs of fluid that rise in convective layers (i.e. layers that are subject to convection).

convergence:
A parameter, κ, in the expression for the inverse magnification tensor used to describe gravitational lensing by large scale structure. Convergence is isotropic so just rescales the lensed images. See also shear and cosmic shear.

cooling flow:
The predicted flow of gas into the centres of clusters of galaxies. The gas in the centre of a galaxy cluster will have a relatively short cooling time and will not have enough pressure to support the weight of gas at larger radii. This compresses the gas still further, and shortens its cooling time even more, so leading to a runaway cooling, known as a cooling flow.

cooling flow problem:
The fact that cooling flows in clusters of galaxies are predicted to exist, but are not widely observed.

cooling rate:
The rate of energy loss due to a cooling mechanism (e.g. radiation), per unit volume. Measured in $J\ s^{-1}\ m^{-3}$ (SI units) or $erg\ s^{-1}\ cm^{-3}$ (cgs units). Sometimes the cooling rate is also given per unit mass rather than per unit volume. In this case the SI unit is $J\ s^{-1}\ kg^{-1}$.

coordinate:
A value, determined within a coordinate system, that may be used to specify the position of a point.

coordinate basis vectors:
Unit vectors that point in the direction of increasing coordinate values.

coordinate differentials:
Infinitesimal elements of coordinates, such as dx, dy for 2-dimensional Cartesian coordinates.

coordinate functions:
Functions that define a parameterized curve by describing each coordinate x^i of every point on the curve as a function $x^i(u)$ of the parameter u.

coordinate infinitesimals:
See coordinate differentials

coordinate singularity:
See singularity.

coordinate system:
An arrangement of axes (usually in three dimensions) by means of which the position of any point (or event) can be specified. A Cartesian coordinate system has three mutually perpendicular axes, usually labelled x, y and z.

coordinate transformation:
A set of equations that links the coordinates of an event in one frame of reference with those of the same event in another frame of reference, which may be moving relative to the first. See, for example, Galilean transformation and Lorentz transformation, and see for comparison velocity transformation.

core:

(1) In relation to radio galaxies, the central bright region, often accompanied by one or two radio lobes. See radio source structure.

(2) In relation to stars, the central regions where hydrogen burning occurs on the main sequence.

core accretion theory:
A theory describing the formation of giant planets such that planets form in a region of the protoplanetary disc that is cool enough (below about 150 K) for water, methane and ammonia to condense into solid ice grains. This region is described as beyond the snowline.

core collapse supernova:
See supernova.

Coriolis force:
A fictitious force that may be used to account for certain aspects of the motion of bodies observed from a rotating (non-inertial) frame of reference. The effect of the Coriolis force is to cause bodies moving towards or away from the axis of rotation to be deflected at right angles to their direction of motion. (This is exemplified by the rightward deflection of air masses travelling north or south in the Earth's Northern Hemisphere.) By introducing such fictitious forces the motion of the bodies may be made to conform with the predictions of Newton's laws, which do not, strictly speaking, apply in such frames. See also centrifugal force.

corona:
The hot, tenuous region of a star's atmosphere above the photosphere. A stellar corona has a temperature of millions of kelvin, and so its thermal emission is in the X-ray region of the spectrum, allowing it to be studied with X-ray satellites even if the optical emission from the photosphere is obscured. The mechanism that heats coronae to such high temperatures is still not fully understood, but it seems likely to be related to the strong magnetic field at the star's surface.

coronagraphy:
The use of an optical instrument to block out the light from the Sun or a star in order to observe either the Sun's corona or planets close to a star.

co-rotation radius:
The radius of a circular Kepler orbit with the same angular speed as the spin angular speed of the rotating star in the centre of the orbit.

correlated noise:
Noise that is not randomly distributed in a given sample of data.

correlation function:
In cosmology, the probability that a galaxy will have a neighbour at a certain distance from it. It is a function which expresses the excess of clustering over what is expected in a non-clustered case.

cosine:
See trigonometric functions.

cosine curve:
See trigonometric functions.

cosmic abundance:

The relative abundances of the different elements as measured in the solar system.

Cosmical Dynamics Experiment:
See CODEX.

cosmic composition:
The sources of cosmic gravitation are specified at any given time by the densities of matter ρ_m, radiation ρ_r, and dark energy ρ_Λ. Given these three values, the cosmic density and pressure at any other cosmiic time can be determined provided the scale factor is known as an explicit function of cosmic time.

cosmic dust:

Small solid particles, composed mainly of carbon and silicon compounds, found in interstellar space. Particle sizes range from 10 μm to less than 10 nm. Dust is thought to be created in the atmospheres of evolved stars or in supernovae, and is often associated with star-forming regions such as molecular clouds; it is destroyed by high temperatures. The principal effect of dust is the absorption of light, giving rise to interstellar extinction.

cosmic microwave background radiation:
Low-energy black body radiation seen with almost identical properties in all directions. Its black body spectrum corresponds to a temperature around 2.7 K. In the Big Bang cosmological model, the background radiation is a relic of the early stages of the Universe, when the temperatures and densities were much higher, the whole Universe was optically thick, and matter and photons were in thermal equilibrium. Study of the microwave background radiation therefore gives important information about the structure of the young Universe.

cosmic rays:
Highly energetic particles (including protons, electrons and nuclei) found in interstellar space. Cosmic rays can be directly detected at the surface of the Earth and in the atmosphere by a number of techniques, including the detection of the Čerenkov radiation produced when they (or their by-products) pass through a detector. They are observed to be distributed through the Milky Way galaxy (and other galaxies) because of the synchrotron radiation emitted by the electron component. The energies of individual cosmic rays extend above 10^{20}eV (see electronvolt). While lower-energy cosmic rays are thought to gain their energy in the shock waves generated by supernovae, the acceleration process for the highest energy cosmic rays is not known; they may originate in nearby active galactic nuclei.

cosmic rest frame:
An inertial frame of reference in which the expansion of the Universe is isotropic. The reference frame of the cosmic microwave background radiation.

cosmic shear:
Weak gravitational lensing by large scale structure which can be detected statistically from the tendency of galaxy ellipticities to align with each other. Characterised by the inverse magnification tensor which depends on two parameters: the convergence and the shear.

cosmic star formation history:
See Madau diagram.

cosmic time:
A universally meaningful time which corresponds to the proper time measured by a fundamental observer.

cosmic variance:
The statistical uncertainty that is inherent in observations of the cosmic microwave background radiation.

cosmological constant:

A non-zero value of Λ in the Einstein field equations of the form $R_{\mu\nu} - R\, g_{\mu\nu}/2 + \Lambda\, g_{\mu\nu} = -\kappa\, T_{\mu\nu}$.

Its value is given by $\Lambda = 3\Omega_{\Lambda,0} H_0^2/c^2 = 1.3\times10^{-52}\,\mathrm{m}^{-2}$.

cosmological event horizon:
The past lightcone for observers at our position infinitely far in the future. It separates events that we might observe at some finite time from those that we will never be able to see, no matter how long we wait. It lies at a proper distance of about 60 billion light-years or 20 Gpc.

cosmological model:
A mathematical model that describes the large-scale features of the universe.

cosmological principle:
The principle that, at any given time, and on a sufficiently large size-scale, the universe is homogenous (i.e. the same everywhere) and isotropic (i.e. the same in all directions).

cosmological probe:

An astronomical object (such as a quasar) sufficiently old and distant that it, or radiation from it, can be used as an indicator of conditions in the Universe as they were at a time in the distant past.

cosmological redshift:

Redshift arising from the expansion of the Universe. It is related to the scale factor by

$1+z = R(t_{ob})/R(t_{em})$

where t_{ob} and t_{em} are the times at which the radiation was observed and emitted respectively.

cosmological time dilation:
The ratio of the scale factor of the Universe now to the scale factor at some earlier time. See also dimensionless scale factor.

cosmology:
The branch of science that is concerned with the study of the Universe as a whole, including its structure and history.

Coulomb barrier:
The energy required to overcome the repulsion that exists between two nuclei due to their being positively charged.

Coulomb potential energy:

The potential energy of a charged particle due to its proximity to another charged particle, resulting from the electrostatic (Coulomb) force between two particles. The potential energy is given by

$$E = \frac{q_1 q_2}{4\pi\epsilon_0 r}$$

where q_1 and q_2 are the charges, r is their separation, and ε_0 is the permittivity of free space.

Coulomb's law:

The law that describes the electrostatic force on a stationary charged particle, due to another stationary charged particle, located some distance away, in a vacuum. Coulomb's law can be represented mathematically by the equation

$$\mathbf{F}_{\rm el} = \frac{q_1 q_2}{4\pi\epsilon_0 r^2}\hat{\mathbf{r}}$$

where $\boldsymbol{F}_{\rm el}$ is the force on one of the particles, q_1 and q_2 are the charges, r is the distance between them, ε_0 is the permittivity of free space and $\hat{\boldsymbol{r}}$ is a *unit vector* directed towards the particle on which the force is acting from the other (source) particle. Thus, $\hat{\boldsymbol{r}} = \boldsymbol{r}/r$, where $\boldsymbol{r}$ is the position vector of the particle on which the force is acting, when the origin is taken to be at the position of the source particle. In agreement with Newton's third law, the existence of this force implies that there is also a force $-\boldsymbol{F}_{\rm el}$ acting on the source particle. This is consistent with the rule that: like charges repel one another and unlike charges attract.

covariant:

(1) A covariant tensor is a tensor whose indices are in the 'down' position and which transforms in the same way as a set of derivatives. For example, under a Lorenz transformation, $[B'_\mu] = [(\Lambda^{-1})^\mu{}_\nu]\ [B_\nu]$ where $[(\Lambda^{-1})^\mu{}_\nu]$is the matrix inverse of the Lorentz transformation matrix.

See contravariant.

(2) A covariant equation is an equation that takes the same form in different coordinate systems. (It may or may not involve covariant tensors.) See generally covariant.

covariant derivative:

The combination of partial derivatives and connection coefficients that transforms as a tensor under general coordinate transformations and is given by

$$\nabla_\beta v^\alpha = \frac{\partial v^\alpha}{\partial x^\beta} + \sum_\lambda \Gamma^\alpha_{\lambda\beta} v^\lambda$$

covering factor:
The fraction of sky covered by broad line region clouds as seen from the central source in an AGN.

CO white dwarf:

A white dwarf composed chiefly of carbon and oxygen, formed from the core of a star whose initial mass was between $3M_\odot$ and $8M_\odot$. They will have masses in the range $0.5M_\odot$ to $1.2M_\odot$.

Crab nebula:
A supernova remnant from a supernova explosion that was observed in 1054. At its centre is the Crab pulsar.

Crab pulsar:

A pulsar found at the centre of the Crab Nebula, a supernova remnant from a supernova explosion that was observed in 1054. The pulsar is a particularly bright one, with pulses that can be detected in the radio, optical, X-ray and gamma-ray wavebands. Its period is about 33ms. Radiation from the pulsar, and jets emitted from it, provide energy to the nebula.

critical density:

1) With reference to atomic transitions, the condition in which radiative and collisional de-excitation are equally probable.

2) With reference to cosmological models, the quantity defined by $\rho_c(t) = 3\,H^2(t)/8\pi G$.

critical lines:
In gravitational lensing, the positions on the sky where images merge.

critical model:
See Einstein-de Sitter model.

cross correlation:
A technique of comparing two light curves, or other time varying signals, in order to establish whether the two are correlated with one another and if so what is the time delay between one and the other.

cross correlation function:

A function of the time delay *t* that describes the result of performing a cross correlation on two time varying signals, $L(t)$ and $C(t)$:

$$F_{\mathrm{CCF}}(\tau) = \int_{-\infty}^{\infty} L(t)C(t-\tau)\,\mathrm{d}t$$

The cross correlation function will have a maximum value at the time delay corresponding to the lag between the two correlated light curves.

cross product:
See vector product.

cross section:
A measure of the probability that a certain kind of scattering will occur at a specified energy. It is often denoted by the symbol σ and has the units of area. Cross sections are usually expressed in terms of the non-SI unit known as the barn, represented by the symbol b where 1 b = 10^{-28} m^2.

cross-section:

A measure of the probability that a certain kind of scattering will occur at a specified energy. It is often denoted by the symbol σ and has the units of area. Cross-sections are usually expressed in terms of the non-SI unit known as the barn, represented by the symbol b where 1 b = 10^{-28} m^2.

CTIO:
The Cerro-Tololo Inter-American Observatory in Chile.

cumulative distribution:
An accumulated count. In astronomy, a cumulative distribution of source number, $N(S)$ is the total number of sources with observed flux exceeding a value S. If a histogram is plotted of the number of sources with a given flux against the value of the flux, then $N(S)$ is the area under the histogram between the flux of the brightest source detected and the flux S.

Curie temperature:
The Curie temperature of a ferromagnetic material is the temperature above which it becomes paramagnetic. Below the Curie temperature, the magnetic moments are aligned parallel to each other and as the temperature is increased the alignment decreases. Above the Curie temperature, the material is paramagnetic so that the magnetic moments are disordered.

curvature:
See curvature parameter, curvature density.

curvature density:

An equivalent density parameter defined in terms of the curvature parameter as

$$\Omega_k(t) = -\frac{kc^2}{R^2(t)H^2(t)}$$

Observationally, $\Omega_k \simeq 0$.

curvature parameter:
The quantity k in the Robertson-Walker metric that can take values of +1, 0 or -1.

curvature scalar:
The rank 0 tensor R defined in terms of the Ricci tensor by $R \equiv \sum_{\alpha\beta} g^{\alpha\beta} R_{\alpha\beta}$. Sometimes

referred to as the Ricci scalar.

curvature tensor:
See Riemann tensor.

curved:
A space that is not flat i.e. a space for which the Riemann tensor does not vanish. Consequently, a space for which no coordinate system can be found such that the metric coefficients are constant.

curve of growth:
The variation of the equivalent width of an absorption line with optical depth at the line centre.

curvilinear coordinates:
Spherical coordinates are an example of curvilinear coordinates.

CV:
Common acronym for cataclysmic variable.

CV catalogue:
A list of known cataclysmic variables containing information about each system.

cycle:
The set of successive values that a periodic function passes through as its *argument* is increased by one *period*. For example, in the case of the periodic function $A \sin(\omega t + \phi)$, a cycle would consist of the succession of values between A and $-A$ that the function passes through as $\omega t + \phi$ increases by 2π.

cyclotron frequency:
The frequency, f_C, of the circular or helical motion of a charged particle in a uniform magnetic field. It depends only on the magnitude of the particle's charge to mass ratio $|q|/m$ and the magnetic field strength B:

$$f_C = \frac{|q|B}{2\pi m}$$

Also known as the Larmor frequency or the gyrofrequency.

cyclotron harmonics:
Integer multiples of the cyclotron frequency.

cyclotron motion:
The circular or helical motion of a charged particle in the plane perpendicular to a magnetic field.

cyclotron radiation:
The electromagnetic radiation emitted by non-relativistic electrons that move in a magnetic field. When the electrons are relativistic, the radiation is referred to as synchrotron emission.

cyclotron radius:
The radius of the circle or helix described by a particle undergoing cyclotron motion in a uniform magnetic field.

Cygnus A:
A radio galaxy, and one of the strongest radio sources in the sky.

cylindrical coordinates:
See cylindrical polar coordinate system.

cylindrical polar coordinate system:
A coordinate system in which the position $\boldsymbol{R}$ of a point is given by the three coordinates (r, ϕ, z) where r is the distance from the origin to the tip of the projection of $\boldsymbol{R}$ on to the xy-plane, ϕ is the angle between the x-axis and the projection of $\boldsymbol{R}$ on to the xy-plane and z is the perpendicular distance of the point above the xy-plane. This coordinate system is particularly useful for systems that exhibit cylindrical symmetry.

D

dark energy:
In the modified form of the Einstein field equations, $R_{\mu\nu} - Rg_{\mu\nu}/2 = -\kappa\,(T_{\mu\nu} + \Lambda g_{\mu\nu}/\kappa)$ the second term on the right hand side, containing the cosmological constant Λ, can be represented as arising from an ideal fluid with density ρ_Λ and pressure p_Λ. In this case, $\rho_\Lambda c^2$ is the density of dark energy given by Λ/κ and p_Λ is the pressure due to dark energy given by -Λ/κ.

dark matter:
Matter that does not produce radiation, and so can only be detected (at present) by its gravitational effects on other matter. Evidence from the rotation curve of spiral galaxies, the velocity dispersion of clusters of galaxies, gravitational lensing and

observations of the cosmic microwave background radiation suggest that there is more dark matter than luminous matter in the Universe by a large factor, and that most of it is non-baryonic (that is, not made primarily of protons and neutrons as normal matter is). The nature of the non-baryonic dark matter is one of the major puzzles of modern astrophysics.

data inversion:
The process of inferring underlying physical properties of a system from observed data which are the result of processes taking place within the system.

data reduction:
The process of correcting raw data for instrumental effects.

de Broglie formula:

The equation $\lambda_{dB} = h/p$ for the de Broglie wavelength of a material particle in terms of the Planck constant, h, and the magnitude of its (relativistic) momentum, p. The result is also valid for photons, which are massless.

de Broglie wave:
See probability wave.

de Broglie wavelength:

According to quantum mechanics, any force-free particle can be described by a sinusoidal de Broglie wave. The wavelength of the wave is known as the de Broglie wavelength λ_{dB}, and is related to the particle's momentum p by $\lambda_{dB} = h/p$, where h is the Planck constant.

decay:
A general process whereby an (unstable) particle can spontaneously change into two or more other particles.

deceleration parameter:

A parameter in the Big Bang cosmological model that describes the rate at which the expansion of the universe is decelerating. In terms of the scale factor, R,

$$q_0 = \frac{-R(\mathrm{d}^2R/\mathrm{d}t^2)}{(\mathrm{d}R/\mathrm{d}t)^2}$$

q_0 = 0 implies no deceleration, which would be the case in an empty Universe. Values greater than 0.5 would be expected in a closed Universe; the deceleration in this case would be great enough that the expansion of the universe would eventually stop and reverse, ending in a big crunch. Values less than or equal to 0.5 imply an open Universe.

The expansion of the Universe is actually thought to be accelerating, implying $q_0 < 0$.

deceleration radius:

(Of a gamma-ray burst) - the radius at which the fireball begins to decelerate. The decleration radius must be greater than the dissipation radius in all observed GRBs. It may be expressed as

$$r_{\mathrm{dec}} \simeq 10^{14} \left[\left(\frac{E_0}{10^{44}\ \mathrm{J}} \right) \left(\frac{10^6\ \mathrm{m}^{-3}}{n} \right) \left(\frac{300}{\gamma_\mathrm{s}} \right)^2 \right]^{1/3}\ \mathrm{m}$$

where where the Lorentz factor has a maximum value of $\gamma_\mathrm{s} = E_0/Mc^2$ and E_0 is the energy of the explosion and M is the mass involved.

deceleration timescale:

(Of a gamma-ray burst) - the time at which the expansion of the fireball reaches the deceleration radius. It may be expressed as

$$t_{\mathrm{dec}} \simeq \frac{r_{\mathrm{dec}}}{2\gamma_\mathrm{s}^2 c}$$

where where the Lorentz factor has a maximum value of $\gamma_\mathrm{s} = E_0/Mc^2$ and E_0 is the energy of the explosion and M is the mass involved.

declination:
One of the two coordinates used to describe positions on the sky (celestial sphere) in the equatorial coordinate system. The declination of a point describes its angular displacement from the celestial equator. A point with 0° declination lies on the celestial equator; +90° corresponds to the north celestial pole and -90° to the south celestial pole. Compare with right ascension.

definite integral:
A mathematical expression indicating the limit of a sum, usually as some particular quantity becomes vanishingly small. Definite integrals can be thought of as representing the (signed) area under a given curve between given limits, and may be evaluated using a technique called integration.

deflection length:

The typical distance a plasma particle travels before it is appreciably deflected from its initial trajectory, due to the effect of many weak, 'distant' collisions with other plasma particles.

degeneracy:
The phenomenon whereby more than one quantum state is associated with a particular energy level in a given system. Any energy level that corresponds to more than one quantum state is said to be degenerate.

degeneracy parameter:
The ratio of the temperature of a gas to its Fermi temperature. If the degeneracy parameter is less than 1, the gas is degenerate.

degeneracy pressure:
A pressure that arises in degenerate matter as a result of the Pauli exclusion principle, which forbids two particles in a system from occupying the same quantum state. This means that a degenerate system always has a non-zero kinetic energy density and therefore a non-zero pressure, independent of its temperature. Degeneracy pressure is important in certain phases of the evolution of stars, as well as being the pressure that supports a white dwarf or a neutron star against collapse.

degenerate:
See degenerate matter.

degenerate matter:
Matter that is so dense that the laws of quantum mechanics must be used to describe the behaviour of the particles that it consists of. The critical density for degeneracy is the quantum concentration; if the density exceeds this value then the system will be degenerate. In a non-degenerate system, the energy levels occupied by the particles are sparsely populated – that is, there are many more available energy levels than particles – and so a normal Maxwell-Boltzmann energy distribution applies. In a degenerate system there are as many particles as there are accessible energy levels, and consequently every quantum state up to a certain energy is populated. This gives rise to degeneracy pressure.

degree:
A unit of angle, equal to 1/360 of a complete circle.

degrees of freedom:
Each independent term involving the square of a displacement or velocity, or angular displacement or angular velocity, in the expression for the total energy of a particle is said to correspond to one degree of freedom. The total number of such squared terms is called the number of degrees of freedom of the particle, and is often represented by the symbol s, but occasionally f is also used. For an ideal monatomic gas, $s = 3$, for an ideal diatomic gas, $s = 5$, whilst for an ideal triatomic gas, $s = 6$.

delta function:
A mathematical description of a sharp pulse. In principle it has zero duration and hence an instantaneous rise followed by an instantaneous decline.

delta Scuti star:

A star which is a member of a class of variable stars typified by the star δ Scuti. They have masses between 1.5 and 3 solar masses and spectral types ranging from about A3 to F6. They are members of the class of pulsating variables, and are located in the instability strip of the H–R diagram. They pass through the instability strip as they evolve away from the main sequence to the giant branch, so that their pulsation is relatively short-lived. Large-amplitude δ Scuti stars are sometimes called dwarf Cepheids.

density:

Also known as mass density. The ratio of mass to volume for a homogeneous system. It is possible to define the density at a given point in any system by taking a small volume element around that point and evaluating the ratio of mass to volume for that volume element.

Contrast with number density.

density evolution:
The suggestion that almost all galaxies harbour AGN, but that they spend much of their time in a dormant state. In this scenario the change in the quasar luminosity function is attributed to the fraction of galaxies which are active at any given time changing as a function of redshift or lookback time. See also luminosity evolution. A more appropriate explanation of the evolution of the quasar luminosity function is believed to be luminosity-dependent density evolution.

density of states:
For a confined particle in a quantum system, the available states are quantized, forming a number of distinct energy levels. The density of states describes the number of available quantum states per unit energy interval at any specified energy. The density of states may be measured in units of J^{-1}, and in situations where there are a great many states per unit energy interval it may be treated as a continuous function of energy.

density parameter:

One of the fractional densities defined by:

matter density: $\Omega_m(t) = \rho_m(t)/\rho_c(t)$

radiation density: $\Omega_r(t) = \rho_r(t)/\rho_c(t)$

dark energy density: $\Omega_\Lambda(t) = \rho_\Lambda(t)/\rho_c(t)$

where $\rho_c(t)$ is the critical density.

depolarization:
A reduction in the amount of polarization of electromagnetic radiation. See Faraday rotation.

derivative:
The derivative of a function $f(y)$ with respect to y is another function of y, sometimes called the derived function, that is equal to the rate of change of $f(y)$ with respect to y at each value of y. Its value at any given value of y is equal to the ratio $\Delta f/\Delta y$ in the limit as Δy becomes very small and is usually written as $\mathrm{d}f/\mathrm{d}y$. The value of $\mathrm{d}f/\mathrm{d}y$ at any given value of y is also equal to the gradient of the graph of f plotted against y at the given value of y.

derived function:
See derivative.

de Sitter model:

A model of the universe with curvature parameter $k=0$, matter density $\rho_m = 0$, and radiation density $\rho_r = 0$. Hence it contains only dark energy. It has been used to describe the inflationary era of the universe. It may also describe the far future of our universe when continued expansion will have reduced the density of matter and radiation to negligible levels.

In the de Sitter model:

the Hubble parameter $H(t)$ = constant

and the scale factor $R(t) = R_0 \exp H_0\,(t - t_0)$

de Sitter spacetime:
See de Sitter model.

detached binaries:
See detached binary.

detached binary:
A binary system in which both stars lie within their Roche lobes; there is consequently no gravity-driven mass flow between the two. Contrast with contact binary and semidetached binary.

deuterium:
An isotope of hydrogen, consisting of one proton and one neutron in a bound system (so that it has atomic number 1 and mass number 2). It is sometimes denoted D or d; the nucleus of a deuterium atom is called a deuteron. It plays an intermediate step in the proton-proton chain, and so is important in the energy production in stars.

deuteron:
The nucleus of deuterium, the heavier stable isotope of hydrogen. It consists of one proton and one neutron bound together by nuclear forces.

de Vaucouleurs' law:

An empirical expression for the surface brightness profile of an elliptical galaxy:

$$I(r) = I_0 \exp\left(-(r/r_0)^{1/4}\right)$$

dex:

A logarithmic unit often used to quantify stellar metallicity. For example, the following equation has the units of dex:

$[\mathrm{Fe/H}] = \log_{10}(\mathrm{Fe/H})_* - \log_{10}(\mathrm{Fe/H})_\odot$

It describes the metallicity of a star relative to that of the Sun.

diatomic:
A term used to describe a molecule consisting of two atoms bound together by interatomic forces.

differential equation:

An equation involving derivatives, such as the simple harmonic motion equation

$$\frac{\mathrm{d}^2x(t)}{\mathrm{d}t^2} = -\omega^2 x(t)$$

The solution of a differential equation is generally a function, and involves a number of arbitrary constants in addition to the parameters (such as ω) that appear in the equation itself. In the case of the simple harmonic motion (s.h.m.) equation, for example, the general solution is $x(t) = A \sin(\omega t + \phi)$, where A and ϕ are arbitrary constants.

differential geometry:
The branch of mathematics that applies the techniques of calculus to the analysis of geometric problems.

differential light curve:
The light curve obtained after dividing the measured light curve of an object by that of a star of constant brightness.

differential magnification:
In gravitational lensing, if the light from the background source is partially obscured by dust in the lensing galaxy, it could give the appearence of different colours in different image components. Hence the observed magnification of the lensed images could be different in different wavebands.

differential number count:
See number count.

differential photometry:
Measurement of the brightness of a star relative to the brightness of other stars.

differential rotation:

Rotation where the angular speed varies with distance from the rotation axis.

In the case of the atmosphere of a star or planet, the effect is such that bands at different latitudes rotate at different rates.

differential source count:
See number count.

differentiation:
A mathematical process that allows the derivative of a function to be determined.

diffraction-limited:

Astronomical images are said to be diffraction-limited if the resolution of the image (the smallest angular separation at which two objects can be distinguished) is determined only by diffraction at the aperature of the telescope. This gives a resolution $\theta \approx \lambda/d$, where λ is the wavelength of observation, d is the size of the aperture, and θ is measured in radians. In practice, for ground-based optical telecopes, the diffraction limit is hard to achieve because of turbulent structure in the Earth's atmosphere, but diffraction-limited images are produced by the Hubble Space Telesope and now also by some ground-based instruments at infrared wavelengths.

diffusion:
A process described by a diffusion equation.

diffusion damping:
As the opacity of the Universe dropped after it became transparent to its own radiation, the photons began to diffuse away from the positions they had while the universe was opaque.This diffusion smoothed out, or damped, the structure on the smallest scales. Also known as Silk damping.

diffusion equation:
A differential equation where the time derivative of a quantity is proportional to its second spatial derivative.

Digitized Sky Survey:
Digitized versions of the photographic plates taken by Schmidt (all-sky) survey telescopes.

dimensional analysis:
A method of investigating order of magnitude estimates for quantities by ensuring that equations are balanced dimensionally.

dimensionless frequency:
The quantity $h\nu/kT_{\mathrm{CMB}}$ used to characterise part of the spectrum of the cosmic microwave background radiation.

dimensionless power spectrum:
A power spectrum obtained by expressing the variance per logarithmic interval of wavenumber.

dimensionless scale factor:
The ratio of the scale factor at some earlier time to the scale factor now. See cosmological time dilation.

dipole anisotropy:
The distortion to the cosmic microwave background radiation caused by the motion of the observing equipment relative to the frame of the local fundamental observer.

direction:
The property of a vector that determines its orientation. A common way of expressing the direction of a vector is to specify the angle between a particular axis or reference line and the vector. For example, in two dimensions, it is customary to specify the direction of a vector in terms of the angle (measured anticlockwise) between the positive x-axis and the vector. An alternative method is to specify the components of the vector relative to a particular coordinate system.

directly proportional:
See proportionality.

disc:

(1) In descriptions of the structure of spiral galaxies, the flat, thin structure which contains the spiral arms and the bulk of the young stellar population. Elliptical galaxies have no disc.

(2) See accretion disc.

(3) Any flat rotating structure, such as a protoplanetary disc.

disc luminosity:
See accretion disc luminosity.

displacement:

The displacement of a point from a given reference point is the difference in the positions of those points. In the case of a particle moving in one dimension, along the *x*-axis, if the particle starts at position x_1 and moves to position x_2, then the displacement of the particle from its initial position is

$s_x = x_2 - x_1$

The magnitude of this displacement is the distance *s* between the two points, so $s = |s_x|$.

Displacement is a vector quantity characterized by a direction as well as a magnitude. In one dimension the sign of s_x suffices to indicate the direction, but in two or three dimensions some other method must be used to indicate direction. This is often achieved by expressing the displacement vector in terms of its (Cartesian) components. Thus, if point P_1 has the position vector $\boldsymbol{r}_1 = (x_1, y_1, z_1)$ and point P_2 has the position vector $\boldsymbol{r}_2 = (x_2, y_2, z_2)$, then the displacement $\boldsymbol{s} = (s_x, s_y, s_z)$ from P_1 to P_2 is defined by

$\boldsymbol{s} = \boldsymbol{r}_2 - \boldsymbol{r}_1 = (x_2 - x_1, y_2 - y_1, z_2 - z_1)$

In this case the distance between the two points is given by

$$s = |s| = \sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2 + (z_2 - z_1)^2}$$

Note that a displacement is entirely specified by its magnitude and direction; it is not tied to any particular starting point or finishing point, even though such points may be used to specify it.

displacement vector:
See displacement.

dissipation radius:

(Of a gamma-ray burst) - the radius at which the energy of the flow is converted into thermal energy of electrons, which then radiate away this energy. The dissipation radius must be greater than the photospheric radius in all observed GRBs. It may be expressed as

$$r_{\text{dis}} \simeq 5 \times 10^{11} \left(\frac{\gamma_s}{300}\right)^2 \left(\frac{\Delta t_{\text{var}}}{10\text{ms}}\right) \text{m}$$

where where the Lorentz factor has a maximum value of $\gamma_s = E_0/Mc^2$ and E_0 is the energy of the explosion and *M* is the mass involved.

dissociation:
The separation of a molecule into its constituent atoms. This occurs when energy exceeding that associated with the molecular bond is deposited in the molecule by collisions or a photon.

distance:

The distance between two points is the magnitude of the displacement of one point from the other. For example, in one dimension,

$s = |s_x| = |x_2 - x_1|$.

distance-limited sample:
An observed sample (e.g. of active galaxies) which is complete (i.e. includes all members of the population) out to a particular distance. Compare with flux-limited sample.

distance modulus:

A numerical quantity which is defined to be the difference between the apparent and absolute magnitudes of an astronomical object. Since the absolute magnitude is the magnitude that the object would have if it were at a fixed distance, the difference between the two quantities is related to the distance of the object, via

$M - m = 5 - 5 \log_{10} d - A$

where M is the absolute magnitude, m the apparent magnitude, d the distance in parsecs, and A the amount of *extinction* towards the object. If the extinction is known, the distance modulus therefore indicates the distance.

distant red galaxies:
Galaxies at high redshift with an infrared colour, J-K > 2.3.

distribution function:
A function which, when multiplied by a small range of a given variable, tells us the fraction of particles for which the given variable has values in the given range. Gases are commonly described in terms of their speed distribution function or translational energy distribution function. See Maxwell-Boltzmann energy distribution for an example.

divergence:
The mathematical operation of mutiplying the vector differential operator ∇ by a vector field in order to produce a scalar field. The div or divergence of a vector field $\boldsymbol{T}$ is the scalar field $\nabla \cdot \boldsymbol{T}$ (i.e. div$T$).

divergence theorem:

The theorem that, for a volume V enclosed by a surface S, the surface integral of a field passing through a surface S is equal to the volume integral of the divergence of the field throughout the volume V.

$$\int\int(\mathbf{F}\cdot\mathbf{n})\mathrm{d}S = \int\int\int(\nabla\cdot\mathbf{F})\mathrm{d}V$$

DOGs:
Dust Obscured Galaxies.

donor:
Also donor star. The Roche-lobe filling component in a semidetached binary.

Doppler boosting:

The combined effect of beaming and time dilation which boosts the emission from a relativistic jet, in its direction of motion, by a factor equal to γ^3, i.e. the Lorentz factor cubed. If the emission has a synchrotron spectrum with a power law dependence (F_ν proprtional to $\nu^{-\alpha}$) the detected luminosity is enhanced by a further factor of γ^α to give a total boosting factor of $\gamma^{3+\alpha}$. Also known as relativistic beaming or Doppler favouritism.

Doppler broadening:
The broadening of a spectral line (either an emission line or an absorption line) as a result of motions in the material responsible for the line. The broadening arises as a result of the Doppler shift; if the atoms or molecules all have high-speed random motions, some towards us and some away from us, then the spectral line we see is the sum of all the Doppler-shifted lines from individual atoms and molecules, and so its width will depend on the distribution of speeds in the material. Either thermal motions (in which case the speeds will obey a Maxwell-Boltzmann distribution) or large-scale bulk motions such as rotation can produce Doppler broadening.

Doppler effect:
The effect that causes the observed frequency of the waves from a source to depend on the relative motion of the source and the observer. If the relative motion is such that the source and the observer approach each other, the observed frequency is higher than the emitted frequency (the observed wavelength is shorter). If the relative motion is such that the source and observer recede from each other, the observed frequency is lower than the emitted frequency (the observed wavelength is longer). The Doppler effect is widely used to measure the speed of approach or recession of a source of radiation, particularly in astronomy. See Doppler shift.

Doppler favouritism:
See Doppler boosting.

Doppler shift:

The shift that is observed in the wavelength or frequency of light when the body emitting the light is moving with respect to the observer. Light from a body moving away from us will be shifted to longer wavelengths (a redshift); light from a body moving towards us will be shifted to shorter wavelengths (a blueshift).

At speeds much less than the speed of light, the magnitude of the Doppler shift is given by the formula $\Delta\lambda/\lambda_0 = V/c$ where $\Delta\lambda$ is the change in wavelength, λ_0 is the original (emitted) wavelength, V is the speed of the body and c is the speed of light.

The relativistic formula for the received frequency f_{rec} in terms of the emitted frequency f_{em} when the emitter is approaching the receiver with speed V is $f_{rec} = f_{em} [(c + V)/(c - V)]^{1/2}$. The sign of V is reversed if the emitter is receding.

The Doppler shift can be measured by observing the wavelengths of known emission lines or absorption lines, and is one of the few ways in which we can measure the speeds of motion of astronomical bodies.

Doppler tomography:
A data inversion technique whereby spectroscopic measurements of a binary star system are used to infer details of the light emitting structures (such as an accretion disc) that are present.

dot product:
See scalar product.

double degenerate:
A compact binary star system whose components are both either a white dwarf, a neutron star or a black hole. The term is often reserved specifically for systems consisting of two white dwarfs. The prototype double degenerate undergoing mass transfer is AM Canes Venaticorum (AM CVn).

double integral:
An integral performed over two variables successively.

double-lined spectroscopic binary star:
A binary star whose spectrum reveals spectral features from *both* components.

double-peaked emission line:
A splitting of a spectral line into two components typically as a result of the Doppler shift. One peak is redshifted and the other blueshifted with respect to the line centre. Can indicate the presence of an accretion disc.

double pulsar:
A binary star system consisting of two neutron stars, both of which are detected as radio pulsars. The first (and so far only) such system to be discovered is PSR J0737-3039A/B. The system provides an excellent test bed for general relativity.

doublet:
A spectral line with two components due to fine structure sublevels in one of the energy levels involved in an atomic transition.

down quark:
A quark with electric charge $-e/3$. Along with the up quark, a member of the lightest generation of quarks.

downsizing:
A top-down mechanism of galaxy formation. Contrast with hierarchical formation.

DQ Her star:
A star which is a member of a class of magnetic cataclysmic variables (named after the prototype system, DQ Herculis) also known as intermediate polar systems. See magnetic cataclysmic variable for a definition.

dragging of inertial frames:
The Kerr spacetime around a rotating body exhibits an effect whereby the exterior spacetime is dragged along with the rotating body so that time and space are effectively skewed in the ϕ-direction. It arises due to the cross term proportional to $dt d\phi$ in the line element described by Kerr metric used to describe spacetime in the vicinity of a rotating black hole.

DRGs:
Distant Red Galaxies.

drift velocity:
The radial component of the velocity of matter in an accretion disc. This radial inward or outward drift due to viscous diffusion is very slow compared to the Keplerian motion.

dry merger:
The merger of galaxies with very little gas, so no star formation results.

dual metric:
The inverse of the metric tensor regarded as a matrix, such that $\Sigma_k g^{ik} g_{kj} = \delta^i_j$ (the Kronecker delta function).

dummy index:
Writing the Lorentz transformation as a summation:

$x'^{\mu} = \Sigma_{\nu=0}^{3} \Lambda^{\mu}{}_{\nu} x^{\nu}$

The index ν is a dummy index since it is summed over, but could be replaced by another symbol (say α) without changing anything. Contrast with free index.

dust:

(1) See cosmic dust.

(2) In general relativity, a cloud of non-interacting particles may be described as dust.

dust-obscured galaxies:
Red galaxies with a ratio of 24 micron flux to R-band flux of $S_{24}/S_R > 1000$.

duty cycle:
The proportion of time occupied by a given process or event as a fraction of the total time.

dwarf Cepheid:
See delta Scuti star.

dwarf galaxies:
See dwarf galaxy.

dwarf galaxy:
A very small galaxy containing only a few million stars. They include dwarf elliptical galaxies and dwarf irregular galaxies, but there are no dwarf spiral galaxies. Dwarfs may make up the majority of the galaxy population, but they are hard to observe because of their faint magnitudes.

dwarf nova:
A member of a particular subclass of cataclysmic variable which alternates between bright states (outbursts) and dim states (quiescence) with an amplitde of a few magnitudes. The outbursts typically last for a few days and recur every few weeks. The cause of the phenomenon is a thermal-viscous instability in the accretion disc.

dwarf novae:
See dwarf nova.

dynamical time:
Characteristic time for a gravitating system to undergo significant changes if all effects except for gravity are ignored. For a binary star this is the orbital period. In many cases the dynamical timescale is the free-fall time.

dynamical timescale:
See dynamical time.

dynamical viscosity:

The constant of proportionality between stress and strain. Usually represented by η. See also kinematic viscosity.

dyne:
The cgs unit of force, defined by the relation 1 dyne = 1 g cm s^{-2}. An unbalanced force of magnitude 1 dyne will cause a particle of mass 1 g to accelerate at 1 cm s^{-2} in the direction of the force.

E

E-AGB:
Abbreviation for Early Asymptotic Giant Branch. This is the first stage of asymptotic giant branch evolution before the He shell periodically undergoes He shell flashes, i.e. before the thermally pulsing asymptotic giant branch (TP-AGB) phase. The H-burning shell is inactive during this phase.

Early Asymptotic Giant Branch:
See E-AGB.

early Integrated Sachs-Wolfe effect:
The Sachs-Wolfe effect detectable in the cosmic microwave background radiation.

early-type:

(1) Galaxy: for historical reasons, referring to elliptical galaxies. There is no evolution from early to late-type galaxies.

(2) Star: referring to high mass stars of spectral type O, B, or A.

See late-type.

eccentricity:
A numerical quantity that gives a measure of how elliptical an orbit is; the ratio *c/a* of the distance between the centre of the ellipse and one of its foci (*c*), and the semimajor axis (*a*). The symbol *e* is normally used for eccentricity. For a circular orbit the two foci coincide at the centre of the circle, and so $e = 0$.

eclipse:
The phenomenon whereby one orbiting astronomical body periodically passes in front of another giving rise to a decrease in brightness which persists for (usually) a small fraction of the orbit.

eclipse mapping:
An indirect imaging technique of the accretion flow in a close binary star that makes use of the shape of the light curve in eclipsing system.

eclipsing binaries:
See eclipsing binary.

eclipsing binary:

A binary system with high inclination in which the stars periodically move in front of one another as seen from the Earth, so that one star totally or partially eclipses the other, causing a dip in the light curve. If a particular binary is eclipsing, that implies that our line of sight lies close to the orbital plane of the binary, which allows calculation of the binary's orbital parameters. Because eclipsing binaries tend to be large stars in small orbits, mass transfer between the stars is often important. Three subcategories are recognised:

(EA) Algol-type eclipsing systems. Binaries with spherical or slightly ellipsoidal components. It is possible to specify, for their light curves, the moments of the beginning and end of the eclipses. Between eclipses the light remains almost constant or varies insignificantly because of reflection effects, slight ellipsoidality of components, or physical variations. Secondary minima may be absent. An extremely wide range of periods is observed, from 0.2 to more than 10000 days. EA-type light curves are most likely produced by detached binaries (although in some cases may arise in semi-detached binaries).

(EB) Beta Lyrae-type eclipsing systems. These are eclipsing systems having ellipsoidal components and light curves for which it is impossible to specify the exact times of onset and end of eclipses because of a continuous change of a system's apparent combined brightness between eclipses; secondary minimum is observed in all cases, its depth usually being considerably smaller than that of the primary minimum; periods are mainly longer than 1 day. Binaries with EB-type light curves will have components that are close to filling their Roche-lobes. Most likely one of them will actually fill its Roche lobe, so the system will be semi-detached (although some EB-type light curves may arise in just-detached or just-contact binaries also.)

(EW) W Ursae Majoris-type eclipsing variables. These are eclisping binaries with periods shorter than 1 day, consisting of ellipsoidal components and having light curves for which it is impossible to specify the exact times of onset and end of eclipses. The depths of the primary and secondary minima are almost equal or differ insignificantly. They are contact binary stars.

Eddington accretion rate:
The mass accretion rate corresponding to the Eddington limit. This is an approximate upper limit on the accretion rate since radiation pressure prevents accretion at a higher rate.

Eddington-Lemaitre model:
A model of the Universe with curvature parameter, k=+1 and dark energy density parameter, $\Omega_{\Lambda,0} = \Omega_{\Lambda,E}$ where $\Omega_{\Lambda,E}$ is given by $\Omega_{m,0}/2$, i.e. the dark energy density parameter in the static Einstein model.

Eddington limit:

An upper limit to the luminosity that can be generated in a system powered by accretion. The limit arises because the photons emitted by the accreting body exert a force on the electrons in the accreting material (see Thomson scattering, Compton scattering). The electrons are bound to the protons and other nuclei by electrostatic forces (see electromagnetic interaction) so the protons feel the force due to the photons too. At the Eddington luminosity, the force exerted by the photons is sufficient to overcome the inward gravitational attraction. The Eddington luminosity is given by

$L_{edd} = 4\pi G M m_p c/\sigma_T$

where G is the gravitational constant, M is the mass of the accreting body, m_p is the mass of a proton, c is the speed of light, and σ_T is the Thomson cross-section. This calculation assumes spherical accretion, and so is only approximate in the case of accretion from an accretion disc, for example.

Eddington luminosity:
The accretion luminosity corresponding to the situation where an object is accreting matter at the Eddington limit. This is an approximate upper limit on the accretion luminosity since radiation pressure prevents accretion at a higher rate.

Eddington timescale:

The time which an object would take to radiate away all its rest mass, at the Eddington luminosity.

$$t_{\rm Edd} = Mc^2/L_{\rm Edd}$$

E-ELT:
The planned European Extremely Large Telescope, which will have a 40m diameter mirror.

effective area:
Used to quantify the sensitivity of (for example) an X-ray detector.

effective temperature:

The temperature of a black body with the same luminosity and radius as the object being considered. It is given by the Stefan–Boltzmann law:

$T_{eff} = (L/4\pi\sigma R^2)^{1/4}$

where L is the luminosity, R the radius and σ is the Stefan–Boltzmann constant. For objects whose emission is similar to black body radiation, such as stars, the effective temperature is close to the actual surface temperature.

egress:
The time at the end of an eclipse between third contact (when the eclipsing body just begins to move away from the eclipsed body) and fourth contact (when the eclipsing body has completely moved away from the eclipsed body). See ingress.

Einstein:
A NASA X-ray observatory, operating from 1978 to 1981, which was the first fully-imaging X-ray satellite. It resolved X-ray sources in other nearby galaxies, including the Andromeda Galaxy and the Magellanic Clouds.

Einstein coefficients:
(of absorption and of induced and spontaneous emission). Parameters describing the probability of a particular atomic transition occurring in the presence of black body radiation of a particular energy density.

Einstein constant:
A constant in the Einstein field equations given by $\kappa = 8\pi G/c^4$.

Einstein cross:
An arrangement of four gravitaionally lensed images around a central source.

Einstein-de Sitter model:

A model of the universe with curvature parameter k=0, radiation density $\rho_{r,0}$=0, and dark energy density $\rho_{\Lambda,0}$=0. Hence it contains only matter. It is sometime referred to as the critical model.

In this model:

the Hubble parameter $H(t) = 2/3t$

and the scale factor $R(t) = R_0\ (3H_0t/2)^{2/3}$

Einstein field equations:
The fundamental field equations of general relativity, written in terms of the Ricci tensor, curvature scalar, metric tensor, and energy-momentum tensor as $R_{\mu\nu} - R\ g_{\mu\nu}/2 = -\ \kappa\ T_{\mu\nu}$, where κ is sometimes called the Einstein constant.

Einstein model:
A static model of the universe, i.e. one in which the scale factor is constant with cosmic time. Ignoring the effect of radiation (i.e. assuming $\Omega_{r,0} = 0$), such a model arises when the effect of dark energy exactly balances the effect of matter. For this to be the case, it follows that $\Omega_{\Lambda,0} = \Omega_{m,0}/2$. This dark energy density parameter is often written as $\Omega_{\Lambda,E}$.

Einstein radius:

In gravitational lensing, the angular size of a gravitationally lensed image consisting of a ring that arises when the lensing object and the lensed object lie in a direct line with the observer. Given by

$$\theta_E = \sqrt{\frac{4GM}{c^2}\frac{D_{LS}}{D_L D_S}}$$

where D_{LS} is the distace from the lensing object to the lensed object, D_L is the distance from the lensing object to the observer, and D_S is the distance from the lensed object to the observer.

Einstein ring:
See Einstein radius.

Einstein ring radius:
See Einstein radius.

Einstein tensor:

The rank 2 tensor $[G^{\mu\nu}]$ defined in terms of the Ricci tensor, curvature scalar, and metric tensor with components given by $G^{\mu\nu} \equiv R^{\mu\nu} - g^{\mu\nu} R/2$.

elastic:
A term used to describe the ability of a body to recover fully from a distortion, as long as it is not stretched too far. An elastic collision is one in which kinetic energy is conserved.

electric charge:
A fundamental property of matter that determines the electric and magnetic interactions of particles. It obeys the principle of conservation of electric charge. There are two types of charge, positive and negative. Protons in atomic nuclei are positively

charged (with charge e) and electrons are negatively charged (with charge $-e$). According to Coulomb's law, charges experience electrostatic forces; like charges repel and opposite charges attract. According to the Lorentz force law, charges moving across a magnetic field experience magnetic forces in a direction perpendicular both to their direction of motion and to the magnetic field. The SI unit of electric charge is the coulomb (C).

electric dipole:
Any system that produces an electric field similar to that of two electric charges of the same magnitude q, but with opposite signs, separated from one another by a fixed distance d. Such a system is characterized by an electric dipole moment of magnitude qd.

electric field:

The vector quantity $\mathcal{E}(\mathbf{r})$ that determines the electrostatic force acting on any charged particle placed at the point specified by the *position vector* $\mathbf{r}$. It is defined as the electrostatic force per unit charge, so if $\mathbf{F}_{el}$ is the electrostatic force on a particle of *charge* q at point $\mathbf{r}$, then $\mathcal{E}(\mathbf{r}) = \mathbf{F}_{el}/q$. The electric field has both magnitude and direction at each point in space, so it is an example of a vector field, and electric fields due to different sources add vectorially at every point. For an important example of an electric field see electric field due to a point charge. At any point, the electric field component in a given direction is equal to minus the gradient of the electric potential, V, in that direction. For example, the x-component and the radial component are given respectively by $\mathcal{E}_x = -dV/dx$ and $\mathcal{E}_r = -dV/dr$. The SI unit of electric field is N C^{-1} or (equivalently) V m^{-1}.

electric field due to a point charge:

The electric field due to a point charge is spherically symmetric around the charge. If a charge Q is placed at the origin, the electric field at a point specified by the position vector $\mathbf{r}$ is

$$\mathcal{E}(\mathbf{r}) = \frac{Q}{4\pi\epsilon_0 r^2}\hat{\mathbf{r}}$$

where $\hat{\mathbf{r}}$ is a unit vector in the direction of $\mathbf{r}$ and ε_0 is the permittivity of free space. Thus, the magnitude of the electric field depends only on the distance r from the charge and it is directed away from a positive charge or towards a negative charge.

electromagnetic four-tensor:

A 16-component entity which expresses the electric field and magnetic field. In its contravariant form, $[F^{\mu\nu}]$, the elements are:

$$[\mathrm{F}^{\mu\nu}] \equiv \begin{pmatrix} \mathrm{F}^{00} & \mathrm{F}^{01} & \mathrm{F}^{02} & \mathrm{F}^{03} \\ \mathrm{F}^{10} & \mathrm{F}^{11} & \mathrm{F}^{12} & \mathrm{F}^{13} \\ \mathrm{F}^{20} & \mathrm{F}^{21} & \mathrm{F}^{22} & \mathrm{F}^{23} \\ \mathrm{F}^{30} & \mathrm{F}^{31} & \mathrm{F}^{32} & \mathrm{F}^{33} \end{pmatrix} = \begin{pmatrix} 0 & -\mathcal{E}_x/c & -\mathcal{E}_y/c & -\mathcal{E}_z/c \\ \mathcal{E}_x/c & 0 & -B_z & B_y \\ \mathcal{E}_y/c & B_z & 0 & -B_x \\ \mathcal{E}_z/c & -B_y & B_x & 0 \end{pmatrix}$$

In its covariant form, $[F_{\mu\nu}]$, the elements are:

$$[\mathrm{F}_{\mu\nu}] \equiv \begin{pmatrix} \mathrm{F}_{00} & \mathrm{F}_{01} & \mathrm{F}_{02} & \mathrm{F}_{03} \\ \mathrm{F}_{10} & \mathrm{F}_{11} & \mathrm{F}_{12} & \mathrm{F}_{13} \\ \mathrm{F}_{20} & \mathrm{F}_{21} & \mathrm{F}_{22} & \mathrm{F}_{23} \\ \mathrm{F}_{30} & \mathrm{F}_{31} & \mathrm{F}_{32} & \mathrm{F}_{33} \end{pmatrix} = \begin{pmatrix} 0 & \mathcal{E}_x/c & \mathcal{E}_y/c & \mathcal{E}_z/c \\ -\mathcal{E}_x/c & 0 & -B_z & B_y \\ -\mathcal{E}_y/c & B_z & 0 & -B_x \\ -\mathcal{E}_z/c & -B_y & B_x & 0 \end{pmatrix}$$

Sometimes referred to as simply the field tensor.

electromagnetic interaction:
See fundamental forces.

electromagnetic radiation:
Radiation comprising any part of the electromagnetic spectrum.

electromagnetic spectrum:

The complete range of electromagnetic radiation, ranging from γ-rays at short wavelengths (high frequencies) through X-rays, ultraviolet radiation, visible light, infrared radiation and microwaves to radio waves at long wavelengths (low frequencies).

electromagnetic wave:
A fluctuating pattern of electric and magnetic fields, in which each field takes the form of a wave. At any point in an electromagnetic wave, the electric and magnetic fields are mutually perpendicular, and each field is also perpendicular to the direction of propagation of the wave. The existence of such waves is implied by Maxwell's equations, which also predict that the waves will travel through a vacuum at the speed of light. Electromagnetic waves of appropriate wavelength (or frequency) may be used to model each of the kinds of electromagnetic radiation that comprise the electromagnetic spectrum.

electron:

A type of elementary particle with charge -1.602×10^{-19} C, mass $9.109\,56 \times 10^{-31}$

kg (or about 0.511 MeV/c^2), and spin 1/2. The electron is a stable lepton. As far as is known, it has no internal structure, and is therefore regarded a truly fundamental particle. Electrons are constituents of all atoms.

electron capture:

A form of β-decay in which a nucleus absorbs one of its own electrons, causing a proton to become a neutron and a neutrino to be emitted.

electron charge:
The charge carried by the electron, $-e = -1.602 \times 10^{-19}$ C.

electron degeneracy:
A condition in which the quantum nature of electrons cannot be ignored.If electrons are packed so densely that their separations are comparable to their de Broglie wavelength, then the Pauli exlcusion princliple prohibits the overlapping of electrons with the same energy. This leads to the decoupling of pressure and temperature in a degernerate electron gas. See degenerate matter.

electron density:
A numerical quantity used to describe the number density of electrons in a system, usually given the symbol n_e. Units are m^{-3} (SI) or cm^{-3} (cgs).

electron neutrino:

A type of elementary particle that has no known substructure and is therefore regarded as a truly fundamental particle. It is the partner to the electron in the first generation of leptons. It has spin 1/2, no charge and a mass of less than 0.000 015 MeV/c^2.

electron–positron pair production:

The spontaneous production of a matter–antimatter pair of particles by high-energy electromagnetic radiation. Electron–positron pair production can occur if two *γ-ray* photons have energies E_1 and E_2 such that $E_1E_2 > (m_ec^2)^2$ where m_e is the mass of the electron.

electron scattering:
An important source of opacity in astronomical plasmas, especially at high temperature and/or low density, due to the scattering of photons by free electrons as an electron responds to the photon’s oscillating electric field. Also called Thomson scattering, electron scattering is independent of wavelength and depends only on the number density of free electrons. See also Compton scattering.

electron temperature:
The temperature that would give rise to an observed mean electron energy, according to $E = 3/2\ kT$. A population of free electrons need not be in thermal equilibrium with their surroundings, so the electron temperature of that population may not be the same as the temperature of other material in the same region.

electronvolt:
A unit of energy, represented by the symbol eV and defined by the relation 1 eV = 1.602×10^{-19} J. The electronvolt is the change in potential energy of an electron that is displaced through a potential difference of 1 volt.

electrostatic force:

The force that acts on a body due to its interaction with an electric field. In the case of a point particle of charge q, it is given by $\mathbf{F}_{el}$ (on q at $\mathbf{r}$) = $q\mathcal{E}(\mathbf{r})$, where $\mathcal{E}(\mathbf{r})$ is the electric field at the position r of the particle. The electrostatic force between two charges is described by Coulomb’s law.

electrostatic potential energy:
The potential energy of a particle or body that arises from its interaction with other particles or bodies via the (conservative) electrostatic force. The electrostatic potential energy of a charge q, placed at a point where the electric potential is V, is given by $E_{el} = qV$.

element:
Traditionally, a substance which cannot be divided by chemical means, heating or the passage of an electric current. More specifically, a pure sample of any given element consists of matter entirely composed of atoms with a specific number of protons in their nuclei.

ellipse:
A conic section which is a closed curve. An ellipse has two foci on the ellipse's major axis, on either side of the center, such that the sum of the distances from any point of the ellipse to the two foci is constant and equal to the length of the major axis. The eccentricity of an ellipse is the ratio of the distance between the foci to the length of the major axis. The eccentricity lies between 0 and 1; it is zero if the major and minor axes of the ellipse are equal, in which case the ellipse is a circle.

ellipsoidal variation:
A periodic modulation of the light curve of a semidetached binary due to the

non-spherical shape and surface brightness distribution of the Roche-lobe filling donor star.

elliptical galaxies:
See elliptical galaxy.

elliptical galaxy:
A galaxy that appears as an ellipsoidal, structureless distribution of old (population II) stars. Most ellipticals show very little evidence of ongoing star formation and contain little or no cold gas, though they may contain hot gas that can be detected through its X-ray emission. Giant elliptical galaxies known as cD galaxies are found at the centres of clusters of galaxies, and are likely to have formed by the merger of several smaller systems.

emergent spectrum:
The spectrum of light emerging from a planet as a result of modification of the incident spectrum (from a star) which is modified by reflection and absorption effects within the planet's atmosphere or surface.

emission:
See emission line spectrum.

emission line:
See emission line spectrum.

emission line spectrum:
A spectrum containing emission lines, which occur when free electrons combine with atoms, or when excited electrons in atoms or molecules make transitions to lower energy levels, causing the excess energy to be radiated as photons. Energy must be supplied to excite the electrons or ionize the atoms (see ionization); this can be from collisions with other particles or from incoming radiation, for example. Because the energy levels of an atom are fixed and discrete, emission lines occur at fixed, discrete wavelengths and frequencies (see hydrogen spectrum). Doppler shifts of emission lines are important for measuring speeds of astronomical objects; emission lines also tell us about the different types of atoms and molecules in an astronomical object and their physical state.

emission nebula:
See HII region.

emission profile:
The detailed shape of an emission line. Profiles contain information about the motion of the material in which the lines arise and about the motion of material in which the emission is subsequently absorbed.

empty (spacetime):
A spacetime region for which the energy-momentum tensor $[T_{\mu\nu}] = 0$ or, equivalently, the Ricci tensor $[R_{\mu\nu}] = 0$.

empty Universe:
A model of the Universe that contains no matter. Contrast with open Universe and closed Universe.

enclosed mass:
The mass within the orbit of a body which is responsible for that body’s motion under the influence of gravity.

endothermic:
A process or reaction in which energy is absorbed. See also exothermic.

energy:
The property of a system that measures its capacity for doing work. The SI unit of energy is the joule, represented by the symbol J where $1\ \text{J} = 1\ \text{kg m}^2\ \text{s}^{-2}$. The cgs unit of energy is erg where $1\ \text{erg} = 1\ \text{g cm}^2\ \text{s}^{-2} = 10^{-7}$ joule.

energy conservation:
See conservation of energy.

energy level:
Oner of the allowed energies of a particle in a quantum mechanical system. If the particle is in a bound state, the energy levels are discrete. If the particle is not bound they form a continuum. Do not confuse energy levels with quantum states. Many different quantum states can correspond to the same energy level.

energy-momentum tensor:
The rank 2 tensor, usually written $[T^{\mu\nu}]$, that is the source term in Einstein's field equations and describes the density and flow of energy and momentum in spacetime.

energy-time uncertainty principle:
The Heisenberg uncertainty principle states that energy conservation may be violated by and amount ΔE for a time interval Δt provided that $\Delta E\ \Delta t \leq h/2\pi$. This allows quantum fluctuations inthe vacuum to give rise to transient particle-antiparticle pairs

known as virtual particles.

ensemble:
A large number of particles participating in a physical process.

entropy:
A quantity which gives a macroscopic description of energy exchanges related to the microstates accessible to a system at a molecular level. Often taken to be a measure of 'disorder'.

entropy per baryon:

A measure of the baryon asymmetry in terms of the photon abundance. Given by

$$\eta = \frac{n_{\mathrm{B}} - n_{\overline{\mathrm{B}}}}{n_{\gamma}}$$

where n_{B} is the comoving number density of baryons, n_{B} is the comoving number density of anti-baryons,and n_{γ} is the comoving number density of photons.

envelope:
That part of a star outside the core.

equation of a straight line:
An equation of the form $y = mx + c$, where m and c are constants that represent the gradient and the intercept of the line respectively.

equation of continuity:

(1) The equation that describes the law of conservation of mass in an ideal fluid.

(2) The equation that describes the law of conservation of electric charge.

equation of geodesic deviation:
See geodesic deviation.

equation of motion:
An equation that expresses (explicitly or implicitly) the position of a moving object as a function of time. Such equations often take the form of differential equations and are obtained by combining Newton's second law of motion with the force laws that are appropriate to the system under consideration.

equation of state:

An equation that relates the variables of pressure, volume and temperature for a macroscopic system in an equilibrium state.

(1) For an ideal gas, the equation of state is $PV = NkT$, where k is the Boltzmann constant.

(2) In cosmological models, an equation of state is used to express the relationship between pressure and density as $p = wpc^2$. For non-interacting matter (referred to as 'dust') $w = 0$, for radiation $w = +1/3$, and for dark energy $w = -1$.

equatorial coordinate system:
A commonly used coordinate system for describing the location of points on the sky (celestial sphere). The system is based on two angular coordinates; right ascension and declination.

equilibrium:
A system is said to be in a state of equilibrium if its measurable properties remain constant in time.

equilibrium energy distribution:
See Maxwell-Boltzmann energy distribution.

equilibrium speed distribution:
See Maxwell speed distribution.

equilibrium state:
A settled and unchanging state of thermodynamic equilibrium.

equilibrium temperature:

The temperature of a planet based on the principle that, in equilibrium, the energy received from the host star per unit time is exactly equal to the thermal energy radiated away by the planet per unit time. Given by

$T_{\mathrm{eq}} = [(1-A)F_{*}/4\sigma]^{1/4}$

where A is the albedo of the planet and F_{*} is the flux of radiation from the star.

equipartition of energy:

In thermal equilibrium at temperature T, the *average* energy per particle is $E = (kT/2)$ x s where s is the number of degrees of freedom of each particle. Note that this does not depend on the mass of the particle.

equivalence principle:
See weak equivalence principle; strong equivalence principle

equivalent width:
A quantity that gives a measure of the strength of an observed absorption or emission line. The equivalent width is the area of the line divided by the level of the nearby continuum. The units depend on the units being plotted on the spectrum; in optical spectra they might be angstroms or nanometres, and in X-ray spectra electronvolts. See curve of growth.

erg:
The cgs unit of energy and of work, defined by the relation 1 erg = 1 g m^2 s^{-2}. One erg of work is done when a force of one dyne moves its point of application one centimetre in the direction of the force.

ergosphere:
The region between the static limit and the outer event horizon of a rotating black hole described by the Kerr solution is called the ergosphere. See Kerr metric.

EROs:
Extremely Red Objects.

escape speed:
A numerical quantity that gives the minimum speed required for an object to escape the gravitational influence of a massive body. In Newtonian gravity, the escape speed is given by

$v_{esc} = (2GM/r)^{1/2}$

where G is the universal gravitational constant, M is the mass of the gravitating body, and r is the initial distance from its centre. The escape speed from the Earth's surface is about 11.2 km s^{-1}.

escape velocity:
See escape speed.

ether:
A hypothetical all-pervading medium through which electromagnetic disturbances were supposed to travel. Now known not to exist.

EUCLID:
A planned space telescope intended to map the large scale distribution of dark matter via measurements of cosmic shear.

Euclidean:
A term used to describe space in which geometric properties accord with everyday experience, i.e. one in which the effects of general relativity are ignored. In Euclidean space, the internal triangles of a triangle add up to 180° and the volume of a sphere is $4\pi r^3/3$, for instance.

Euclidean-normalized differential source count:
The regular differential source count dN/dS multiplied by $S^{2.5}$. If the source counts are Euclidean, then a plot of $S^{2.5}$ dN/dS would be a horizontal line.

Euclidian geometry:
Geometry in which the internal angles of a triangle add up to 180°, a circle of radius R has a circumference of length $2\pi R$, and a sphere of radius R has surface area $4\pi R^2$.

Euler equation:
Newton's second law of motion, expressed for a continuous fluid.

Euler-Lagrange's equations:
The equations

$$\frac{\mathrm{d}}{\mathrm{d}s}\left(\frac{\partial F}{\partial\left(\frac{\mathrm{d}x^m}{\mathrm{d}s}\right)}\right) - \frac{\partial F}{\partial x^m} = 0$$

(where F is the integral of unknown function(s)) that give maxima or minima of F and are of fundamental importance to the study of the calculus of variations.

event:
An instantaneous occurrence at a specific point in space.

event horizon:
See black hole, Kerr metric, Schwarzschild metric.

excess:
See spectral excess, colour excess, soft X-ray excess, infrared excess, ultraviolet excess.

excitation potential:
The threshold kinetic energy required to raise an atom to a particular *excited state*.

excited state:
One of the states of a quantum system which have more energy than the ground state. In the context of an atom, the excited states correspond to energy levels of higher energy than the ground state energy level.

exomoon:
A natural satellite of an exoplanet.

exoplanet:
A planet orbiting a star other than the Sun. According to the International Astronomical Union, an exoplanet has a mass that is below the limiting mass for thermonuclear fusion of deuterium (currently calculated to be 13 times the mass of Jupiter for objects with the same isotopic abundance as the Sun) and orbits a star or stellar remnant. This definition takes no account of how the object formed, so it is possible that the definition may include objects that would othwerwise be classified as a brown dwarf.

exothermic:
A process or reaction in which energy is released. See also endothermic.

exponential:
See exponential function, exponential process.

exponential decay:
See exponential process.

exponential function:

A function that may be written in the form $v(t) = v_0 e^{at}$, where v_0 and a are constants. Any function of the form $y = a^x$, where a is a positive constant, may be written as $y = e^{kx}$ since it is always possible to find a constant k such that $e^k = a$, and we can then write $a^x = (e^k)^x = e^{kx}$.

exponential growth:
See exponential process.

exponential process:

A process of growth or decay that can be described by an exponential function $v(t) = v_0 e^{at}$. Exponential growth corresponds to a positive value of α, exponential decay to a negative value of α. In either case the process is characterized by the fact that the quantity v changes its value by equal factors in equal intervals of time, irrespective of when those intervals begin or end. A particularly well known example is the decay of radioactive nuclei described by

$N(t) = N_0 \exp(-\lambda t)$

where N_0 is the number of parent nuclei at $t = 0$, and the decay constant λ is the reciprocal of the mean lifetime τ and is related to the half-life $T_{1/2}$ by $T_{1/2} = \log_e(2)/\lambda$.

extended narrow line region:
A region of an active galactic nucleus that extends beyond the narrow line region. A region where ionization cones are sometimes seen.

extinction:

A quantity that describes the reduction in the amount of light received from an astronomical object as a result of absorption and scattering by cosmic dust. The amount of extinction is normally measured in magnitudes; it gives rise to an uncertainty in the conversion between absolute and apparent magnitude. Because the effect of extinction is greater at shorter wavelengths, it also makes objects appear redder than they actually are (not to be confused with the redshift due to the Doppler effect) and these objects are said to be reddened. The amount of reddening is usually expressed in terms of the colour excess,

$E(B - V) = (B - V) - (B_0 - V_0)$

where $B - V$ is the colour between the blue and visual bands and $B_0 - V_0$ is the colour that would be expected in the absence of extinction. Formulae exist to calculate $E(B - V)$ if the amount of dust is known. A typical value of $E(B - V)$ is a few tenths of a magnitude.

extinction law:
The variation of extinction as a function of wavelength.

extragalactic astrophysics:
The astrophysics of objects outside our own Galaxy.

extrasolar planet:
See exoplanet.

extreme environment:

In astrophysics, referring to a location where the physical conditions include one or more of: extremely hot, extermely energetic, extremely strong magnetic field, extemely strong gravitational field.

extreme Kerr black hole:
See Kerr metric.

Extremely Red Objects:
A population of galaxies found in deep field surveys which are very faint at optical wavelengths but very bright in the near infrared.

extrinsic curvature:
Curvature which does not change the geodesics of space-time.

F

Faber-Jackson relation:
The observed proportionality between the velocity dispersion of an elliptical galaxy and its luminosity or absolute magnitude. More luminous, and therefore more massive, galaxies have a larger velocity dispersion as a consequence of the virial theorem. Since the velocity dispersion and the galaxy's apparent magnitude can both be measured, the Faber–Jackson relationship can be used to estimate a galaxy's distance. Contrast with Tully-Fisher relation.

factorization:

The mathematical process of writing an expression of the form $a_0 + a_1x + a_2x^2 + \ldots a_nx^n$ as a product of factors of the form $a_n(x - \alpha)(x - \beta)\ldots(x - \omega)$. For example, $ax^2 + bx + c$ can be written as $a(x - \alpha)(x - \beta)$, where the quantities α and β can be expressed in terms of a, b and c.

faint blue galazxies problem:
The observation that there are too few faint blue galaxies to be consistent with an unevolving population of galaxies.

false vacuum:
A secondary (or local) minimum of the inflaton field from which the universe may quantum tunnel through to a lower energy state.

Fanaroff-Riley classes I and II:
Two classes into which the radio galaxy population can be divided. Fanaroff and Riley suggested, in 1974, that radio galaxies could be divided into two populations according to the distribution of their radio emission in low-resolution maps; objects that were brightest towards the centre are classed as FR I while those that were brightest at the edges are FR IIs. Fanaroff and Riley's key result was that FR I sources tend to have low radio luminosity, while FR II sources are more luminous. The difference in radio structure must therefore reflect differences in the physics of the sources. It is now thought that the FR II sources have more powerful jets which are able to pass through the host galaxy without being decelerated and disrupted. See radio source structure.

Faraday depolarization:
See Faraday rotation.

Faraday effect:
Another name for Faraday rotation.

Faraday rotation:

The rotation of the direction of polarization that occurs when linearly polarized light propagates through an ionized medium containing a magnetic field. The angle through which the direction of polarization is rotated is given by

$$\Delta\phi \propto \lambda^2 \int n_e B \mathrm{d}l$$

where B is the component of magnetic field strength along the line of sight, n_e is the number density of electrons, and dl is the line element along the line of sight. This equation is often written

$$\Delta\phi \propto \lambda^2 RM$$

where RM is called the rotation measure. Because the rotation is proportional to the square of the wavelength, the Faraday effect is most important for long wavelengths, and is seen in astronomical contexts in radio polarization. Polarized radio waves, such as synchtrotron radiation, have their direction of polarization rotated on passing through an ionized medium; by observing the direction of polarization at several wavelengths it is possible to determine the rotation measure, and so to estimate values for the electron density or magnetic field strength in the medium. If the telescope beam contains several regions with different values of RM, or if the ionized medium is mixed in with the radio-emitting plasma, then the resulting sum of differently rotated polarized emission will reduce the degree of polarization measured, and may even cause the polarization measured to drop to zero. This effect is known as Faraday depolarization.

fastness parameter:

The ratio of the angular speed of a magnetic accreting star to the Keplerian angular speed at its Alfvén radius. For steady accretion to occur, the fastness parameter must be less than one.

feedback:
In relation to star formation in galaxie, the process whereby the current amount of star formation can affect the future star formation rate because supernova-driven superwinds can influence subsequent star formation.

Fermi energy:

When a system of fermions is at absolute zero temperature, the quantum states fill from the ground state up. The energy of the highest occupied state is called the Fermi energy, E_F. A degenerate gas may be regarded as very cold, the available energy levels being much higher than those corresponding to the temperature of the material. For this reason, the Fermi energy is useful in considering the state of degenerate matter in the cores of low-mass giant stars or in compact stellar remnants. For a system of fermions in thermal equilibrium at temperature $T > 0$ K, the Fermi energy is the energy at which the Fermi occupation factor equals 1/2.

Fermi kinetic energy:

The kinetic energy $p_F^2/2m$ (in the non-relativistic case) of a particle whose momentum is the Fermi momentum p_F.

Fermi level:
The boundary line on an energy-level diagram between filled states and unfilled states for a system of fermions in thermal equilibrium at 0K. The Fermi level occurs at an energy equal to the Fermi energy E_F.

Fermi momentum:

The momentum magnitude p_F of a particle whose energy is the Fermi energy E_F, where $E_F = mc^2 + p_F^2/2m$ (in the non-relativistic case).

Fermi occupation factor:

The factor

$$F_F(E) = \frac{1}{\exp(E - E_F)/kT + 1}$$

that determines the average number of particles in a single quantum state of energy E for a system of identical fermions in thermal equilibrium at absolute temperature T. The energy E_F that is a characteristic of the system is called the Fermi energy.

fermion:

A particle with half odd-integer spin (i.e. spin 1/2, 3/2, etc.). Fermions obey the Pauli exclusion principle. Consequently, only one fermion can occupy any given quantum state.

Fermi temperature:

The quantity

$T_F = n^{2/3}h^2/(2\pi mk)$

If the temperature of a gas is less than the Fermi temperature, it is degenerate.

fictitious force:
A force with no basis in physical reality, but which can, nonetheless, be used to account for the motion of bodies observed from a non-inertial frame of reference. By introducing such fictitious forces, the bodies can be made to conform to Newton's laws of motion, even though those laws do not, strictly speaking, apply in non-inertial frames. (Also known as pseudo-forces.) See centrifugal force and Coriolis force.

fiducial phase:
A reference point in an orbit from which other phases are measured.

field:
A physical quantity to which a definite value can be ascribed at every point throughout some region of space. Scalar fields (e.g. temperature, pressure and electric potential fields) are specified by a scalar value at every point; vector fields (e.g. electric fields, magnetic fields and gravitational fields) are specified by a vector value at every point. Historically, fields were introduced into physics as a means of accounting for the propagation of forces and other measurable phenomena without having to admit the possibility of action at a distance.

field lines:
Lines used in pictorial representations of vector fields. They are directed along the field direction at every point and their spacing in any region indicates the magnitude of the field in that region: the closer together the lines, the stronger the field. Electric field lines emerge from positive charges and disappear into negative charges. Closed electric field lines can surround regions of changing magnetic flux. According to Maxwell's equations, magnetic field lines are continuous and have no beginning or end. However, outside a permanent magnet, magnetic field lines emerge from north

poles and disappear into south poles. (To maintain continuity, the opposite is true inside the magnet, although this is not observed directly.) Closed magnetic field lines can surround electric currents and regions of changing electric flux. Gravitational field lines begin at infinity and terminate at masses.

filling factor:
Specifically, the proportion of the broad line region or narrow line region in an *AGN* which is occupied by clouds. Given by $\varepsilon = N_c l^3 / r^3$ where N_c is the number of clouds, l their typical size and r the size of the region in question.

fine structure:
A term used to describe the small energy splitting in atomic energy levels due to spin–orbit interaction effects.

fingers of God:
Filaments in the large scale structure of the Universe revealed by galaxy redshift surveys caused by clusters of galaxies elongated in redshift space along an axis pointed towards the observer. The effect arises because the galaxies in a given cluster acquire the typical redshift of the cluster plus or minus its velocity dispersion. Contrast with Kaiser effect.

fireball:
Decriptive name of the region which produces a gamma-ray burst.

first-ascent giant branch:
The red giant branch comprising H-shell burning stars which have not yet initiated He burning. First-ascent giants can be distinguished from clump red giant stars (which are He burning) and asymptotic giant branch stars.

first dredge-up:

An event experienced by $M \geq 3M_\odot$ stars as they reach the base of the giant branch, when the deepening outer convective zone reaches down to material which has been processed by the CN cycle. As a result, recently synthesized ^{14}N and ^{13}C is brought to the surface.

flare:
A sudden short lived brightening of small regions of the Sun's chromosphere, or similar outbursts on other stars. Flares are thought to arise from the sudden release of energy stored in the magnetic field and result in the emission of particles and radiation.

flat:
A space that is not curved i.e. a space for which the Riemann tensor vanishes. Consequently, a space for which a coordinate system can be found such that the metric coefficients are constant.

flatness problem:
The recognition of the fact that the initial density of the Universe is apparently very finely-tuned such that the density is currently extremely close to the critical value required for a flat universe.

flat, pure radiation model:

A model of the universe with curvature parameter k=0, matter density $\rho_{m,0}$=0, and dark energy density $\rho_{\Lambda,0}$=0. Hence it contains only radiation. It has been used to describe the early evolution of the universe, immediately after inflation.

In this model:

the Hubble parameter $H(t) = 1/2t$

and the scale factor $R(t) = R_0\ (2H_0 t)^{1/2}$

flat-spectrum radio source:

An extragalactic radio source (radio galaxy, quasar or BL Lac object) that has a radio spectral index less than 0.5. The spectral index a is a measure of the rate of change of flux density with respect to frequency,

$$\alpha = -\frac{\mathrm{d}\log_{10} S}{\mathrm{d}\log_{10} \nu}$$

so a flat-spectrum radio source's flux density decreases only slowly (or may even increase) with increasing frequency.

fluctuation analysis:
The process of measuring the angular power spectrum of the distribution of pixel values in a confusion-limited map in order to constrain the clustering of sources below the confusion limit.

fluid:
A form of matter that is able to flow. Both liquids and gases are fluids.

fluid dynamics:
The branch of fluid mechanics that concentrates on fluids that are moving, and the forces they exert on immersed solid objects. Fluid dynamics is also called

hydrodynamics, even if the fluid involved is not water.

fluid mechanics:
The branch of classical physics that investigates and predicts the behaviour of fluids, whether at rest or in motion.

fluid statics:
The branch of fluid mechanics that studies fluids that are in a state of rest, and the forces they exert on immersed solid objects. Fluid statics is also called hydrostatics, even if the fluid involved is not water.

fluorescence:
The process whereby an atom absorbs photons at one frequency but re-emits them at a lower frequency. It happens when the atom is excited to some high energy level, then decays to an intermediate energy level before returning to its original state. The energy of the emitted photon is independent of the energy of the incoming photon; the remaining energy is dealt with by other processes.

flux:
A quantity used to describe the energy passing through unit area per unit time. In an astronomical context, the flux of an object in a certain waveband normally means the energy (carried by photons) arriving at the Earth in that waveband from the object. It is therefore related to apparent magnitude as a measure of the source's brightness. The SI units of flux are W m^{-2}.

flux density:
See flux and spectral flux density.

flux limit:
The limit in flux density below which an object will not be included in a sample. A sample of objects selected such that all of them have flux densities greater than some limiting value is said to be flux limited.

flux-limited sample:
An observational sample (of galaxies for instance) which is limited by the minimum flux that can be detected. Since flux is a function of both distance and intrinsic luminosity, a flux limited sample is naturally biased to preferentially detect only more luminous objects at large distances. Compare with distance-limited sample.

forbidden line:
An emission line that occurs as a result of a transition between atomic energy levels that is very unlikely to occur spontaneously as a result of the quantum mechanical selection rules that govern atomic transitions. In laboratory plasmas, the excited state that leads to a forbidden line is likely to be de-excited rapidly by atomic collisions before it can give rise to radiation. As such these lines are said to be collisionally suppressed. In astrophysical plasmas the density is often very low, so that atomic collisions are infrequent, and in these situations 'forbidden' transitions can actually occur. See permitted lines.

forbidden transition:

A radiative transition is said to be forbidden if it corresponds to a change in quantum numbers that does not satisfy the relevant selection rules. Such transitions have a very low probability of occurring in comparison to permitted transitions which do satisfy the selection rules. In low-density regions which occur in certain astrophysical situations, forbidden lines can be produced as a result of atomic transitions which give rise to electric quadrupole radiation. The low density means that collisions between atoms are rare, and so the only way to de-excite atoms in excited states with no permitted transitions is by a low probability forbidden transition. Forbidden lines are represented by a square bracket notation, such as [OIII] λ5007.

force:

Informally, this is the amount of 'push' or 'pull' exerted on a particle, which, if unopposed, causes it to depart from the uniform motion predicted by Newton's first law of motion. It is, therefore, that which causes (or tends to cause) acceleration. It is a vector quantity, and so has both magnitude and direction. It is quantified by means of Newton's second law of motion, which says that the acceleration $\boldsymbol{a}$ of a particle is proportional to the resultant force $\boldsymbol{F}$ that acts on it, and inversely proportional to its mass m. Thus, in terms of vectors:

$\boldsymbol{F} = m\boldsymbol{a}$

or in terms of (scalar) components

$F_x = ma_x F_y = ma_y F_z = ma_z$

The SI unit of force is the newton (N) where 1 N = 1 kg m s^{-2}. The cgs unit of force is the dyne where 1 dyne = 1 g cm s^{-2} = 10^{-5} newton.

force law:
A term used to describe any law that describes the magnitude and direction of a particular force under specified conditions. Examples include Newton's law of universal gravitation, Coulomb's law and the Lorentz force law.

form invariance:
The idea that the laws of physics should take the same form in every inertial frame of

reference.

forward shock:
The shock that propagates forwards (in the direction of the flow) from an event such as a gamma-ray burst.

four-current:
A contravariant four-vector expressing the charge density and current density $[J^\mu] = (c\rho, \boldsymbol{J})$ where ρ is the density of electric charge and ***J*** is a vector representing the electric current density.

four-displacement:
A generalisation of the four-position which may be expressed as $[\Delta x^\mu] = (c\Delta t, \Delta x, \Delta y, \Delta z)$.

four-force:
In special relativity, the result of differentiating the four-momentum of a particle with respect to the proper time.

$[F^\mu] = [dP^\mu]/[d\tau] = (\gamma(v)\boldsymbol{f}.\boldsymbol{v}/c, \gamma(v)\boldsymbol{f})$

where $\gamma(v)$ is the Lorentz factor of the particle, and ***f*** is a 'conventional' force vector.

Fourier transformation:
A mathematical technique to enable the amplitudes of the sinusoidal and cosinusoidal components of a time series to be determined. Used in the construction of a power density spectrum.

four-momentum:
In special relativity, the result of multiplying the four-velocity of a particle by its mass.

$[P^\mu] = m[U^\mu] = m[dx^\mu]/[d\tau] = (\gamma(v)mc, \gamma(v)m\boldsymbol{v}) = (E/c, \boldsymbol{p})$

where $\gamma(v)$ is the Lorentz factor of the particle, E is its total relativistic energy and ***p*** is its relativistic momentum.

four-position:
A four-vector whose components describe the position of an event in time and space. Represented by $[x^\mu] = (ct, x, y, z)$. See four-displacement.

four-tensor:
A type of tensor that is of relevance to special relativity. Examples include the electromagnetic four-tensor and the Minkowski metric (both of which have rank 2), the four-position, four-displacement, four-velocity, four-momentum, four-force and four-current which are all four-vectors (i.e. four-tensors of rank 1).

The defining characteristic of any four-tensor is its behaviour under Lorentz transformations. Contravariant four-tensors transform by multiplying by the Lorentz transform matrix; covariant four-tensors transform by multiplying by the inverse Lorentz transform matrix.

four-vector:
See four-position, four-displacement, four-velocity, four-momentum, four-force, four-current. These are all contravariant four-vectors which transform according to $[A'^\mu] = [\Lambda^\mu{}_\nu]\,[A^\nu]$ where $[\Lambda^\mu{}_\nu]$ is the Lorentz transformation matrix. A four-vector is a four-tensor of rank 1.

four-velocity:
In special relativity, the derivative of the four-position of a particle moving with velocity ***v*** with respect to the proper time:

$[U^\mu] = [dx^\mu]/[d\tau] = (c\gamma(v), \gamma(v)\boldsymbol{v})$

where $\gamma(v)$ is the Lorentz factor of the particle. See four-momentum.

fragmentation:
The process by which a contracting interstellar cloud breaks up into a number of separate cloudlets as energy is radiated from the cloud and the Jeans mass decreases.

frame dragging:
See dragging of inertial frames.

frame of reference:
A system of coordinate axes and synchronized clocks, that makes it possible to specify uniquely the location in space and time of any given event.

free-bound:
A term used to describe a transition involving an electron and a nucleus in which the electron goes from being unbound ('free') to being bound. This will usually be accompanied by radiation as the electron gives up its excess energy. See recombination.

free fall:

The state of motion of a body when no forces other than gravity act on it. See free-fall time.

free-fall time:
The time it would take for a body to collapse under the influence of gravity alone, neglecting any resistance to collapse from gas pressure or centrifugal forces.

free-free:
A term used to describe a transition involving an electron and a nucleus in which the electron remains unbound to the nucleus at all times. Because the electron's path is bent by the electromagnetic interaction between the negatively charged electron and the positively charged nucleus, it emits radiation, known as free-free radiation or bremsstrahlung (from the German for 'braking radiation') even though no atomic transition is made. Free-free emission can be observed from a variety of astrophysical plasmas.

free index:

Writing the Lorentz transformation as a summation:

$x'^{\mu} = \Sigma_{\nu=0}^{3} \Lambda^{\mu}{}_{\nu} x^{\nu}$

The index μ is a free index since it may take any value we choose, and whatever choice we make indicates a different equation. Contrast with dummy index.

freeze-out:
The process by which ratios of certain particles, such as the neutron:proton ratio, become fixed as the Universe cools enough for equilibrium conversion reactions to cease. At this time, the ratio is said to be frozen-out.

frequency:

The rate at which cycles of a periodic oscillation are completed. For an oscillation of period *T*, the frequency is given by the reciprocal of the period; $f = 1/T$. The SI unit of frequency is the hertz (Hz), where $1\ \text{Hz} = 1\ \text{s}^{-1}$. The concept of frequency may also be extended to the case of waves, where a wave of period *T* is said to have a frequency $f = 1/T$. In this case the frequency represents the rate at which complete cycles of the wave pass a fixed point. When dealing with electromagnetic radiation, the symbol ν (Greek letter nu) is often used for frequency rather than *f*.

Friedmann equations:

The equations relating the scale factor *R* and its derivatives to the density parameters and the curvature parameter *k*.

energy equation: $\left[\frac{1}{R}\ \frac{dR}{dt}\right]^2 = \frac{8\pi G\rho}{3} - \frac{kc^2}{R^2}$

acceleration equation: $\frac{1}{R}\ \frac{d^2R}{dt^2} = -\frac{4\pi G}{3}\left(\rho + \frac{3p}{c^2}\right)$

where ρ is the density (of matter, radiation and dark energy) and *p* is the pressure (of matter, radiation and dark energy).

The two equations may be combined to form the fluid equation:

$$\frac{d\rho}{dt} + \left(\rho + \frac{p}{c^2}\right)\frac{3}{R}\frac{dR}{dt} = 0$$

Friedmann-Robertson-Walker models:
A relativistic cosmological model based on the Robertson-Walker metric with a scale factor determined by the Friedmann equations. Three of the simplest FRW models are the de Sitter model, the flat, pure radiation model, and the Einstein-de Sitter model.

full width half maximum:
Used to quantify the strength of a feature such as a peak in a power density spectrum or a spectral line. Defined as the full width of the feature at half its maximum value.

function:
A term used to describe the mathematical relationship that exists between two variable quantities, *y* and *x* say, when the value of *y* depends on the value of *x*. The dependent variable *y* is said to be a function of the independent variable *x* and may be written as $y(x)$ to emphasize this dependence. The nature of any particular function is usually expressed in terms of an equation, such as $y = mx + c$, or $y = A \sin(kx)$, and may often be conveniently represented by means of a graph of *y* against *x*.

fundamental forces:
The four forces that together govern all the interactions of matter. They consist of two forces with potentially infinite range, the gravitational force, which occurs between any two particles with mass, and the electromagnetic force, which occurs between any two particles with charge; and two forces which are only important at very small distances, the weak nuclear force (which is responsible for certain kinds of radioactive decay) and the strong nuclear force (which binds together the quarks that make up protons, neutrons and other massive sub-atomic particles). On cosmological scales, it is the gravitational force that dominates, as the universe is charge-neutral on these scales.

fundamental observer:
An observer who moves with the Hubble flow. The universe is isotropic to such an observer.

fundamental plane:

A generalization of the Faber-Jackson relation, which defines a relationship between the luminosity of an elliptical galaxy, its surface brightness, and its velocity dispersion as:

$$L \propto I_0^x \sigma_V^y$$

Typically *x* is of order -0.7 and *y* is in the range 3 to 4.

fusion cross-section:
The effective cross-section of a target for undergoing nuclear fusion with some projectile. It has units of area. It may be thought of as the product of the geometrical cross-section of the target with the probability that a fusion reaction occurs when struck.

G

Galactic bulge:
See galaxy.

Galactic bulge source:
One of the subgoup of persistently bright X-ray binaries that belong to the Galactic bulge. The term is largely historical, as these were the first X-ray sources discovered as a group.

Galactic coordinate system:
A coordinate system based on the Galaxy. The Galactic latitude of an object is its angular distance north or south of the Galactic equator. The Galactic longitude of an object is its angular distance eastwards from the galactic centre

Galactic disc stellar population:
The population of stars in the plane of the Galaxy.

Galactic halo:
See halo.

Galactic latitude:
See galactic coordinate system.

Galactic longitude:
See galactic coordinate system.

Galactocentric distance:
The distance of the Sun from the centre of the Galaxy.

galaxies:
See galaxy.

galaxy:
An assembly of gravitationally bound stars, gas and dark matter. The most massive known galaxies contain up to 10^{12} stars; dwarf galaxies can contain only a few million, while globular clusters can be even smaller. Galaxies are classified by their appearance in optical images (see Hubble classification). Elliptical galaxies generally show a featureless, ellipsoidal distribution of stars, while spiral galaxies, like our own Milky Way, show a gas-rich disc with active star formation, which often has observable spiral arms, usually surrounding an ellipsoidal galactic bulge containing mainly older stars, and in turn surrounded by a low-density halo. Lenticular galaxies (also called S0 galaxies) are intermediate between ellipticals and spirals; they have a bulge and disc but little cold interstellar gas and no spiral arms. Irregular galaxies have no well-defined shape. The central supermassive black hole, which may exist in all galaxies, powers an active galactic nucleus in a small fraction of galaxies as a result of accretion of matter. When the words 'Galaxy' or 'Galactic' have an initial capital letter they refer to the Milky Way.

galaxy-galaxy gravitational interaction:
An interaction between two galaxies as a result of gravity. The gravitational force due to the stars, gas and dark matter of one galaxy may distort the structure of the other, leading to observable features like 'tidal tails' of stars as well as increased star formation activity.

galaxy harassment:
The tidal disruption caused by close encounters with other galaxies in a rich environment.

Galaxy Zoo:
A project using input from the general public to carry out morphological classifications of all galaxies in the sloan digital sky survey (SDSS).

Galilean relativity:
A theory in which all inertial observers will agree about the laws of Newtonian mechanics and in which the Galilean transformation holds true.

Galilean transformation:
The coordinate transformation of classical physics or Newtonian physics. If an event has coordinates (x, y, z and t) in frame of reference A, then the coordinates of the same event in frame of reference B, which is in standard configuration with A, are $x' = x - Vt$, $y = y'$, $z = z'$ and $t = t'$, where V is the relative speed of B with respect to A. These equations provide an approximation to the Lorentz transformation at low speeds.

gamma-decay:
A type of radioactive decay process in which a nucleus spontaneously emits a gamma-ray. This process often involves the decay of an excited daughter nucleus produced by a prior alpha-decay or beta-decay.

gamma-factor:
See Lorentz factor.

gamma-ray burst:
An extremely bright, short-duration (less than 10s) flash of gamma rays that originates from a galaxy in the distant Universe. Because they have been found to originate away from the centre of these galaxies, they are probably not powered by an active galactic nucleus. The most likely explanation at the time of writing is that they are related to accretion processes going on in the final stages of a massive supernova explosion (known as a hypernova) or from the mergers of two neutron stars or black holes.

gamma-rays:
Electromagnetic radiation with a wavelength shorter than around 10^{-11} m or a frequency greater than about 3×10^{19} Hz. A common source of such radiation is decaying radioactive nuclei.

Gamow energy:
$E_G = (\pi \alpha Z_A Z_B)^2 2 m_r c^2$. It is a measure of the height of the Coulomb barrier, which resists the approach of two nuclei towards one another. Particle thermal energies are usually well below the Gamow energy, but quantum tunnelling permits a fraction of nuclei to penetrate the barrier regardless.

Gamow peak:
The energy at which the fusion probability is a maximum within the Gamow window, given by $E_0 = E_G^{1/3}(kT/2)^{2/3}$ where E_G is the Gamow energy.

Gamow width:
The characteristic width of the Gamow window, given by $\Delta \approx 1.8(E_G/kT)^{1/6} kT$, where E_G is the Gamow energy.

Gamow window:
The energy range over which a specific fusion reaction occurs. Below the lower energy limit, particles have too little energy to penetrate the Coulomb barrier, while above the upper limit there are too few energetic particles. Within the Gamow window the fusion rate has an approximately *Gaussian* shape. The Gamow peak occurs at

$$E_0 = E_G^{1/3}(kT/2)^{2/3}$$

and the window has a characteristic Gamow width

$$\Delta \approx 1.8(E_G/kT)^{1/6} kT$$

gas:
A phase of matter that has a low density and is able to flow and adopt the size and shape of any empty container. The molecules in gases have relatively large kinetic energies, and move around freely, occasionally colliding with one another or with the walls of their container.

gauss:
The cgs unit of magnetic field strength. (1 gauss = 10^{-4} tesla.) See tesla.

Gaussian curvature:
The quantity $K = k_{max} k_{min}$ for a point on a 2-dimensional surface, where k_{max} and k_{min} are the maximum and minimum values of the radii of the circles best approximating curves through the point.

Gaussian distribution:
Also known as a bell curve or normal distribution, this function indicates how certain populations of values are distributed about their mean (or average) value. The values may be different measurements of a single quantity, in which case the spread reflects the size of the measurement errors. Alternatively, the values may genuinely differ from

one object to another in a population, in which case the spread reflects the variety in the population. The spread of many populations in nature resemble Gaussian distributions. The equation for a Gaussian distribution is

$$G(x) = \frac{1}{\sigma\sqrt{2\pi}} \exp \frac{-(x-\bar{x})^2}{2\sigma^2}$$

where $\bar{x}$ is the mean and s is the standard deviation which quantifies the width (or spread) of the distribution. The Gaussian distribution peaks at the mean, and is symmetric about that peak. 68% of values lie within $\pm s$ of the mean.

Gaussian random field:
A field whose joint probabilty distribution follows a multivariate Gaussian distribution.

G-dwarf problem:
The over-prediction, by closed-box models, of the number of low-metallicity stars in the solar neighbourhood.

general coordinate transformations:
A coordinate transformation of the form $x'^{\mu} = x'^{\mu}(x^{\nu})$ i.e. the new coordinates are functions of the old coordinates.

generally covariant:
A term used to describe a correctly formed tensor equation, which will therefore take the same form in any coordinate system.

general relativity:
See general theory of relativity.

general solution:
In the context of a differential equation, the general solution is a function that satisfies the equation and which contains a number of arbitrary constants equal to the order of the differential equation. An example is the general solution to the (second-order) simple harmonic motion equation; in this case the required function may be written as $x(t) = A \sin(\omega t + \phi)$, where A and ϕ are arbitrary constants that are determined by the initial conditions of the motion (ω is not an arbitrary constant since it appears in the simple harmonic motion equation). Subject to certain common conditions, any solution to a differential equation may be obtained from the general solution by making appropriate choices of the arbitrary constants.

general theory of relativity:
The theory published by Albert Einstein in 1917 that generalizes the ideas of his earlier special theory of relativity by extending them to non-inertial frames of reference. An important principle of the theory asserts that an accelerating frame of reference is locally equivalent to one that is located in a gravitational field. Consequently, the general theory of relativity is also a theory of gravitation, and as such supersedes Newton's theory of gravity. (The predictions of Newton's theory approximate those of general relativity in situations where the gravitational fields are weak.) According to general relativity, gravity manifests itself in the geometric structure (curvature) of space-time. Mass and other sources of gravity determine that curvature, and moving bodies respond to that curvature, giving rise to the appearance of a 'gravitational force'.

geodesic:

In space (as opposed to spacetime), geodesics are the shortest curve between two points for the curve lying entirely within the surface. Alternatively, a curve for which the tangent vector is constant along the curve. Any parameterised pathway defined by a set of n functions $x^i(s)$ where $i = 1, ..., n$ that satisfies the geodesic equations will be a geodesic in the n-dimensional Riemannian space with metric $[g_{ij}]$ and connection coefficients $\Gamma^i{}_{jk}$.

In the spacetime of general relativity, geodesics are paths between two events along which the proper time is a maximum.

geodesic deviation:

A way of describing tidal effects within the framework of general relativity. The separation vector between two geodesics satisfies the following equation of geodesic deviation:

$$\frac{\mathrm{D}^2\xi^\mu}{\mathrm{D}\lambda^2} + \sum_{\alpha\beta\gamma} R^{\mu}{}_{\alpha\beta\gamma}\xi^{\alpha}\frac{\mathrm{d}x^{\beta}}{\mathrm{d}\lambda}\frac{\mathrm{d}x^{\gamma}}{\mathrm{d}\lambda} = 0$$

where $\frac{\mathrm{D}^2\xi^\mu}{\mathrm{D}\lambda^2}$ represents the second order derivative along the curve of the separation vector component $\xi^{\mu}(\lambda)$ and $R^{\mu}{}_{\alpha\beta\gamma}$ is the Riemann tensor. Compare with covariant derivative.

geodesic equations:

The equations

$$\frac{\mathrm{d}^2x^i}{\mathrm{d}\lambda^2} + \sum_{jk} \Gamma^{i}{}_{jk}\frac{\mathrm{d}x^j}{\mathrm{d}\lambda}\frac{\mathrm{d}x^k}{\mathrm{d}\lambda} = 0$$

satisfied by a geodesic, where λ is an affine parameter and $\Gamma^i{}_{jk}$ are the connection coefficients.

geodesic gyroscope precession:
The precession of a gyroscope that is transported through curved spacetime. See geodetic effect.

geodetic effect:
The precession of a gyroscope in Earth orbit due to geodesic gyroscope precession.

geometry:
The study of shape and spatial relationships.

Ginga:
A Japanese X-ray astronomy satellite that was in operation from 1987 to 1991. It revealed the first black hole transients and a 6.4 keV emission line in many active galaxies, due to fluorescent iron.

Global Positioning System:
A system of satellites that transmit microwave signals so enabling GPS receivers on or near the Earth's surface to determine their position, speed, direction and time.

globular cluster:
A spherically symmetrical cluster of stars containing from a few tens of thousands to a million stars of very similar age and chemical composition. Globular clusters are found associated with, and gravitationally bound to, larger galaxies, and around the Milky Way they are mostly distributed spherically symmetrically in the galactic halo. The age and composition of globular clusters suggests that they were formed early on in the process of galactic formation, with most having had no significant star formation for the last 12 billion years or more. Many globular clusters contain a population of cataclysmic variables and low-mass X-ray binaries.

globular cluster luminosity function:
The number of globular clusters per unit volume per unit luminosity. It is found to be approximately Gaussian in shape, and its mean value can be used as a standard candle.

grad:

The mathematical operation of applying the vector differential operator ∇ to a scalar field in order to produce a vector field. The grad or gradient of a scalar field T is the vector field ∇T (i.e. grad T). At any point, ∇T points in the direction in which T is decreasing most rapidly, and has a magnitude that is proportional to that rate of decrease.

gradient of a graph:
The gradient of a graph of y (plotted vertically) against x (plotted horizontally) is a measure of how rapidly y changes in response to a change in x, at any point on the graph. If the graph is a straight line, then the gradient is the same at all points, and is given by the ratio $\Delta y/\Delta x$ where Δy is a change in y and Δx is the corresponding change in x. If the graph is a curved line, the gradient at any point P on the curve is defined as the gradient of the tangent to the curve at P. The gradient is also equal to the *derivative* of y with respect to x, evaluated at the point P.

gradient of a scalar field:
See grad.

grain:
See cosmic dust.

grain emitting efficiency:
The fraction of the radiation falling on a cosmic dust grain that is re-emitted. This is often expressed as a function of the frequency of the radiation.

graph:
A representation of a function in pictorial form. In the case of a function $y(x)$, the usual procedure is to plot the values of y vertically and the values of x horizontally.

gravitational collapse:
The shrinking of a body to a point of infinite density. See black hole.

gravitational constant:
See law of universal gravitation.

gravitational deflection of light:
The prediction of general relativity that light passing a massive body is deflected towards the body.

gravitational energy release by accretion:
See accretion.

gravitational field:
The gravitational field $\boldsymbol{g}(\boldsymbol{r})$ is a vector quantity that determines the gravitational force acting on any mass placed at the point specified by the position vector $\boldsymbol{r}$. It is defined as the gravitational force per unit mass, so if $\boldsymbol{F}_{GR}$ is the gravitational force on mass m at point $\boldsymbol{r}$, then $\boldsymbol{g}(\boldsymbol{r}) = \boldsymbol{F}_{GR}/m$. The gravitational field has both magnitude and direction at each point in space, so it is an example of a vector field, and gravitational fields due to different sources add vectorially at every point. For an important example of a gravitational field see gravitational field due to a point mass. At any point, the gravitational field component in a given direction is equal to minus the gradient of the gravitational potential, Φ, in that direction. For example, the x-component and the radial component are given respectively by $g_x = -d\Phi/dx$ and $g_r = -d\Phi/dr$. The SI unit of gravitational field is N kg^{-1} or (equivalently) m s^{-2}.

gravitational field due to a point mass:

The gravitational field due to a point mass is spherically symmetric around the mass. If a mass M is placed at the origin, the gravitational field at a point specified by the position vector $\boldsymbol{r}$ is

$$\mathbf{g}(\mathbf{r}) = -\frac{GM}{r^2}\hat{\mathbf{r}}$$

where $\hat{\boldsymbol{r}}$ is a unit vector in the direction of $\boldsymbol{r}$ and G is the universal gravitational constant. Thus, the magnitude of the gravitational field depends only on the distance r from the point mass and is directed towards that mass.

gravitational force:
The force that acts on a body due to its interaction with a gravitational field. In the case of a point particle of mass m, it is given by $\boldsymbol{F}_{GR}$ (on m at $\boldsymbol{r}$) = $m\boldsymbol{g}(\boldsymbol{r})$, where $\boldsymbol{g}(\boldsymbol{r})$ is the gravitational field at the position $\boldsymbol{r}$ of the particle. The gravitational force on a point mass due to another point mass is described by the law of universal gravitation.

gravitational interaction:
See fundamental forces.

gravitational lens:

A system in which the light from a distant object, such as a galaxy or quasar, is bent by the gravity of an intervening object (a prediction of general relativity) in such a way as to magnify and brighten the distant object as seen from the Earth. Gravitational lenses allow us not only to study fainter objects than we could normally see, but also to map the distribution of mass in the intervening object.

Normally massive intervening objects, such as galaxies or clusters of galaxies, are required to produce an effect ('macrolensing'). This gives rise to large-scale magnifications and distortions of the lensed source, including 'gravitational lens arcs', multiple images of the same source, and (if the lensing and lensed objects are very well aligned along the line of sight) 'Einstein rings' whose radius (the Einstein ring radius) gives a direct measurement of the lensing mass.

However, even very small objects can have a strong effect on the brightness of a distant point source if they pass close to our line of sight (microlensing). Microlensing has been used to explain some short-timescale variations in the brightnesses of lensed quasars (where an intervening star is thought to be the source of the microlensing), to allow searches for dark compact objects, such as stellar mass black holes, in the halo of our own Galaxy, and to discover exoplanets.

gravitational lensing:
The process in which a massive body (such as a galaxy or a cluster of galaxies), located between an observer and a distant source of electromagnetic radiation, causes the observer to see distorted or multiple images of the source. See gravitational lens.

gravitational mass:
The quantity that determines the force that a particle experiences due to, or exerts on, another particle as a result of gravity. The gravitational mass is defined through Newton's law of gravitation for the force $\boldsymbol{F}_{12}$ on a particle 1 of gravitational mass μ_1 due to a particle 2 of gravitational mass μ_2, and the magnitude of this force can be written as $|\boldsymbol{F}_{12}| = G\,\mu_1\mu_2 / |\boldsymbol{x}_1 - \boldsymbol{x}_2|^2$.

gravitational microlensing:
See gravitational lens.

gravitational potential:

The gravitational potential $\Phi(\boldsymbol{r})$ at a point specified by the vector $\boldsymbol{r}$ is the gravitational potential energy per unit mass at that point. So, if E_{GR} is the gravitational potential energy of a mass m at a point $\boldsymbol{r}$, the gravitational potential at that point is $\Phi(\boldsymbol{r}) = E_{GR}/m$. Gravitational potential has a scalar value at every point in space, so it is an example of a scalar field. The SI unit of gravitational potential is the J kg^{-1}. An important example of a gravitational potential field is that due to a point mass M located at the origin of a coordinate system: $\Phi = -GM/r$, where G is the universal gravitational constant and r is the distance from the point mass. Note that, by convention, the gravitational potential energy has been taken to be zero at $r = \infty$ in this case.

gravitational potential energy:

The potential energy of a particle or body that arises from its interaction with other particles or bodies via the (conservative) gravitational force.

A particular example is the potential energy associated with terrestrial gravitation, in which case $E_{GR} = mgh$, where *m* is the mass of the body, *g* is the magnitude of the acceleration due to gravity, and *h* is the height of the body above an arbitrarily agreed position of zero gravitational potential energy.

Another important example is the potential energy of a body of mass *m* at a distance *r* from the centre of the Earth $E_{GR} = -GM_E m/r$, where *G* is the *universal gravitational constant* and M_E is the mass of the Earth.

More generally, the gravitational potential energy of a test mass *m*, placed at a point with gravitational potential Φ due to a central body of mass M, is given by $E_{GR} = m\Phi = -GMm/r$, where *M* is the mass of the central body.

gravitational potential energy of two point masses:

The gravitational potential energy of a point mass m_1 due to its gravitational interaction with another point mass m_2, separated from it by a distance *r* is

$$E_{GR} = -\frac{Gm_1m_2}{r}$$

where *G* is the universal gravitational constant and, by convention, E_{GR} is taken to be zero when $r = \infty$.

gravitational redshift:
A redshift undergone by electromagnetic radiation as it climbs out of the potential well of a massive object, as a result of the loss of energy of the radiation to the field. Gravitational redshift is a consequence of general relativity and has been observed in the emission from neutron star systems and possibly also from the accretion disc of active galactic nuclei; it has also been observed as a very weak effect in the Earth's gravitational field. The frequency of radiation observed by a distant observer is given by $f_{obs} = f_{em}(1 - 2GM/c^2r)^{1/2}$ where f_{em} is the frequency of radiation emitted at a distance *r* away from a mass *M*.

gravitational singularity:
See singularity.

gravitational time dilation:
The slowing of the rate of a ticking clock in a gravitational field, as seen by a distant observer. The duration of a 'tick' as seen by a distant observerwill be increased by a factor $1/(1- 2GM/c^2r)^{1/2}$ relative to that observed at a distance *r* from the mass *M*.

gravitational wave:
In general relativity, a wave-like disturbance in space-time that carries away energy from an accelerating distribution of mass. General relativity predicts that they should travel at the speed of light. Because gravity is by far the weakest of the fundamental forces, gravitational waves interact only very weakly with matter; nevertheless, they can in principle be observed on Earth, though there is as yet no definite detection of a signal from an astronomical source. Their existence is strongly supported by observations of a binary pulsar system, PSR 1913+16, whose orbital period can be measured very precisely and is found to be decaying at a rate consistent with the predictions of energy loss via gravitational waves.

Gravity Probe A:
An experiment, in 1976, in which a hydrogen maser was briefly sent to a height of 10km above the Earth, while its emissions were monitored from the ground. This experiment confirmed the predictions of gravitational time dilation to about 70 parts per million.

Gravity Probe B:
A polar orbiting satellite, launched in April 2004, designed to measure the geodesic gyroscope precession and Lense-Thirring effect due to the Earth's gravitational field.

grazing incidence:
The mode of operation for an imaging X-ray telescope, as used on the X-ray astronomy satellites Einstein, ROSAT, ASCA, Chandra and XMM-Newton. High energy photons reflect off the gold-coated surfaces of nested paraboloid and hyperboloid mirrors at very high angles of incidence (>88 degrees), to be focussed onto an image plane.

GRB:
See gamma-ray burst.

great circle:
The curve on the surface of a sphere created by the intersection of the sphere and a plane that passes through its centre.

green valley:
The under-populated narrow region between the red sequence and the blue cloud in the distribution of galaxies in the colour-magnitude plane.

grey-body emissivity index:
The thermal emission from interstellar dust does not entirely follow a black body shape. The spectrum is modified by a wavelength-dependent factor $k_d \propto \lambda^{-\beta}$ where β (in the range 1 - 2) is known as the grey-body emissivity index.

ground state:
The state that corresponds to the lowest discrete energy level of a quantum system. An example is the 1s state of the hydrogen atom.

Gunn-Peterson test:
If we see the highest-redshift Universe becoming opaque, on average, to Lyman alpha photons, then the number density of ionizing photons must have dropped sharply, and the Universe at this time will be predominantly neutral. The transition between opaque and transparent would probe the epoch of reionization in which the first Stromgren spheres expand around the very first luminous objects in the Universe.

gyrofrequency:
The frequency with which a charged particle orbits in a magnetic field. See cyclotron frequency and synchrotron radiation.

gyroradius:
Same as cyclotron radius or Larmor radius.

gyroscope:
A device that uses the angular momentum of a spinning body to indicate a particular direction in space.

H

habitable zone:
The range of distances from a star within which liquid water could exist on the surface of a terrestrial planet.

half-life:
The time required for half of a given sample to decay when the relevant decay is an exponential process.

half-light radius:
The radius within which half the total light of an elliptical galaxy is generated.

halo:
A structural component of spiral galaxies, consisting of a low-density distribution of relatively old, low-metallicity (population II) stars which is approximately spherically symmetrical around the centre of the galaxy. About 1% of the halo stars are contained in globular clusters.

halo occupation distribution:
The probability distribution of the number of galaxies that a dark matter halo contains.

H alpha:
The first spectral line of the Balmer series corresponding to transitions between the $n = 2$ and $n = 3$ energy levels.

hardness:
The relative amount of 'hard' to 'soft' (i.e. high energy to low energy) photons in a spectrum. See softness.

hard X-rays:
High energy X-rays. The dividing line between hard and soft X-rays will vary according to context, but a typical division is around ~2 keV.

Harrison-Zel'dovich spectrum:
A form of the power spectrum of the cosmic microwave background which is scale-invariant.

Hawking radiation:
The physical vacuum is subject to quantum fluctuations in which particle-antiparticle pairs can enjoy a short-lived existence before undergoing mutual annihilation. If a particle-antiparticle pair is created just outside the event horizon of a black hole, the one with negative energy might enter the event horizon whilst the one with positive energy escapes to a distant observer. From the point of view of the distant observer the black hole would emit particles and gradually lose mass. The rate of emission of energy is proportional to $1/M^2$. See Hawking temperature.

Hawking temperature:
A black hole behaves as a body with a temperature that is inversely proportional to its mass, $T_H = hc^3/16\pi^2 GkM$.

Hayashi limit:
The region of the Hertzsprung-Russell diagram where stars become fully convective. It is a roughly vertical region, at constant temperature of around 3500 K. Stars follow a Hayashi track (a vertical path close to the Hayashi limit) as protostars whilst approaching the main sequence, they also approach the Hayashi limit again on their first ascent of the red giant branch when they leave the main sequence.

Hayashi track:
The pathway on the Hertzsprung-Russell diagram followed by fully convective

protostars as they contract towards the main sequence. Protostars following a Hayashi track have a roughly constant temperature and a decreasing radius. See Hayashi limit.

HDM:
See hot dark matter.

heat:
Energy that is transferred as a result of a temperature difference.

heat capacity:
The quantity of energy per unit temperature rise needed to raise the temperature of a given body under specified conditions (such as constant pressure^{-1}. or constant volume). The SI unit of heat capacity is the J K

heat capacity at constant pressure:
The heat capacity of a body when its pressure is kept constant.

heat capacity at constant volume:
The heat capacity of a body when its volume is kept constant.

heating rate:
The rate of energy generation per unit volume due to a heating mechanism (e.g. viscous dissipation, nuclear fusion, etc.). Measured in J s^{-1} m^{-3} (SI units) or erg s^{-1} cm^{-3} (cgs units). Sometimes the heating rate is given per unit mass rather than per unit volume. In this case the SI unit is J s^{-1} kg^{-1}.

Heisenberg uncertainty principle:

A quantum mechanical principle asserting that there is an inherent limit to the precision with which the values of certain pairs of physical quantities may be simultaneously known. It can be expressed in many forms, two of which are:

(1) There is a fundamental limit to the precision with which the position x and the momentum component p_x of a particle can be simultaneously known. For any choice of x-axis, the product of the uncertainties Δx and Δp_x obeys the inequality $\Delta x \Delta p_x \geq \hbar/2$.

(2) There is a fundamental limit to our knowledge of a particle's energy E, when it is measured in a finite time interval Δt: the uncertainty ΔE in the energy obeys the inequality $\Delta E \Delta t \geq \hbar/2$.

helioseismology:
The study of the interior of the Sun by observing oscillations of the photosphere that result from sound waves propagating through the interior. Measurements are carried out by observing the Doppler shift of spectral lines in the Sun's atmosphere.

helium burning:
A nuclear fusion process in which helium nuclei react with one another to produce carbon. The process is initiated at temperatures of around 10^8 K, and can, for a time, be the dominant means of energy production in the cores of post-main-sequence stars. In stars in the red giant phase of their evolution, helium burning is initiated in the central part of the star, possibly in a helium flash. When the core helium is exhausted helium shell burning begins and the star enters the asymptotic giant branch.

helium flash:
A runaway thermonuclear reaction that takes place in the centres of low-mass (< 2.5 solar masses) stars when they initiate helium burning. Because the electrons in the centres of these stars are degenerate when helium burning starts, and because the electron pressure in the centre is dominant, the cores do not respond to the increased energy supply by expanding. The temperature increase drives an increase in the reaction rate, which in turn increases the temperature, and so on in a runaway process that is only terminated when the pressure from the nuclei becomes dominant, the core expands, and the electron degeneracy is removed. The helium flash lasts only a few seconds, but a significant amount of the core helium is burnt during that time.

Henyey track:
The pathway on the Hertzsprung-Russell diagram followed by contracting protostars as they evolve from the base of the fully convective Hayashi track to the main sequence. A Henyey track is almost horizontal on the H-R diagram.

Herbig-Haro objects:
Small bright clouds of gas and dust whose emission is either a result of illumination by a protostar such as a T Tauri object or excited by an outflow (see mass loss) from the protostar.

Herschel Space Observatory:
A satellite-based telescope operating in the far infrared and submillimetre part of the spectrum.

hertz:
The SI unit of frequency, represented by the symbol Hz, where 1 z = 1 s^{-1}. A frequency of 1 Hz is equivalent to one *cycle* per second.

Hertzsprung gap:

The gap in the Hertzsprung-Russell diagram between the main sequence turnoff and the base of the red giant branch. Subgiant stars, which are burning hydrogen in a shell as their outer layers expand, are found in this region, but it is sparsely populated because of the short lifetime of the subgiant phase.

Hertzsprung-Russell diagram:
A graph showing the relationship between temperature and luminosity for a group of stars. A 'theoretical' H–R diagram plots inferred luminosity and temperature directly, while an 'observational' H–R diagram plots absolute magnitude and colour index. Conventionally, temperature increases to the left in an H–R diagram. Because stars are black bodies to a good approximation, their luminosity depends only on their temperature and radius. The H–R diagram therefore tells us how the radii and surface temperature of stars are distributed. Discrete regions of the H–R diagram contain stars in different evolutionary states, including protostars, the main sequence, the Hertzsprung gap, the red giant branch and the asymptotic giant branch. As stars form, they evolve onto the main sequence; towards the end of their lifetimes, they evolve away from the main sequence towards the giant phases. Plotting the H–R diagram for a star cluster and locating the absolute magnitude of the main-sequence cutoff therefore allows us to estimate the maximum lifetime of the stars in the main sequence and therefore the age of the cluster.

He white dwarf:
A helium white dwarf would form from a main-sequence star whose mass is less than $0.5 M_\odot$. Such a star will have a main-sequence lifetime of order 100 billion years, hence no such stars will yet have evolved to become white dwarfs. Any He white dwarfs seen must have formed as part of a binary star sysmte which has undergone a phase of mass transfer which alters the mass and composition of one or both of the components.

hierarchical binary:
A binary star with at least one component that is itself a binary, but with a much smaller orbital separation than that of the parent binary. Multiple hierarchical levels of binarity are possible.

hierarchical formation:
As applied to large-scale strucutre in the Universe, the idea that small dark matter haloes merge to form larger dark matter haloes as time progresses, in a bottom-up process of structure formation.

hierarchical multiple:
A star system which can be broken down into combinations of binary systems. They are the only multiple star systems which are gravitationally stable. In a mobile diagram, hierarchical multiple systems have only two branches descending from each node.

hierarchical structure formation model:
A model for the formation of elliptical galaxies in which they are formed piece-wise by the accretion and influence of neighbours. See monolithic collapse model.

high-energy cutoff:
The photon energy above which the emission from an astrophysical source begins to fall to zero.

high-mass X-ray binaries:
See X-ray binary.

high mass X-ray binary:
An X-ray binary where the donor star has a mass above about $10\ M_\odot$

HII region:
A region of predominantly ionized hydrogen, detected by its emission lines from the hydrogen spectrum and in free-free emission. The term 'HII' indicates singly ionized hydrogen. Usually the hydrogen is ionized by the ultraviolet emission from hot stars; HII regions are associated with star formation, since only massive, short-lived stars are hot enough to produce them.

Hill radius:

The radius of the Hill sphere defined by

$R_H = a_{planet}(m_{planet}/m_{star})^{1/3}$

where a_{planet} is the semi-major axis of the planet's orbit around a star, m_{planet} is the mass of the planet and m_{star} is the mass of the star. Contrast with Roche limit.

Hill sphere:
The volume of space around a planet where the planet, rather than the star, dominates the gravitational attraction. See Hill radius.

Hipparcos:
A satellite used to measure accurate parallax and proper motion values for a large number of stars. Named for the Greek astronomer Hipparchus of the second century BC.

HLIRG:

See hyper-luminous infrared galaxy.

HMXBs:
Acronym for High Mass X-ray Binaries.

homogenous:
Being the same everywhere. See isotropic.

homology:
Referring to a similarity in structure throughout a star such that its temperature, density, pressure, etc. each scale by a particular factor at all radii within the star.

horizon problem:
The recognition of the fact that objects that are further apart than a certain distance could not have been in causal contact in the past. This poses a problem in understanding how parts of the cosmic microwave background that are more than a few degrees apart ever managed to look so similar.

horizontal branch:
A horizontal region of the Hertzsprung-Russell diagram to the left of the red giant branch. To lie on the horizontal branch stars must have low metallicity and must have lost mass during the red giant phase. All horizontal branch stars in a given cluster have similar absolute magnitudes, but lower-mass stars are hotter.

hot big bang:
See big bang.

hot dark matter:
Dark matter whose particles travel at speeds at or close to the speed of light. See cold dark matter, warm dark matter.

hot Jupiter:
A giant exoplanet in an extremely close orbit around a star.

hot spot:

1) A region of enhaned optical/UV emission at the edge of an accertion disc in an accreting binary star where the accretion stream from the donor star impacts the accretion disc around the acretor.

2) A region of enhanced radio emission in the lobe of a radio galaxy.

H-R diagram:
See Hertzsprung-Russell diagram

H-shell burning:
See shell hydrogen burning.

Hubble classification:
The classification of galaxies into elliptical, spiral¸ lenticular and irregular types. Ellipticals are subdivided according to the apparent degree of flattening, with a numerical index that ranges from 0 to 7; the roundest are E0 and the flattest E7. Spirals (type S) and barred spirals (SB) are classified as type a, b, c or d, with type d having the most prominent spiral arms and the smallest bulge. Lenticular galaxies are always of type S0.

Hubble constant:

The current value of the Hubble parameter, and therefore the quantity that relates the observed cosmological redshift of a galaxy to its distance away from us according to Hubble's law. The Hubble constant conventionally has units km s^{-1} Mpc^{-1}, and the best estimate of its value is currently around 70 km s^{-1} Mpc^{-1}. The value of Hubble's constant is sometimes expressed in terms of the numerical quantity h_0 where: $H_0 = h_0 \times 100$ km s^{-1} Mpc^{-1} so that $h_0 \approx 0.7$.

In the Big Bang cosmological model, the Hubble constant should more properly be called the Hubble parameter, as it changes with cosmic time. The subscript 0 in the notation H_0 is a reminder that we are talking about the present-day value of the parameter. In terms of the scale factor $R(t)$, the Hubble parameter at any given time can be written $H(t) = 1/R(t) \times dR(t)/dt$.

Hubble deep field:
A project with the Hubble Space Telescope to obtain a series of very deep exposures to search for galaxies at high redshift.

Hubble diagram:
A plot of apparent magnitude against redshift.

Hubble distance:
The proper distance at which an object participating in the Hubble flow would have a proper radial velocity of the speed of light.

Hubble flow:
The large scale apparent motion of galaxies arising from the overall expansion of the

universe.

Hubble parameter:

In terms of the scale factor $R(t)$, the Hubble parameter at any given time can be written

$$H(t) = \frac{1}{R(t)}\frac{\mathrm{d}R(t)}{\mathrm{d}t}$$

Hubble's law:

The linear relationship, discovered by Edwin Hubble in 1929, between the distance of a galaxy and its cosmological redshift, expressed as an apparent recession speed. The law states

$v = H_0 d$

where v is the apparent recession speed in km s^{-1} and d is the distance in megaparsecs. H_0 is the Hubble constant.

Hubble time:
The reciprocal of the Hubble constant. In a universe in which Hubble's constant did not change with time, this would give the age of the universe (the time at which all objects were at the same point in space). For H_0 = 70 km s^{-1} Mpc^{-1}, $1/H_0$ is about 13.5 billion years. In the Big Bang cosmological model, the age of the universe differs from the Hubble time by a factor which depends on the geometry and expansion history of the Universe, but they are still of the same order of magnitude.

Hubble ultra-deep field:
An ultra-deep survey made by the Hubble Space Telescope using the Advanced Camera for Surveys. It yielded galaxy candidates out to redshift $z \sim 10$.

Hubble volume:
The volume enclosed by the radius of the observable Universe. for the currently accepted values of the density parameters, the radius of the observable Universe is about $3.53c/H_0$ which is about 15 Gpc.

Hulse-Taylor binary pulsar:
See binary pulsar.

hydrodynamics:
See fluid dynamics.

hydrogen burning:
A nuclear fusion process in which hydrogen nuclei react with one another (possibly with the involvement of other nuclei) to produce helium. The process occurs in the cores of main-sequence stars, where it is the dominant form of energy production. It can also be responsible for shell burning in post-main-sequence stars. See proton-proton chain and CNO cycle for further details.

hydrogen spectrum:

Hydrogen has a particularly simple emission line and absorption line spectrum as a result of having only one electron (the same is true of any other element ionized to a 'hydrogen-like' state with only one electron remaining). The n^{th} energy level of a hydrogen electron is given by

$E_n = -R/n^2$

where R is a constant, called the Rydberg constant, with the value 13.6 electronvolts (eV) or about 2.2×10^{-18}J. The energy is conventionally negative to denote a binding energy; so it is necessary to supply at least 2.2×10^{-18}J of energy to remove a single electron altogether from the lowest-energy (n = 1) state and ionize the hydrogen atom. More generally, the difference in energy between any two energy states (n, m) is given by

$\Delta E = R(1/n^2 - 1/m^2)$

and in emission and absorption (in a bound-bound transition) this energy must be supplied by the emission or absorption of a photon with wavelength

$\lambda = hc/\Delta E = hc/R(1/n^2 - 1/m^2)$

Accordingly, the hydrogen emission (or absorption) spectrum consists of a set of 'series' of lines representing transitions to (or from) a given energy level. The shortest-wavelength lines correspond to transitions to the n = 1 level, the lowest-energy state or ground state; these are known as the Lyman series and their energy corresponds to wavelengths in the ultraviolet range of the spectrum. The longest-wavelength line in the Lyman series, the m = 2 to n = 1 transition is called Lyman alpha and has a wavelength of 121.6 nm; higher-m Lyman transitions (Lyman beta, Lyman gamma, etc) have shorter wavelengths and the Lyman series converges as m tends to infinity at a wavelength of 91.2 nm, the Lyman limit. The transitions to n = 2 are known as the Balmer series, and have wavelengths in the visible range. The longest-wavelength line in the Balmer series, the m = 3 to n = 2 transition (H alpha), is at 656.4 nm; the next, m = 4 to n = 2 (H beta) is at 486.1 nm, and so on, converging as m tends to infinity at a wavelength of 364.6 nm, the Balmer limit. The transitions to n = 3 are called the Paschen series and those to n = 4 the Brackett series; these appear in the infrared.

hydrostatic equilibrium:

A situation in which the forces acting on a fluid (normally gravitational forces) are balanced by the internal pressure of the fluid (including thermal, degeneracy and radiation pressure), so that the fluid neither collapses nor expands. The equation of hydrostatic equilibrium for a spherically symmetric self-gravitating system is given by

$dP/dr = -GM(r)\rho(r)/r^2$

where P is the pressure, $M(r)$ the mass inside a radius r, $\rho(r)$ the density at that radius and G the universal gravitational constant. A fluid in a gravitational potential well (including its own self-gravity) that is not in hydrostatic equilibrium will collapse on a free-fall timescale until it reaches hydrostatic equilibrium. Stars, and all other long-lived self-gravitating systems where internal pressure is important, are close to hydrostatic equilibrium for most of their lifetimes.

hydrostatics:
See fluid statics.

hyper-luminous infrared galaxy:
(HLIRG) Infrared-luminous galaxies with $>10^{13}$ solar luminosities.

hypernova:
An extremely energetic and bright supernova, believed to originate from the collapse of the core of a very massive star and to be the origin of some gamma-ray bursts. Also referred to as a collapsar.

hyperon:
A term used to describe relatively long lived baryons with masses greater than the proton and the neutron.

I

I-band filter:
A broad band photometric filter used in astronomy spanning the wavelength range from about 700 to 900nm.

ideal flow:
A state of steady flow in a fluid that has constant density, no viscosity and is free of eddies.

ideal fluid:
A fluid that exhibits ideal flow. An ideal fluid is incompressible and has no viscosity; its motion is steady and free of eddies.

ideal gas:
A gas in which the molecular interactions play a completely negligible role. In equilibrium, an ideal gas obeys the ideal gas equation of state.

ideal gas equation of state:

The equation

$PV = NkT$

which applies to a sample of ideal gas in thermal equilibrium, where P is the pressure, V the volume, N the number of particles of gas, T the (absolute) temperature and k is the Boltzmann constant.

ideal gas law:
See ideal gas equation of state.

image polarisation:
An expression of the cosmic shear in terms of a complex number.

IMF:
Abbreviation for initial mass function.

impact parameter:

(1) The perpendicular coordinate distance b from a singularity to the inital direction of motion of a photon.

(2) The perpendicular distance from the centre of a transiting exoplanet to the centre of the star it transits.

inclination:
See angle of inclination.

incoherent:
A term used to describe scattering processes in which the frequency of radiation changes, such as Compton scattering.

independent variable:
A parameter in a mathematical expression which does not have a functional dependence on another parameter.

indirect imaging technique:
A technique used to infer an image of (e.g.) an astronomical obejct indirectly, such as using time varying flux or spectral measurements to infer spatial variations in the system. Examples of such techniques include eclipse mapping, maximum entropy imaging and Roche tomography.

inertial frame:
See inertial frame of reference.

inertial frame of reference:
An inertial frame of reference is a frame of reference in which any particle that is not acted on by an unbalanced force, moves with constant speed along a straight line. In other words, an inertial frame is a frame of reference in which Newton's first law is applicable. Any frame of reference that moves with constant velocity relative to an inertial frame of reference is also an inertial frame of reference.

inertial mass:
The quantity determined by the ratio of the magnitudes of the force and the acceleration of a particle in Newton's second law of motion, $m = |\boldsymbol{F}|/|\boldsymbol{a}|$.

inertial observer:
An observer who uses an inertial frame of reference.

inferior conjunction:
The point in an orbit of a planet around a star when the planet lies directly between the star and the observer. See superior conjunction.

inflation:
See inflationary era.

inflationary era:
A hypothetical epoch in the very early development of the Universe, when the Universe is supposed to have undergone a brief period of very rapid inflation. The Universe may be described by the de Sitter model at this epoch.

inflaton:
The particle associated with the inflaton field which is a scalar field associated with inflation in the early universe.

inflaton field:
The scalar field associated with inflation in the early universe. The hypothetical particle associated with this field is known as the inflaton.

infrared astronomy:
Astronomy in the infrared region of the electromagnetic spectrum. Short-wavelength infrared observations can be made from the ground, but at longer wavelengths the atmosphere is opaque and observations must be made from space.

infrared excess:
The spectral excess over the spectrum of a B type star seen in Be stars and indicating the presence of a cooler circumstellar disc of material.

infrared radiation:
Electromagnetic radiation with a wavelength between about 7×10^{-7} m and 1×10^{-3} m, or a frequency between about 4×10^{14} Hz and 3×10^{11} Hz.

ingress:
The time at the start of an eclipse between first contact (when the eclipsing body just begins to pass in front of the eclipsed body) and second contact (when the eclipsing body is wholly in front of the eclipsed body). See egress.

inhomogenous wave equation:
A type of differential equation used in the study of waves.

initial conditions:
In the context of a differential equation, the initial conditions provide the information required to evaluate the arbitrary constants that arise in the general solution to the differential equation. For example, given a particle that moves in accordance with the simple harmonic motion equation, the general solution to that equation implies that $x = A \sin(\omega t + \phi)$, but in order to know exactly where the particle is at any given time it is necessary to determine the arbitrary constants A and ϕ. This can be done if the position and velocity of the particle are known at time $t = 0$; these are the initial conditions in this case.

initial mass function:
(IMF) The initial distribution of stellar masses in star formation. Masses are always distributed in the sense that there are more low-mass stars than high-mass ones, but the details can vary from region to region and also depend on the metallicity of the protostellar material. A popular estimate of the IMF in our Galaxy was derived by Salpeter in 1955:
$$\frac{\mathrm{d}N}{\mathrm{d}M} \propto M^{-2.35}$$

where dN is the number of stars with masses between M and M + dM . Many other forms of the IMF exist; the detailed physics that determines the IMF is not yet clear.

inner Lagrangian point:
See Lagrangian points.

input physics:
An imprecise term usually subsuming the description of the physical properties of matter (e.g. the equation of state and the opacity) and radiation that enter a theoretical model of a physical system, e.g. of a star or an accretion disc.

insolation:
The amount of sunlight falling on a body per unit area.

instability:
A physical system is stable if it reacts to a small perturbation of its state by opposing the initial perturbation. The system is unstable if its reaction amplifies the initial perturbation. If the system is unstable, the instability develops (i.e. manifests itself) on a characteristic timescale. This so-called growth timescale depends on the physical nature of the system and the perturbation.

instability strip:
A roughly vertical region in the Hertzsprung-Russell diagram, extending upwards from the main sequence, in which stars naturally pulsate, changing periodically in radius and therefore luminosity. See pulsating variable stars.

integral calculus:
The branch of mathematics concerned with the analysis and evaluation of (definite) integrals.

integral number count:

The number of objects brighter than a given flux. Often given the symbol: N (>S), and defined as

$$N(>S) = \int_S^\infty \left(\frac{\mathrm{d}N}{\mathrm{d}S}\right) \mathrm{d}S$$

i.e. the integral of the number count from a given flux S to infinity

integral source count:
See integral number count.

Integrated Sachs-Wolfe effect:
The effect of large clusters of galaxies and voids in the Universe is to impose slight gravitational redshifts and blueshifts on radiation passing through them. The overall effect of this on the cosmic microwave background radiation is known as the Integrated Sachs-Wolfe effect.

integration:
The mathematical process used in the evaluation of (definite) integrals.

integration by parts:

A mathematical technique used in the evaluation of certain (definite) integrals, based on the relation:

$$\int u \mathrm{d}v = uv - \int v \mathrm{d}u$$

It relies on being able to choose the functions u and v such that $\int v\mathrm{d}u$ is easier to integrate than $\int u\mathrm{d}v$.

intensity:
A quantity describing the rate at which energy is transported in a given direction, per unit area perpendicular to that direction. The SI unit of intensity is the watt per square metre (W m^{-2}). When the radiation is composed of (plane) waves travelling in a specified direction, the intensity in that direction is proportional to the square of the amplitude of the waves.

intercept:
The value on the vertical axis of a graph at which a plotted straight line crosses that axis, provided the vertical axis passes through the zero point on the horizontal axis.

intercombination line:
See semi-forbidden line.

interferometer:
A telescope that combines the light collected by two or more spatially separated receivers to make an image or a measurement of the structure of an astronomical object that has a resolution higher than would be achievable by either receiver alone. The technique of interferometry is most widely used in radio astronomy, but has also been successfully applied at optical wavelengths.

intergalactic medium:
The material in space between galaxies.

intermediate-mass X-ray binary:

An X-ray binary where the Roche-lobe filling donor star is an intermediate-mass star (with mass between about 2 and 10 solar masses). This group of X-ray binaries is intermediate between the low-mass and high-mass X-ray binaries. See also X-ray binary.

intermediate polar:
Also intermediate polar system. Same as DQ Her star. See magnetic cataclysmic variable for a definition.

internal energy:
The energy, usually denoted *U*, arising from the kinetic energy of the system's constituents and the potential energy of their mutual interaction. It does not include any contribution from the motion or position of the system as a whole. It is an equilibrium property of a macroscopic system that changes by an amount equal to the sum of the heat transferred to the system and the work performed on the system.

interstellar dust:
Small solid particles, composed mainly of carbon and silicon compounds, found in interstellar space. Particle sizes range from 10 μm to less than 10 nm. Dust is thought to be created in the atmospheres of evolved stars or in supernovae, and is often associated with star-forming regions such as molecular clouds; it is destroyed by high temperatures. The principal effect of dust is the absorption of light, giving rise to interstellar extinction.

interstellar medium:
The gas and dust in space (within a galaxy) between the stars.

interval (between two events):
The difference in the corresponding coordinates of two events.

intrinsically polarized:
Electromagnetic radiation which naturally has polarization as a result of the way it is produced, e.g. synchrotron radiation.

intrinsic curvature:
Curvature which changes the geodesics of space-time.

invariant:
A quantity that has the same value in every inertial frame of reference. Invariant quantities include the speed of light in a vacuum, the spacetime separation, the proper time between time-like separated events, the charge of a particle, and the mass of a particle.

inverse beta-decay:

Also known as beta plus (β^+) decay. A weak interaction process involving the emission of a positron and neutrino from a proton, to leave a neutron: $p \rightarrow n + e^+ + \nu_e$.

inverse Compton scattering:
The phenomenon by which a low-energy photon scatters off a high-energy electron, so gaining energy in the process. See Compton scattering.

inverse Lorentz transformation:
The reverse operation to that performed by the Lorentz transformation. It is given by replacing *V* with -*V* in the equations and replacing primed quantities with un-primed quantities (and vice versa).

inversely proportional:
See proportionality.

inverse square law:
A term used to describe any law asserting that the value of a quantity is proportional to the reciprocal of the square of some other quantity, usually the distance from some point. Well known examples of inverse square laws include; Coulomb's law, Newton's law of universal gravitation and the law relating the intensity due to a point source of radiation to the distance from that source.

ion:
An atom that has become electrically charged, through having lost or gained one or more electrons.

ionization:
The process of removing one or more electrons from an atom to make an ion. The energy required to remove one electron from an atom is known as the first ionization potential. Removing the second electron in general takes more energy, since it is more tightly bound to the nucleus; this amount of energy is known as the second ionization potential, and so on. Ionization can be a result of interactions between atoms ('collisional ionization') or the absorption of a photon by an atom ('photoionization').

The reverse process is known as recombination.

ionization cone:

Sometimes seen in the extended narrow line region of AGN. Appearing as wedge-shaped structures with opening angles of 30°-100° and within which the [OIII] λ5007 / H alpha flux ratio is >1.

ionization energy:
Also known as ionization potential, see ionization.

ionization front:
A transition zone between ionized and neutral gas surrounding a source of ionizing radiation, such as a hot star or an active galactic nucleus. The ionization front is approximately at the location where the rate of ionization of atoms is equal to the rate at which they recombine. If the ionization front is spherical, as would be the case for a star embedded in a uniform gas distribution, the region of ionized gas behind the front is known as a Stromgren sphere.

ionization parameter:
The photon number density which can ionize a particular atom or ion divided by the particle number density.

ionization potential:
Also known as ionization energy. See ionization.

ionization structure:
The relative fraction of ions to atoms as a function of spatial position within a system.

ionized:
An atom from which one or more electrons has been removed is said to be ionized. See ionization.

ionizing radiation:
Electromagnetic radiation which is capable of removing one or more electrons from an atom or ion.

ion torus:
A torus consisting of ionized material.

IRAS:
The InfraRed Astronomy Satellite was the first ever all-sky infrared survey telescope and operated in 1983.

IRAS galaxy:
A galaxy identified using the satellite IRAS as being highly luminous in the infrared region of the spectrum. The infrared luminosity in these systems is generally a result of a large amount of star formation, similar to starburst galaxies¸ but in the IRAS galaxies the radiation emitted by the newly formed stars is absorbed by dust and re-radiated in the infrared. In some IRAS galaxies an active galactic nucleus also makes a contribution to the infrared luminosity. The most luminous of these systems are known as ULIRGs (ultraluminous infrared galaxy).

IR bump:

An excess in the spectral energy distribution of some active galaxies at wavelengths longer than around 1 μm.

iron peak nuclei:
The nuclei ^{56}Fe, ^{56}Ni and ^{56}Co, etc. that represent the end of the nucleosynthesis sequence by nuclear fusion.

irregular galaxies:
See irregular galaxy

irregular galaxy:
A galaxy which does not have a well-defined structure, in contrast to spiral and elliptical galaxies. Galaxies are often thought to be irregular as a result of earlier galaxy–galaxy gravitational interactions.

ISO:
The Infrared Space Observatory was a space-based infrared astronomy telescope which operated from 1995 - 1998.

isochrone:
A line (in a Hertzsprung-Russell diagram) indicating the location of stars that have the same age.

isodelay surface:
A surface giving rise to light echoes such that the delay times from all points on the surface are equal.

isophote:
A contour of equal surface brightness on an image of an astronomical object.

isothermal condition:
The condition $PV = I$ that may be used to specify a particular isothermal process in a given quantity of *ideal gas*. The isothermal parameter $I = NkT$ will have a constant value for any particular isothermal process, but will have different values for isothermal processes that take place at different temperatures.

isothermal process:
A process in which there is no change of temperature. See also isothermal condition.

isothermal sound speed:
See sound speed.

isotope:

Any one of a set of atoms that have the same value of the atomic number Z (and hence represent the same element), but different values of the mass number A (and hence different values of the neutron number N). The various isotopes of a given element thus represent different 'versions' of the atom of that element. The mass number and atomic number of an isotope are indicated by writing them as a superscript and subscript, respectively, before the relevant chemical symbol. For example, the isotope of silicon with $A = 27$ and $Z = 14$ is written ${}^{27}_{14}\mathrm{Si}$. Less formally, this isotope may be referred to as silicon-27.

isotropic:
Being the same in all directions. See homogenous.

isotropically:
Being uniform in all directions. See isotropy.

isotropy:
The property of being the same in all directions. Radiation is said to be isotropic if it is emitted by a source equally in all directions.

iterative:
A procedure where the results of one operation are used to alter the input values for the next step in order to converge on an acceptable result.

IXO:
The planned International X-ray Observatory, an X-ray astronomy satellite which may launch in 2021.

J

Jacobian coordinate system:
Named for the mathematician Carl Gustav Jacob Jacobi (1804 - 1851) and used to express the motion of bodies in a three-body system. The coordinates describe the motion of the centre of mass of the system, the motion of a second body with respect to the dominant body, and the motion of the third body with respect to the inner binary.

James Webb Space Telescope:
(JWST) The proposed successor to the Hubble Space Telescope which will operate in the infrared and is scheduled for launch in 2014.

jansky:
A unit of spectral flux density commonly used in radio astronomy. $1\ \mathrm{Jy} = 10^{-26}\ \mathrm{W\ Hz^{-1}\ m^{-2}}$.

JCMT:
The James Clerk Maxwell Telescope, a submillimetre wavelength telescope on Hawaii.

Jeans criterion:
A gas cloud whose total energy is negative is bound and will collapse, whereas a cloud whose total energy is positive will not collapse. This simple criterion can be developed into limiting values for the mass and density of potential star-forming regions. See Jeans mass and Jeans density.

Jeans density:
The density of matter corresponding to a Jeans mass in a sphere whose radius is the Jeans radius (or Jeans length). It is the density at which the total energy of the gas is zero. Any loss of energy due to, for example, radiation, will cause the total energy to become negative and the cloud will collapse.

Jeans length:
The characteristic length scale for the gravitational collapse of a pressure-supported gas cloud. For a given density and temperature, a cloud that is larger than the Jeans length will be gravitationally bound and will eventually collapse.

Jeans mass:

The mass enclosed by a spherical volume with radius equal to the Jeans length. For a given density and temperature, a cloud with a mass greater than the Jeans mass will be gravitationally bound and will eventually collapse.

jet:

A term used in the description of radio source structure, with two related meanings:

(1) A long narrow linear feature emanating from the active galactic nucleus, seen in many radio galaxies and quasars, most often via its radio synchrotron emission but sometimes also at optical and X-ray wavelengths.

(2) The underlying flows of energetic particles from the nucleus supplying energy to the radio lobes, which are thought to be present in all radio sources whether or not an observable jet or jets in the first sense is present.

Jets in both senses are also present in a small number of X-ray binaries and believed to be present in gamma-ray bursts.

jet-induced star formation:
The process by which radio jets from radio-loud AGN can trigger star formation in the host galaxy.

jet power:
The power carried by a jet in a radio galaxy. Computer simulations of expanding radio galaxies reveal that for a constant jet power, luminosity decreases with age.

joule:
The SI unit of energy and of work, represented by the symbol J, and defined by the relation $1\ \mathrm{J} = 1\ \mathrm{kg\ m^2\ s^{-2}} = 1\ \mathrm{N\ m}$.

Julian Date:
A numerical quantity that gives the number of days, including fractions of a day, that have elapsed since noon GMT on the 1st of January, 4713 BC. Because the Julian day is unaffected by leap years or reorganizations of the calendar, it is used to calculate the frequency of long-period events. Often a large number is subtracted from the Julian Date to allow it to be used conveniently.

jump conditions:
The relationships betwenn the values of the physical quantities on either side of a shock front.

JWST:
See James Webb Space Telescope.

K

Kaiser effect:

Also known as "pancakes of God" (contrast with "fingers of God").

Galaxies between us and a distant cluster (but near to it in space) will tend to be falling in to the cluster. This adds a Doppler component to the redshift and makes the galaxies appear further away. Galaxies on the far side of the cluster will also tend to be falling in to the cluster, and their Doppler component will subtract from the redshift, making them appear nearer. The net effect, referred to as the Kaiser effect, is to produce flattened structures in the distribution of galaxies with redshift seen in galaxy redshift surveys.

K-band filter:
A broad band photometric filter used in astronomy spanning the wavelength range from about 2.0 to 2.5 μm.

K-correction:
The correction of observed fluxes to fluxes in the rest frame of a cosmological source, such as an active galaxy. Originallly applied in the K-band (infrared) but now used to refer to a correction applied in any waveband.

kelvin:
The SI unit of temperature and temperature difference, represented by the symbol K. The kelvin is one of the seven SI base units, and is defined as 1/273.16 of the absolute temperature of the triple point of H_2O. A temperature difference of one kelvin (1 K) is equivalent to a temperature difference of one degree Celsius (1 °C), but the absolute and Celsius scales have different origins.

Kelvin-Helmholtz contraction:
The process by which a self-gravitating body undergoes gravitational contraction.

Kelvin-Helmholtz contraction time:

The timescale on which a body will collapse under its own gravity if it loses energy only by radiation and has no internal energy source. It is given by

$$\tau_{\mathrm{KH}} = \frac{GM^2}{RL}$$

where G is the universal gravitational constant, M the mass of the body, R its radius and L its luminosity. The Kelvin–Helmholtz contraction time defines the timescale for the collapse of protostars. Once hydrogen burning sets in, the energy lost to radiation is supplied by thermonuclear reactions and a star no longer contracts on this timescale.

Kelvin-Helmholtz luminosity:

The luminosity liberated as a result of gravitational contraction. Given by

$L_{KH} = GM^2/\tau_{KH}R$

where τ_{KH} is the Kelvin-Helmholtz contraction time.

Kelvin-Helmholtz timescale:
See Kelvin-Helmholtz contraction time.

Kepler:
A NASA satellite designed to detect transiting Earth-sized exoplanets, launched in 2009. See kepler.nasa.gov

Keplerian:
A term used to denote quantities that relate to properties of a (circular) Keplerian orbit, e.g. Keplerian speed, Keplerian angular speed.

Keplerian angular speed:

The angular speed of a body in a Keplerian orbit, i.e.

$\omega_K= (GM/R^3)^{1/2}$

Keplerian orbit:
The orbit a point mass executes if it is subject only to the gravitational force from another point-like mass. Quite often this term is used in a stricter sense to denote a circular orbit with constant angular speed that obeys Kepler's third law.

Keplerian speed:

The (tangential) speed of a body in a Keplerian orbit, i.e.

$v_K = (GM/R)^{1/2}$

Kepler orbit:
See Keplerian orbit.

Kepler's third law:

One of three laws of planetary motions derived by Kepler. The third law states that the square of a planet's orbital period is proportional to the cube of the semimajor axis of its orbit $P^2 \propto a^3$. More generally:

$a^3 / P^2 = GM / 4\pi^2$

where M is the total mass of the star and planet. The law may equally be applied to the case of binary stars.

Kerr black hole:
See Kerr metric.

Kerr metric:

The Kerr metric describes the Kerr solution to the Einstein field equations of general relativity. The line element may be written as:

$$(\mathrm{d}s)^2=\left(1-\frac{R_{\mathrm{S}}r}{\rho^2}\right)c^2(\mathrm{d}t)^2+\frac{2R_{\mathrm{S}}rac\sin^2\theta}{\rho^2}\mathrm{d}t\mathrm{d}\phi-\frac{\rho^2(\mathrm{d}r)^2}{\Delta}-\rho^2(\mathrm{d}\theta)^2-\left((r^2+a^2)\sin^2\theta+\frac{R_{\mathrm{S}}ra^2\sin^4\theta}{\rho^2}\right)(\mathrm{d}\phi)^2$$

The coordinates used to describe the metric are Boyer-Lindquist coordinates which differ from standard spherical coordinates.

The Kerr metric depends on just two parameters: the Schwarzschild radius $R_S = 2GM/c^2$ and $a = J/Mc$ where M and J are the mass and angular momentum of the black hole. The metric describes a black hole only when $a \le R_S/2$, i.e. when $J \le GM^2/c^2$. The limiting case is known as an extreme Kerr black hole.

Two functions Δ and ρ are used to simplify the line element, and are defined by $\Delta^2 = r^2 - R_S r + a^2$ and $\rho^2 = r^2 + a^2 \cos^2 \theta$.

Note that the metric coefficients do not depend on the coordinate φ, which ensures the axial symmetry of the solution. As r tends to infinity, Δ tends to r and ρ^2 tends to r^2 which ensures asymptotic flatness of the solution. In the limit as a tends to zero, the Kerr solution approaches the Schwarzschild solution.

The Kerr metric is singular when ρ = 0 and when Δ = 0. The first of these is a physical gravitational singularity and the second is a coordinate singularity. The gravitational singularity at ρ = 0 takes the form of a ring of coordinate radius a in the equatorial plane. The coordinate singularity corresponding to Δ = 0 is represented by two closed surfaces which both behave as event horizons. The inner and outer surfaces are described by

$r_+ = (R_S/2) + [(R_S/2)^2 - a^2]^{1/2}$

$r_- = (R_S/2) - [(R_S/2)^2 - a^2]^{1/2}$

There is also a surface of infinite redshift at

$s_+ = (R_S/2) + [(R_S/2)^2 - a^2 \cos^2\theta]^{1/2}$

known as the static limit. The region between the static limit and the outer event horizon is called the ergosphere.

Kerr solution:

The solution to the Einstein field equations in the case of a rotating black hole, sometimes called a Kerr black hole. See Kerr metric. Compare with Schwarzschild solution.

Kerr spacetime:
See Kerr metric.

kick velocity:
A velocity acquired by a neutron star at its birth, resulting from the supernova that produced it. Such velocities are deduced from the observed large proper motion of individual radio pulsars.

kilo:
A prefix used to indicate the standard SI multiple of 10^3.

kilogram:
The SI unit of mass, represented by the symbol kg. The kilogram is one of the seven SI base units, and is defined by a manufactured standard kilogram kept in France.

kinematic viscosity:
The dynamical viscosity η of a medium, divided by the mass density ρ of the medium: $v = \eta/\rho$.

kinetic energy:
The energy that a body possesses by virtue of its motion. See translational kinetic energy and rotational kinetic energy.

kinetic mode:
A mechanism by which an AGN can inject energy into the surrounding medium, due to acoustic waves. Contrast with radiative mode.

Klein–Nishina limit:
In electron scattering, the dividing line between the situation where a non-relativistic calculation is appropriate (i.e. Thomson scattering with $h\nu << m_e c^2$) and where a relativistic calculation must be performed (i.e. Compton scattering with $h\nu > m_e c^2$).

Kozai resonance:
Synchronised changes in the eccentricity and inclination of an orbit such that one increases whilst the other decreases, in a cyclic manner.

Kramers law:
See Kramers opacity.

Kramers opacity:
Any opacity of the form $\kappa \propto \rho T^{-3.5}$. Bound-free and free-free opacities are of this form.

Kronecker delta:
The symbol δ_{ij} where $\delta_{ij}=1$ if $i = j$ and $\delta_{ij}= 0$ if $i \neq j$.

Kruskal coordinates:
A set of coordinates used to describe the spacetime in the vicinity of a non-rotating balck hole which are non-singular everywhere outside the physical gravitational singularity. They are an extension of the advanced Eddington-Finkelstein coordinates. The Schwarzschild solution is one half of a broader domain referred to as the maximum analytic extension.

K-shell:
The lowest energy 'shell' of an atom, corresponds to the $n = 1$ energy level.

K-shell absorption:
The process by which a high energy photon removes an *electron* from the $n = 1$ energy level (i.e. the K-shell) of an atom.

L

laboratory frame:
A frame of reference fixed in a laboratory. Usually an inertial frame of reference. Also known as a rest frame.

LAGEOS satellites:
Two satellites (launched in 1976 and 1992) that are covered in retro-reflectors and are used for laser-ranging from ground tracking stations.

Lagrangian:
The difference between the kinetic energy and potential energy of a system.

Lagrangian point:
One of five points in space where a small body can maintain a stable orbit in the

combined gravitational fields of two larger bodies that are moving in circular orbits about their common centre of mass, in such a way that the small body stays fixed in the co-rotating frame. The Lagrangian points mark positions where the combined gravitational force of the two bodies exactly cancels the centripetal force required for co-rotation. All five points lie in the orbital plane of the two massive bodies. The inner Lagrangian point (L_1) lies between the two bodies and on the line that joins them; the two outer Lagrangian points, L_2 and L_3, lie on the far side of each body, still on the line joining the two; and the remaining two points, $L_4$and L_5, lie at the unoccupied vertices of the two equilateral triangles that can be constructed in the orbital plane with the two massive bodies at the remaining two vertices (these last two are also known as Trojan points).

In the Earth–Sun system, the Lagrangian points (particularly L_2) are useful positions for astronomical satellites. Asteroids are found at the Trojan points of the Sun-Jupiter system. In a binary star, mass transfer occurs across the inner Lagrangian point.

lambda eff lambda:

The quantity given by wavelength (lambda, λ) multiplied by spectral flux density (eff lambda, F_λ). It is often plotted against wavelength to present a spectral flux distribution in a way which emphasises the power output of an astronomical source across a wide range of wavelengths. See nu eff nu.

Laplacian operator:
The operator ∇^2 defined by $\nabla^2 = \nabla \cdot \nabla$ or, more explicitly, in Cartesian coordinates by $\nabla^2 \Phi = \partial^2\Phi / \partial x^2 + \partial^2\Phi / \partial y^2 + \partial^2\Phi / \partial z^2$

Large Magellanic Cloud:
An irregular galaxy which is a satellite galaxy to the Milky Way. It was the site of Supernova 1987A, the nearest supernova to have been observed in the modern era.

Larmor frequency:
Same as cyclotron frequency or gyrofrequency.

Larmor radius:
Same as cyclotron radius or gyroradius.

late heavy bombardment:
A phase in the Solar System's early history during which the Earth and other planets suffered frequent impacts from meteorites. It finished about 3.8Gyr ago.

late time Integrated Sachs-Wolfe effect:
In a Universe whose expansion is accelerating, the depths of gravitational potenial wells due to large scale structures decrease, leading to a further example of the Sachs-Wolfe effect at these late times.

late-type:

(1) Galaxy: for historical reasons, referring to spiral galaxies. There is no evolution from early to late-type galaxies.

(2) Star: referring to low mass stars of spectral type G, K or M.

See late-type.

law of conservation of angular momentum:
See conservation of angular momentum.

law of conservation of energy:
See conservation of energy.

law of conservation of linear momentum:
See conservation of linear momentum.

law of conservation of mass:
See conservation of mass.

law of universal gravitation:

A law stating that; every particle of matter attracts every other particle of matter with a gravitational force, whose magnitude is directly proportional to the product of the masses of the particles, and inversely proportional to the square of the distance between them. It follows from this that, if a particle of mass m_1 is separated by a distance r from a second particle of mass m_2, then the gravitational force on the second particle due to the first is directed towards the first particle and has magnitude

$$F_{12} = \frac{Gm_1m_2}{r^2}\hat{\mathbf{r}}$$

where $G = 6.673 \times 10^{-11}$ N m^2 kg^{-2} is the universal gravitational constant. By introducing a dimensionless unit vector $\hat{\boldsymbol{r}} = \boldsymbol{r}/r$ parallel to the displacement vector $\boldsymbol{r}$ from the first particle to the second, the force on the second particle, due to the first, may be written

$$F_{21} = -\frac{Gm_1m_2}{r^2}\hat{\boldsymbol{r}}$$

left-circularly polarized:
In left-circularly polarized light the plane of the electric field vector rotates clockwise about the direction of propagation when viewed from the source towards the destination; in right-circularly polarized light, this rotation is anticlockwise.

Lemaitre model:
A model of the Universe with curvature parameter, $k=+1$ and dark energy density parameter $\Omega_{\Lambda,0} > \Omega_{\Lambda,E}$ i.e. greater than that in the static Einstein model.

length contraction:
A phenomenon arising in Einstein's special theory of relativity, often summed up by the statement 'moving rods contract along their direction of motion'. If the proper length of a rod is recorded as ΔL_P in a frame in which the rod is at rest, then the length of the rod measured from a frame of reference in which the rod is moving at speed V, has the contracted value $L = L_P/\gamma(V)$. Length contraction is a consequence of the Lorentz transformation. See also time dilation.

lens equation:
The fundamental vector equation of gravitational lensing:

$$\beta = \theta - \alpha(\theta)$$

where β is the angle between the lensing object and the source of radiation, subtended at the position of the observer; θ is the angle between the lensing object and the lensed image, subtended at the position of the observer; and α is the angle between the source of radiation and the lensed image, subtended at the position of the observer.

Lense-Thirring effect:
The rotational dragging of inertial frames which arises in regions of spacetime described by the Kerr metric.

lenticular galaxies:
See lenticular galaxy.

lenticular galaxy:
A galaxy that is intermediate between ellipticals and spirals; they have a bulge and disc but little cold interstellar gas and no spiral arms. They are also known as S0 galaxies.

lepton:
A fundamental particle of spin ½ that does not participate directly in strong interactions, though it may interact via the weak or, if charged, the electromagnetic interaction. Only six types of lepton are known: electron, electron neutrino, muon, muon neutrino, tauon and tauon neutrino (or, in terms of symbols, e^-, ν_e, μ^-, ν_μ, τ^-, ν_τ). Their antiparticles are known as antileptons.

libration cycle:
A periodic cycle in the value of an orbital parameter, such as the eccentricity of an orbit.

lifetime (of a particle):
The time between the creation of a particle at a certain event, and its decay at a subsequent event.

light:
See visible light.

lightcone:
In the special theory of relativity, the region of spacetime that can be affected by, or can affect, a particular event; so called because the region is cone-shaped in a spacetime diagram with one spatial direction suppressed, with the event lying at the vertex of the cone. Because of the finite speed of light, a given event can affect only a small region of space after a short elapsed time, but a larger region after a longer time.

light-crossing time:
See light travel time.

light curve:
A graph that shows some measure of the brightness of an object – the flux, apparent magnitude or spectral flux density – as a function of elapsed time. Light curves are an important tool with which to study variable objects such as pulsating variable stars, cataclysmic variables, X-ray binaries and active galactic nuclei, particularly highly variable systems such as blazars.

light curve modelling:
The process of finding the best-fit model to a light curve.

light echoes:
In the same way that sound echoes can give information about the physical environment with which the sound waves interact (i.e. sonar), light signals can also be

reflected from structures that are distant from the source of light. Measurement of time delays of these light echoes can thus be used to infer details of the structure of the system within which the light signals are propagating.

light-like separation:

Events with a zero spacetime separation are said to be light-like. Such events are causally related and all observers will agree that they could be linked by a light signal.

See time-like separation and space-like separation.

light time:
See light travel time.

light travel time:
A numerical quantity that gives the time that light or other *electromagnetic radiation*, travelling at 2.998×10^8m s^{-1}, would take to cross a given region.

light-year:
The distance, in a vacuum, travelled by light (or other electromagnetic radiation) in one year. Equal to 9.461×10^{15} m or 0.307 parsec.

LIGO:
The Laser Interferometer Gravitational-Wave Observatory. One of the most sensitive gravitational wave detectors currently in operation.

LI, LII, LIII subshell:
Different angular momentum quantum states for the $n = 2$ energy level of an atom.

limb:
The apparent edge of the disc of any astronomical body (especially, star or planet).

limb-darkening:
The observed darkening towards the limb of the Sun or other star.

limb-darkening coefficient:
A numerical constant in a limb-darkening law. Limb-darkening coefficients vary with wavelength, effective stellar temperature and surface gravity,

limb-darkening laws:

Analytical expressions used to describe the limb-darkening towards the edge of the Sun or other star. A simple limb-darkening law is the linear one:

$I(\mu)/I_0 = 1 - u(1-\mu)$

Others include a logarithmic relationship:

$I(\mu)/I_0 = 1 - u_l(1-\mu) - v_l \mu \ln \mu$

or a quadratic relationship:

$I(\mu)/I_0 = 1 - u_q(1-\mu) - v_q(1-\mu)^2$

where the various u and v quantities are limb-darkening coefficients and $\mu = \cos \gamma$, where γ is the angle between the line of sight and the ouwardly directed radius vector at that point in the star.

Limber's equation:
A relationship between the correlation function and the angular correlation function used to quantify galaxy clustering.

limit cycle:
A repeating cycle of behaviour for a physical system governed by an underlying physical process which causes the system to approach certain limits at either extreme of the cycle. The path of the system in phase space forms a closed loop. The thermal-viscous instability of an acretion disc is a limit cycle, and the behaviour of the system traces out a closed loop known as an S-curve in a plot of mass transfer rate versus accretion disc surface density.

limiting distance:
The furthest distance to which objects of a given luminosity are detectable given a flux limit for a particular detector.

linearised field equation:
A means of representing the Einstein field equations in the weak field limit, giving rise to wave-like solutions.

linear momentum:

The momentum associated with the translational motion of a body. For a particle of mass m travelling with velocity $\boldsymbol{v}$, the linear momentum is

$\boldsymbol{p} = m\boldsymbol{v}$

For a rigid body of mass M,

$\boldsymbol{p} = M\boldsymbol{v}_{CM}$

where v_{CM} is the speed of the body's centre of mass. See also conservation of linear momentum and relativistic momentum.

linear size:
The physical extent of an extended astronomical object.

line element:
The infinitesimal d*l* defined for a space in terms of the metric tensor and the coordinate infinitesimals by $ds^2 = \Sigma_{ij}\, g_{ij}\, dx^i\, dx^j$.

line emissivity:
The amount of energy per unit time per unit volume per unit solid angle carried away from emitting gas by emission line photons.

line flux:
The total amount of energy per unit collecting area per unit time carried by the photons which comprise a spectral line.

line profile:
The observed shape of an emission line in a plot of spectral flux density against wavelength or frequency for an astronomical object. The shape of a spectral line is influenced by Doppler broadening, among other possible factors.

LINER:
A Low-Ionization Nuclear Emission line Region galaxy which is a member of a class of active galaxies that show weak, low-ionization emission lines close to the nucleus. This is generally their only sign of activity, though some radio galaxies have LINER-like emission line properties.

line ratio:
The flux in one spectral line divided by the flux in another spectral line.

LIRG:
See luminous infrared galaxy.

LISA:
The planned Laser Interferometer Space Antenna which is a proposed gravitational wave detector operating in space. It will comprise three free-flying satellites in solar orbit, spaced 5 million kilometers apart.

LMC:
See Large Magellanic Cloud.

LMXBs:
Acronym for Low Mass X-ray Binaries.

lobe:
A large diffuse region of synchrotron-emitting plasma supplied with energy by the jet of an extragalactic radio source such as a radio galaxy or quasar. Normally two lobes are seen, one on either side of the active nucleus. See radio source structure.

Local Group:
The group of galaxies comprising the Milky Way galaxy, the Andromeda galaxy, and around 40 or so other smaller members.

local linear stability analysis:
The theoretical study of the reaction of a physical systems to small and localized perturbations of its current state. The perturbations must be small so that it is sufficient to consider the linear terms in the Taylor series expansion of functions that enter the description of the system.

local supercluster:
The supercluster of galaxies to which the Virgo cluster of galaxies and the Coma cluster of galaxies belong.

Lockman hole:
A region of sky in the constellation of Ursa Major where the neutral hydrogen column density is extremely low ($< 10^{20}\ cm^{-2}$).

logarithmic derivative:
For example, the derivative: $d(\log_e x)/dt$. See logarithmic differentiation.

logarithmic differentiation:
Since $d(\log_e x)/dx = 1/x$, by the chain rule, the derivative of $\log_e x$ with respect to some other variable, say t, is

$$\frac{d(\log_e x)}{dt} = \frac{1}{x} \times \frac{dx}{dt} = \frac{\dot{x}}{x}$$

where $\dot{x}$ is a shorthand for dx/dt.

logarithmic line profile:

A simplified model to explain the profile of emission lines in AGN. It assumes that the principal broadening mechanism is the Doppler shift induced by the motions of individual broad-line clouds, each of which produces a line profile approximated by a delta function.

logarithm to the base e:
Given a positive number *x*, its logarithm to the base e is the power to which e must be raised to obtain the given number. So if $x = e^y$ then we say that *y* is the log to the base e of *x*, and we write $y = \log_e x$ (or $y = \ln x$). In the case where *x* is a positive *variable*, it is possible to define a logarithmic function using the relationship, $f(x) = \log_e x$. The logarithmic function is the inverse of the exponential function, since $\log_e e^y = y$. The idea of a logarithm and of a logarithmic function may be extended to bases other than e, though logarithms to the base e are known as natural logarithms.

logarithm to the base ten:
Given a positive number *x*, its logarithm to the base ten is the power to which 10 must be raised to obtain the given number. So if $x = 10^y$ then we say that *y* is the log to the base ten of *x*, and we write $y = \log_{10} x$. In the case where *x* is a positive variable, it is possible to define a logarithmic function using the relationship, $f(x) = \log_{10} x$.

log N - log S graph:
A graph of the logarithm of the number of sources (*N*) with flux in excess of a certain value (*S*) plotted versus the logarithm of this flux. In Euclidean space, if sources with a fixed luminosity are uniformly distributed within a spherical volume, the log N - log S distribution is a straight line of slope -3/2 implying that *N* is proportional to $S^{-3/2}$.

longitude of periapsis:
See longitude of periastron.

longitude of periastron:
Uusually represented by the symbol ω. One of two angles describing the orientation of an orbit. (The other being the inclination of the orbit with respect to the line of sight.) It describes the angle (longitude) between the periastron position and the ascending node, i.e. the point at which the orbit crosses the plane perpendicular to the line of sight.

longitudinal wave:
A wave composed of oscillations that take place in a direction parallel to the direction of propagation of the wave. Contrast with transverse wave.

lookback time:
The time elapsed between the emission of a photon by a distant astronomical source and its detection by us. For objects at cosmological distances, the lookback time can be a significant fraction of the age of the Universe.

Lorentz factor:

Also known as the γ-factor, the function

$$\gamma(V) = \frac{1}{\sqrt{1-(V^2/c^2)}}$$

which occurs often in equations relating to the special theory of relativity. It is represented by the symbol γ (gamma) and is dimensionless.

Lorentz force:
The force acting on charged particles in an electric and/or magnetic field which results from the Lorentz force law.

Lorentz force law:

A law stating that; a particle of charge *q*, moving with velocity ***v*** at a point specified by the position vector ***r***, is subject to a force $\boldsymbol{F} = q[\boldsymbol{\mathcal{E}}(\boldsymbol{r}) + \boldsymbol{v} \times \boldsymbol{B}(\boldsymbol{r})]$, where $\boldsymbol{\mathcal{E}}(\boldsymbol{r})$ and $\boldsymbol{B}(\boldsymbol{r})$ are, respectively, the electric field and magnetic field at the point ***r***.

In special relativity, the Lorentz force law may be expressed as $[F^{\mu}] = q\,[F^{\mu\nu}][U_{\nu}]$ where $[F^{\mu}]$ is a contravariant four-force, $[F^{\mu\nu}]$ is the contravariant electromagnetic four-tensor and $[U_{\nu}]$ is a covariant four-velocity.

Lorentz scalar:
Quantities that are invariant under a Lorentz transformation are sometimes referred to as Lorentz scalars because they can be formed by the contraction of four-vectors in a smilar way to the formation of a scalar product of (ordinary) three-vectors.

Lorentz transformation:

The coordinate transformation of special relativity. If an event has coordinates (*x*, *y*, *z* and *t*) in frame of reference A, then the coordinates of the same event in frame of reference B, which is in standard configuration with A, are

$$x' = \frac{x-Vt}{\sqrt{1-(V^2/c^2)}}$$

$$y' = y$$

$$z' = z$$

$$t' = \frac{t-(Vx/c^2)}{\sqrt{1-(V^2/c^2)}}$$

where V is the relative speed of B with respect to A. An approximation to the Lorentz transformation at low speeds is provided by the Galilean coordinate transformation.

Lorentz transformation matrix:
Represented by the symbol $[\Lambda^{\mu}{}_{\nu}]$ such that Lorentz transformations may be expressed as $[x'^{\mu}] = [\Lambda^{\mu}{}_{\nu}][x^{\nu}]$, where $[x^{\nu}]$ is the four-position. The components of the Lorentz transformation matrix are such that the elements of the leading diagonal are $\gamma(V)$, $\gamma(V)$, 1, 1 respectively, and the elements $\Lambda^{0}{}_{1} = \Lambda^{1}{}_{0} = -\gamma(V)V/c$, where $\gamma(V)$ is the Lorentz factor. All other elements of the matrix are equal to zero.

low-frequency cutoff:
The downturn in a synchrotron emission spectrum at low frequencies due to synchrotron self absorption.

low mass X-ray binaries:
See X-ray binary.

low-mass X-ray binary:
An X-ray binary where the donor star has a mass below about 2 $M_{\odot}$

LSB galaxies:
Low Surface Brightness galaxies, which have a surface brightness fainter than 22.5 magnitudes per square arcsecond. They have a high mass-to-light ratio, low metallicity, and are dominated by dark matter.

L-shell:
The second lowest energy 'shell' of an atom, corresponds to the n = 2 energy level.

LSST:
The Large Synoptic Survey Telescope. A planned wide field survey telescope to be built in Chile.

luminosity:
A quantity used to describe the energy emitted by a radiating source per unit time, normally in units of W or J s^{-1} (SI) or erg s^{-1} (cgs). The symbol normally used is L. The bolometric luminosity is the luminosity measured across all parts of the electromagnetic spectrum but the luminosity can also be measured in specific wavebands or frequency ranges. In the optical waveband, the absolute magnitude is often used as an alternative to the luminosity.

luminosity boosting:
See Doppler boosting

luminosity classification:

A classification used together with the spectral classification to give the overall type of a star. Stars of a given spectral class can have widely differing luminosities, because of the existence of stars that do not lie on the main sequence, so some additional classification is needed to distinguish them. The most widely adopted system uses roman numerals from I to VII, as follows:

Luminosity class	Description
Ia	bright supergiants
Ib	supergiants
II	bright giants
III	giants
IV	subgiants
V	main sequence (dwarfs)
VI	subdwarfs
VII	white dwarfs

So, for example, the Sun is a G2 V star (a G2 star on the main sequence) while the red giant Aldebaran is a K5 III star.

luminosity-dependent density evolution:
A combination of density evolution and luminosity evolution used to explain the change of the quasar luminosity function with time.

luminosity distance:
One of several cosmological definitions of distance, in this case the distance such that the definition of flux remains unchanged:

$F = L / 4\pi d_L^2$

where F is the flux from a given object, L is its luminosity and d_L the luminosity distance to the object. In flat, non-expanding space the luminosity distance is the same as other measures of distance, but in the curved, expanding space predicted by general relativity, the type of distance being considered must be carefully specified.

luminosity evolution:
The suggestion that the number of galaxies which harbour AGN is a small constant fraction of the whole population of galaxies. In this scenario the change in the quasar luminosity function is attributed to the luminosities of individual sources changing in time. See also density evolution. A more appropriate explanation of the evolution of the quasar luminosity function is believed to be luminosity-dependent density evolution.

luminosity function:
The function that specifies the number density of astronomical objects (e.g. stars, galaxies, quasars) as a function of their luminosity. The number density is usually expressed in terms of number per cubic parsec (for stars) or per cubic megaparsec (for extragalactic objects) and the luminosity function almost always decreases with increasing luminosity: that is, there are almost always more intrinsically faint objects than intrinsically bright ones. Luminosity functions may be calculated in the optical waveband (in which case the luminosity used is often given in terms of absolute magnitude) or in any other part of the electromagnetic spectrum. Differences in the luminosity function tell us about differences in the populations of objects being studied: for example, the luminosity functions of globular clusters and open clusters are different because of their different ages, while the luminosity functions of quasars at different redshifts are different because the quasar population has evolved over cosmic time.

luminous infrared galaxy:
(LIRG) An infrared-luminous galaxy with 10^{11} - 10^{12} solar luminosities.

Lyman alpha:
The first spectral line of the Lyman series corresponding to transitions between the n = 1 and n = 2 energy levels.

Lyman alpha blobs:
A population of galaxies with a strong Lyman alpha emission line but weak continuum emission.

Lyman alpha forest:
The 'forest' of Lyman alpha absorption lines in the spectrum of a quasar corresponding to absorption in many intervening clouds at different redshifts.

Lyman-break galaxy:
A galaxy that shows a sharp decrease in the level of measured radiation shortward of a rest-frame wavelength of 91.2 nm, the Lyman limit. This is caused by absorption of the galaxy's continuum emission by neutral hydrogen near the galaxy; radiation with a wavelength below 91.2 nm is energetic enough to ionize hydrogen, removing photons in the process. If the Lyman break is redshifted into the optical waveband, it gives the galaxies a characteristic colour which allows them to be easily identified in sky surveys.

Lyman-break object:
See Lyman-break galaxy.

Lyman discontinuity:
See Lyman edge.

Lyman edge:
The threshold at which a photon can cause ionization from the n = 1 level of hydrogen, at 91.2 nm (= 912 Å).

Lyman limit:
The wavelength of 91.2 nm (= 912 Å) which corresponds to transitions between the n = 1 energy level of hydrogen and unbound states. See hydrogen spectrum.

Lyman limit absorption:
In the spectrum of a quasar at redshift z, at wavelengths below (1+z) x 91.2 nm, the atoms along the line of sight could be ionized completely and the quasar spectrum noticebly supressed. This is known as Lyman limit absorption.

Lyman series:
A series of lines in the ultraviolet spectrum of atomic hydrogen. These lines correspond to transitions between the n = 1 energy level and energy levels with n = 2, 3, 4, 5, etc. See hydrogen spectrum, Balmer series, Paschen series, Brackett series.

M

M31:
The Andromeda galaxy.

MACHO:
Massive Compact Halo Objects. Hypothetical dark matter objects in the halos of galaxies.

Maclaurin series:
A function $f(x)$ may be expanded about the point x = 0 by writing it as

$f(0) + xf'(0) + x^2f''(0)/2! + x^3f'''(0)/3! \ldots$

where $f'(0)$ is the first derivative of f evaluated at x = 0, and $f''(0)$ is the second derivative of f evaluated at x = 0, and so on. See also Taylor series.

macrolensing:
See gravitational lens.

Madau diagram:
A plot of cosmic star formation history derived from rest-frame ultraviolet luminosities of galaxies. It is a graph of star formation rate (log mass per unit time per unit volume) versus redshift.

Madau-Lilly diagram:
See Madau diagram.

Magellanic clouds:
Two small, irregular satellite galaxies to the Milky Way, namely the Large Magellanic Cloud and the Small Magellanic Cloud.

magic nuclei:
See magic numbers.

magic numbers:
There are more stable nuclei with either the atomic number Z or neutron number N equal to one of the numbers 2, 8, 20, 28, 50, 82 and 126, than might be expected. These nuclei are called magic nuclei. The numbers are called magic numbers and can be understood in the context of the nuclear shell model.

magnetar:
A pulsar with an extremely high magnetic field ($B > 10^{10}$ T) whose emission is powered by the decay of the magnetic field itself. Magnetars are observable as two classes of object: anomalous X-ray pulsar and soft gamma-ray repeater. Contrast with rotation powered pulsar and accretion powered pulsar.

magnetic cataclysmic variable:
A binary star which is a member of a class of cataclysmic variables in which the white dwarf accretor has a magnetic field strong enough to influence the accretion process significantly. Magnetic cataclysmic variables come in two main flavours. In polars (sometimes called AM Her stars) the field is strong enough that it dominates the dynamics of accreting material as soon as it has left the donor star. Polars consequently do not form an accretion disc; instead, the accreting matter forms an accretion column, funnelling matter down to the magnetic poles of the white dwarf. In intermediate polars (sometimes called DQ Her stars), the field is weaker, and an accretion disc can form; the disc is disrupted at an inner radius determined by the field strength, the 'magnetospheric radius' and from this point matter flows from any point on the inner edge of the disc to the magnetic pole in structures known as accretion curtains.

magnetic dipole:
Any system that produces a magnetic field similar to that of an infinitesimally small bar magnet, e.g. a body with north and south magnetic poles.

magnetic dipole radiation:
Electromagnetic radiation emitted by a rotating magnetic dipole.

magnetic dynamo:
The motion of conductive fluids within a planet (such as the Earth) which is responsible for the generation of its magnetic field.

magnetic field:
The vector quantity $\boldsymbol{B}(\boldsymbol{r})$ that determines the magnetic force acting on any charged particle as it moves through the point specified by the position vector $\boldsymbol{r}$. It is defined by the requirement that the magnetic force $\boldsymbol{F}_{mag}$ on a particle of charge q moving with *velocity* $\boldsymbol{v}$ as it passes through the point $\boldsymbol{r}$ is given by $\boldsymbol{F}_{mag} = q(\boldsymbol{v} \times \boldsymbol{B}(\boldsymbol{r}))$. The magnetic field has both magnitude and direction at each point in space, so it is an example of a vector field, and magnetic fields due to different sources add vectorially at every point. See also magnetic field strength.

magnetic field strength:

The magnitude of the magnetic field. A particle of charge q moving with speed v at an angle θ to a magnetic field of strength B experiences a force of magnitude $F_{mag} = |q| vB \sin\theta$. This equation can be used to interpret the SI unit of magnetic field, the tesla (T), where 1 T = 1 N s m^{-1} C^{-1}. A magnetic field of strength 1 T exerts a force of 1 N on a particle of charge 1 C moving perpendicularly to it at a speed of 1 m s^{-1}.

The magnetic field strength near a typical bar magnet is of order of 10^{-1} T; large superconducting magnets produce magnetic field strengths of several hundred tesla. The magnitude of the Earth's magnetic field, measured at the surface, is of the order of 10^{-5} T.

The cgs unti of magnetic field strength is the gauss, where 1 gauss - 10^{-4} tesla.

magnetic force:
The force that acts on a body due to its interaction with a magnetic field. In the case of a point particle of charge q moving with velocity $\boldsymbol{v}$, the magnetic force is given by $\boldsymbol{F}_{mag} = q(\boldsymbol{v} \times \boldsymbol{B}(\boldsymbol{r}))$, where $\boldsymbol{B}(\boldsymbol{r})$ is the magnetic field at the position $\boldsymbol{r}$ of the particle. (This is part of the Lorentz force law.) Note that a magnetic force cannot change the speed of a charged particle, since it always acts at right angles to the direction of motion of the particle, but it can still cause the particle to accelerate by changing the direction of the particle's motion.

magnetic pressure:

The pressure in a fluid due to the presence of a magnetic field. If the magnetic field has magnitude *B*, the magnetic pressure is (in SI units)

$$P\text{mag} = \frac{4\pi}{\mu_0}\frac{B^2}{8\pi} = \frac{1}{2\mu_0}B^2$$

magnetic stellar wind braking:
The spin-down of a rotating star due to its magnetically coupled stellar wind. The star experiencing magnetic braking can also be a component in a binary system. If tidal forces enforce co-rotation of the star with the orbit, magnetic braking leads to the loss of orbital angular momentum.

magneto-hydrodynamics:
The study of the flow of electrically conducting fluids (such as plasmas) in the presence of dynamically important magnetic fields.

magnification bias:
An effect of gravitational lensing on the source counts of extragalactic objects. At any flux S_0 there are many objects fainter than S_0, some of which will be magnified to this flux, and fewer objects brighter than S_0, of which some will be demagnified to this flux. The asymmetry between the brighter and fainter populations changes the distribution of magnifications for objects with a fixed observed flux of S_0. The steeper the source count slope, the more the observed magnification distribution is skewed towards higher magnifications.

magnitude (astronomical):
See apparent magnitude, absolute magnitude.

magnitude (of a scalar):
Given any scalar quantity, positive or negative, its magnitude is a positive quantity, equal to the value of the given scalar apart from any overall minus sign. For example, both 5 and -5 have magnitude 5. The modulus symbol || is used as an instruction to take the magnitude of the enclosed scalar. Thus, for example, |-5| = 5. The magnitude of a scalar is often referred to as its ‘modulus’ or its ‘absolute value’.

magnitude (of a vector):

Given any vector quantity ***v***, its magnitude is a positive scalar quantity *v* that indicates the ‘length’ or ‘size’ of the given vector. The modulus symbol || is sometimes used as an instruction to take the magnitude of the enclosed vector. Thus, for example, the magnitude of ***v*** may be denoted by |***v***| or *v*. If ***v*** is expressed in terms of its Cartesian components ***v*** = (v_x, v_y, v_z), then the magnitude of ***v*** is given by

$$|\mathbf{v}| = v = \sqrt{v_x^2 + v_y^2 + v_z^2}$$

Magorrian relation:
The correlation between the mass of the supermassive black hole in the centre of a galaxy and the luminosity of the spheroid of the galaxy (i.e. the bulge in the case of a spiral galaxy and the entire galaxy in the case of an elliptical galaxy).

main sequence:
A well-defined region in the Hertzsprung-Russell diagram, showing a positive correlation between temperature and luminosity, in which stars in their (core) hydrogen-burning phase can be found. Protostars evolve onto the main sequence and spend most of their lifetime as stars there until core hydrogen burning ceases and they evolve towards the red giant branch.

Malmquist bias:
A selection effect that arises when selecting objects to make a flux-limited sample, i.e. making a catalogue of all objects that are brighter than a certain flux value in a particular region of the sky. Because a flux limit translates to a greater luminosity as the distance being considered increases, the more distant objects in the sample will be systematically more luminous than the nearby ones. This results in a correlation between distance (or redshift, for objects at cosmological distances) and luminosity that can make it difficult to study the effects of either quantity on properties of the sample objects. See also radio galaxy evolution.

Markarian galaxy:
A galaxy contained in the catalogue compiled by B. E. Markarian in the 1960s and 70s, that shows strong ultraviolet continuum emission. Some of these are active galaxies such as Seyferts and BL Lac objects (see UV excess), others are sites of recent massive star formation.

mass accretion:
See accretion.

mass accretion rate:
See accretion rate.

mass continuity:

One of the four stellar structure equations, namely:

$$\frac{dm(r)}{dr} = 4\pi r^2 \rho(r)$$

mass defect:
The mass difference between the initial and final particles in a fusion reaction where the mass of the product is less. The mass defect Δm corresponds to liberated energy, of an amount given by $E = \Delta m\, c^2$.

mass density:
See density.

mass energy:
The energy that a body possess by virtue of its mass, as given by $E_0 = mc^2$, where c is the speed of light in a vacuum. The existence of mass energy is one of the many implications of the special theory of relativity. The mass energy of a free particle is the difference between its (total) relativistic energy and its relativistic translational kinetic energy. Mass energy is also known as rest energy.

mass fraction:
The number fraction weighted by the mass of each type of particle. In astrophysics, the mass fractions of hydrogen, helium and 'all other elements' (metals) are often represented by the symbols X, Y, and Z respectively. The mass fractions of the Sun are $X = 0.70$, $Y = 0.28$, $Z = 0.02$. The mass fraction X_i of a particular type of particle in a sample may be expressed as $X_i = m_i n_i/\rho$, where m_i is the mass per particle, n_i is the number density, and ρ is the overall mass density of the sample.

mass function:
A mathematical expression involving the masses of the two components of a spectroscopic binary system, and the inclination of their mutual orbit that can be equated to a combination of observable parameters (the orbital period P, and the maximum radial speed of one of the stars, v_1). This relation takes the form

$$f(m_1) = \frac{(m_2 \sin i)^3}{(m_1+m_2)^2} = \frac{Pv_1^3}{2\pi G}$$

where G is Newton's gravitational constant. The mass function provides constraints on the masses of the two components of the binary, and represents the most that can be said about those masses if only one of the stars has an observable spectrum.

mass loss:
The loss of material from a star. Main-sequence stars lose mass at a slow rate through stellar winds (see solar wind), but at other phases of a star's evolution mass loss can be much more rapid. Protostars such as T Tauri stars can eject a significant amount of mass in bipolar outflows, while at late stages planetary nebulae and supernovae are examples of catastrophic mass loss. Stars in a binary system can also lose mass through mass transfer.

mass-luminosity relation:
The relationship between the masses and luminosities of main-sequence stars. For stars with masses around the mass of the Sun, it is found empirically that

$$\frac{L}{L_\odot} = \left(\frac{M}{M_\odot}\right)^{3.5}$$

where $L_\odot$ and $M_\odot$ are the luminosity and mass of the Sun. The slope of the relationship (i.e. the index of the power-law dependence on mass) is ~3 for more massive stars.

mass number:
The total number of protons and neutrons in a specified nucleus. The mass number is usually represented by the symbol A, and is equal to the sum of the atomic number Z and the neutron number N, so $A = Z + N$.

mass-radius index:
The exponent or index (represented by the greek letter zeta) in the mass-radius relationship of a star: $R \propto M^\zeta$.

mass ratio:
In a binary star system, the ratio of the mass of one star to that of the other. In an accreting binary star, this is often (but not always) defined as q = donor mass / accretor mass = M_2/M_1.

mass-to-light ratio:
The mass of a galaxy divided by its luminosity.

mass transfer:
The transfer of mass from one star in a binary system to another. The most important type of mass transfer occurs when an evolving star expands so as to fill its Roche lobe; matter then passes into the potential well of the other star by crossing the inner Lagrange point. Normally this matter will go on to form an accretion disc. Mass transfer is the explanation for the Algol paradox.

mass transfer rate:
The rate at which mass is transferred from one star in a binary system to another. It is

sually measured in kilograms (or grams) per second or in solar masses per year. See mass transfer.

matter:
A general term for material substances, irrespective of their form.

matter-antimatter annihilation:
See annihilation.

maximal analytic extension:
See Kruskal coordinates.

maximum entropy imaging technique:
An indirect imaging technique where a model image is calculated from incomplete observational data. The model image is required to resemble a default image, while still being consistent with the data. The closeness of default and model image is measured by a numerical quantity called (image) entropy, and the fitting involves maximising this quantity.

Maxwell-Boltzmann distribution:
See Maxwell speed distribution and Maxwell–Boltzmann energy distribution.

Maxwell-Boltzmann energy distribution:

The equilibrium distribution function for the translational kinetic energy of molecules in a gas at (absolute) temperature *T*:

$$g(E) = \frac{2}{\sqrt{\pi}}\left(\frac{1}{kT}\right)^{3/2}\sqrt{E} \times \exp\left(-E/kT\right)$$

where *E* denotes the translational kinetic energy of a molecule, i.e. $E = E_{KE} = mv^2/2$ where *m* and *v* are the mass and speed of the molecule. The product $g(E)\Delta E$ is the probability of a single molecule having translational energy between *E* and $E + \Delta E$. Consequently, if the total number of molecules in the gas is *N*, the quantity $G(E)\ \Delta E = Ng(E)\ \Delta E$ represents the total number of molecules with energy between *E* and $E + \Delta E$.

Maxwell-Boltzmann speed distribution:
Another term for the Maxwell speed distribution.

Maxwell equations:

The laws that determine the electric and magnetic fields in agiven region of space. They relate the electric and magnetic fields to the charge and current densities that are their sources, and also to each other since a changing magnetic field can produce an electric field, and a changing electric field can produce a magnetic field.

The vector calculus versions are:

$$\nabla \cdot \mathcal{E} = \rho / \epsilon_0$$

$$\nabla \cdot \boldsymbol{B} = 0$$

$$\nabla \times \mathcal{E} = -\frac{\partial B}{\partial t}$$

$$\nabla \times \boldsymbol{B} = \mu_o \boldsymbol{J} + \frac{1}{c^2}\frac{\partial \mathcal{E}}{\partial t}$$

Expressed in terms of tensors, the covariant Maxwell equations are

$$\sum_{\nu=0}^{3} \frac{\partial \mathrm{F}^{\mu\nu}}{\partial x^{\mu}} = \frac{J^{\nu}}{\epsilon_0}$$

$$\frac{\partial, \mathbf{F}_{\lambda\mu}}{\partial x^{\nu}} + \frac{\partial \mathbf{F}_{\nu\lambda}}{\partial x^{\mu}} + \frac{\partial \mathbf{F}_{\mu\nu}}{\partial x^{\lambda}} = 0$$

where $[J^{\nu}]$ is the contravariant four-current, and $[F^{\mu\nu}]$ is the contravariant electromagnetic four-tensor.

Maxwellian distribution:
Another term for the Maxwell speed distribution.

Maxwell speed distribution:

The equilibrium distribution function for the speed of the particles comprising a gas at absolute temperature *T*:

$$f(v) = 4\pi\left(\frac{m}{2\pi kT}\right)^{3/2} v^2 \exp\left(-\frac{mv^2}{2kT}\right)$$

where *m* and *v* are the mass and speed of the molecules, and *k* is Boltzmann's constant. The product $f(v)\Delta v$ is the probability of a single molecule having speed between *v* and $v + \Delta v$.

mean free path:
The average distance travelled by a particle before it undergoes an interaction.

mean molecular mass:

The mean mass *m* of the particles in a gas, expressed in units of m_p, the proton mass, or sometimes *u*, the atomic mass unit. For the latter,

$$\mu = \frac{\sum_i n_i m_i}{u \sum_i n_i}$$

where n_i is the number of particles of type i with mass m_i.

(Nb. The mean molecular mass is sometimes incorrectly referred to as the mean molecular weight.)

mean molecular weight:
Incorrect (but widely used) name for mean molecular mass.

mean motion orbital resonance:

This is said to exist when the periods of two bodies in a planetary system exhibit a simple integer ratio between them. such resonances can either stabilize the orbit, rendering it immune to change, or destabilize the orbit causign it to change rapidly. A resonance of the form j+1:j is referred to as a first order resonance.

MEarth:
A ground-based exoplanet search programme designed to find transiting terrestrial-sized exoplanets around M-type (low mass) stars.

mechanical energy:
The sum of kinetic energy and potential energy of a body or system.

Meszaros effect:
The realisation that if a matter perturbation Fourier mode enters the horizon before the epoch of matter-radiation equality, then this Fourier mode cannot grow through gravitational collapse, because the dominant energy of radiation drives the Universe to expand so fast that matter has no time to self gravitate. The Fourier mode is therefore frozen at a constant value.

metallicity:

A numerical quantity that gives the fraction of heavy elements (metals) by mass in a star, a group of stars, or an astronomical plasma. Metallicity may be expressed as a ratio between the observed fraction of heavy elements and the fraction of heavy elements in the Sun, or as a quantity such as

$[Fe/H] = \log_{10}(Fe/H)_* - \log_{10}(Fe/H)_\odot$

which describes the metallicity of a star relative to that of the Sun. The quantity [Fe/H] has the unit of dex.

Since heavy elements are generated in the late phases of evolution of stars, the elemental abundances of stars tell us about their ages (see population I, population II).

metals:
The astronomical term for elements heavier than helium.

metre:
The SI unit of length, represented by the symbol m. The metre is one of the seven SI base units, and is defined as the distance that light travels in a vacuum in 1/299 792 458 second.

metric:
Often used as an abreviation for metric tensor.

metric coefficients:
Coefficients g_{ij} that define the geometry of a space via the line element $ds^2 = \Sigma_{ij}\, g_{ij}\, dx^i\, dx^j$. Metric coefficients are required to be symmetric in the sense that $g_{ij} = g_{ji}$.

metric tensor:
The tensor whose elements are the metric coefficients.

microlensing:
See gravitational lens.

microlensing event:
A transient brightening of a gravitationally lensed object due to microlensing by an individual star. See gravitational lens.

micron:
Shorthand for 10^{-6} m or 1 μm.

microquasar:
A name sometimes used to refer to an X-ray binary that emits radio jets. The analogy is that these are scaled down versions of quasars.

microvariability:
Small amplitude (~0.1 mag) rapid (timescale ~ hours) variability seen in the light

curves of some blazars.

microwaves:
Electromagnetic radiation with a wavelength between about 1×10^{-3} m and 1×10^{-1} m, or a frequency between about 3×10^{11} Hz and 3×10^{9} Hz.

midplane:
The plane that divides an object, such as a spiral galaxy, into two similar halves; the plane of symmetry of the system.

Milky Way:
The galaxy in which our Sun and Solar System are located, so called because of its appearance in the night sky as a diffuse band of stars. The Milky Way is a large spiral galaxy; our Solar System is located close to the plane of the Galaxy, in the disc, and about 8.51kpc from the Galactic centre.

milli:
A prefix used to indicate the standard SI submultiple of 10^{-3}.

millibarn:
A non-SI unit of area commonly used to measure fusion cross-sections. 1 barn = 10^{-28} m^2, so 1 mbarn = 10^{-31} m^2.

millisecond pulsar:
Also known as recycled pulsars. They are neutron stars which have been spun-up to a rapid rotation rate during a previous phase of accretion in a binary star system. Millisecond pulsars are therefore rotation powered pulsars which often found in binary systems, although in some cases the pulsar has evaporated away its former companion star.

minimum stable circular orbit:
For a Schwarzschild black hole, the minimum radius for a stable circular orbit lies at about 3 times the Schwarzschild radius from the central singularity.

mini-Neptune:
An exoplanet with a mass that is a fraction of that of Neptune. (Also sometimes known as a super-Earth.)

Minkowski diagram:
See spacetime diagram.

Minkowski metric:
A sixteen component four-tensor that may be expressed as a matrix whose leading diagonal contains the elements 1, -1, -1, -1. All other elements of the matrix are zero. It can be represented by $[\eta_{\mu\nu}]$. (Nb. the choice of signs is just a convention and the Minkowski metric may be defined with the signs reversed from that given here.)

model:
A description of a system or process that aims to capture the essence of the true situation but incorporates various simplifications or idealizations. In physics, models are often of a mathematical nature, and are frequently designed to make mathematical analysis tractable.

model fitting:
The process of finding an appropriate mathematical model which best represents a set of data.

Modified Newtonian Dynamics.:
An alternative to dark matter used to explain galaxy rotation curves.

modulus sign:
The mathematical symbol || used to denote the magnitude of the enclosed quantity. For example, |-3.41| = 3.41. The terms ‘modulus’ and ‘magnitude’ are often used to mean the same thing.

molecular band:
Spectral features produced by absorption or emission of radiation by molecules. Typcially they are broader than spectral lines, and often found in the infrared part of the spectrum.

molecular cloud:
A cloud of dense cold gas containing molecules, principally molecular hydrogen (H2), together with dust. Molecular clouds are generally detected through emission lines of molecular species at radio frequencies; important species include CO, OH and CN. Because molecular clouds are cold and dense, they are important sites for star formation.

molecular viscosity:
Viscosity in a plasma that arises due to the thermal motion of ions. The magnitude of the corresponding kinematic viscosity is the deflection length times the sound speed.

molecule:
The smallest part of a given pure substance that retains the chemical identity of that substance. From a microscopic point of view, a molecule is a particular group of atoms bound together in a given way.

moment of inertia:

The moment of inertia about a given axis for a system of particles, or for a rigid body, is a measure of the distribution of the system's mass about that axis. For a system of particles with masses m_i at perpendicular distances r_i from the axis, the moment of inertia I is

$$I = \sum_i m_i r_i^2$$

A similar expression applies to a rigid body, but in that case, the continuous nature of the mass distribution means that the sum must usually be replaced by a definite integral. The SI unit of moment of inertia is the kg m^2.

momentum:
A vector quantity, useful in various situations as a measure of a body's tendency to continue in its existing state of rotational or translational motion. See angular momentum and linear momentum for further details.

monatomic:
A term indicating that the basic particles of a pure substance (usually a gas) are single atoms rather than molecules containing two or more atoms.

MOND:
MOdified Newtonian Dynamics.

monolithic collapse model:
A model for the formation of elliptical galaxies whereby they formed early in the history of the Universe ($z>2$) in a large starburst, followed by a phase of passive stellar evolution. See hierarchical structure formation model.

monopole problem:
Grand unified theories predict about one magnetic monopole per horizon size at the time the Universe was at the critical GUT temperature. Therefore the present day Universe should have many magnetic monopoles and they would dominate the energy density of the Universe. The fact that we see none is known as the monopole problem.

morphological K-correction:
A correction for the effect that observing high redshift galaxies in optical imaging might affect their observed morphology because this corresponds to rest-frame ultraviolet light. (The name reflects the photometric K-correction used to correct observed fluxes to fluxes in the rest frame of a cosmological source.)

morphology:
Technical term for shape.

morphology-density relation:
The relationship between the shape of a galaxy (elliptical, spiral, etc) and the density of its environment. Elliptical galaxies are more often found in galaxy clusters, spiral galaxies and irregular galaxies are more often found not in clusters.

Mossbauer effect:
Rudolf Mossbauer demonstrated, in 1958, that in some crystalline solids a significant number of relatively low energy gamma-ray emissions involve the whole crystal lattice, so absorbing the recoil momentum. In such cases, the movement of the emitting atom is very small and consequently the energy of the emitted gamma-ray photon is very well-defined.

M-theory:
An extension of string theory to include multi-dimensional branes.

multiplet:
A spectral line with multiple components due to fine structure sublevels in one or both of the energy levels involved in an atomic transition.

muon:
A type of elementary particle, similar to an electron, but with a mass that is about 207 times greater. Muons are unstable leptons that spontaneously decay with a mean lifetime of 2.2×10^{-6} s in a frame of reference in which they are at rest. Muons may occur with either positive or negative charge, the positive muon ($\mu+$) being the antiparticle of the negative muon ($\mu-$).

muon neutrino:

A type of elementary particle that has no known substructure and is therefore regarded as a truly fundamental particle. It is the partner to the muon in the second generation of leptons. It has spin 1/2, no charge and a mass of less than 0.17 MeV/c^2.

N

nabla:

The vector differential operator

$$\nabla = \left(\frac{\partial}{\partial x}, \frac{\partial}{\partial y}, \frac{\partial}{\partial z}\right)$$

The grad of a scalar field *T* is given by ∇T, the result of which is a vector field.

narrow-line clouds:
Clouds of material responsible for the narrow emission lines seen in the spectra of AGN. Narrow-line clouds are believed to be further from the central engine of AGN than are broad-line clouds. See narrow-line region.

narrow-line radio galaxy:
See radio galaxy.

narrow-line region:
The region responsible for producing the narrow emission lines seen in the spectra of active galaxies. See also quasar and Seyfert galaxy.

narrow-line region mass:
The total mass of the narrow-line region clouds.

narrow-line X-ray galaxy:
An active galaxy displaying narrow optical emission lines which is also a strong source of X-rays. They are Seyfert galaxies whose optical spectra are heavily reddened and extinguished by dust within the galaxy.

natural line width:
The width of a spectral line arising from fundamental quantum physical factors, irrespective of the environment in which the line was formed.

natural logarithm:
See logarithm to the base e.

N-body simulations:
Computer simulations involving many interacting particles.

nebula:
A cloud of gas and dust in space. Usually a large cloud in which a proportion of the atoms have been ionized to form a plasma.

neon burning:

A nuclear fusion process in which neon nuclei undergo photodisintegration, releasing an alpha-particle which is then captured by another neon nucleus to produce magnesium. The process can become the dominant form of core energy production in the post-main-sequence life of initially massive stars ($M_{ms} \geq 10M_{\odot}$) following a period dominated by carbon burning.

neutralino:
A hypothetical particle which may be a component of dark matter. It is a partner particle to the neutrino predicted by supersymmetry and an example of a Weakly Interacting Massive Particle (WIMP).

neutrino:

A spin ½ uncharged lepton of very small mass. Three different types of neutrino are known; electron neutrino, muon neutrino and tauon neutrino.

neutron:
An uncharged elementary particle with mass 1.675×10^{-27} kg (about 0.1% greater than that of the proton), and spin 1/2. Neutrons are non-strange baryons, and, when free, are unstable, having a mean lifetime of about 15 minutes. They are found in the nucleus of every atom (except for the lightest isotope of hydrogen).

neutron-capture cross-section:
The fusion cross-section for neutron-capture reactions.

neutron-capture reaction:

A nuclear fusion reaction of the form

$$^{A}_{Z}X_{N} + n \rightarrow {}^{A+1}_{Z}X_{N+1} + \gamma$$

or equivalently

$$^{A}_{Z}X_{N}(n,\gamma)\,^{A+1}_{Z}X_{N+1}$$

in which a more neutron-rich isotope of an element is produced. If the resultant nucleus is unstable it will beta-decay via the process

$$^{A+1}_{Z}X_{N+1} \rightarrow {}^{A+1}_{Z+1}[X+1]_{N} + \mathrm{e}^{-} + \bar{\nu}_{\mathrm{e}}$$

(see s-process) unless another neutron capture occurs first (see r-process).

neutron drip:
Under conditions of extremely high density $\rho \sim 10^{14}$ kg m^{-3}, the most stable nuclei are those with large neutron excesses compared to normal. At still higher densities, $\rho \sim 4 \times 10^{14}$ kg m^{-3}, free neutrons 'drip' from the nuclei, giving rise to a sea of nuclei, electrons, and free neutrons.

neutronization:
The fusion of an electron with a proton in a nucleus to produce a neutron, thus reducing the atomic number Z of the nucleus by 1 and increasing the neutron number N by 1. Neutronization occurs in the high density of compact stellar remnants, and produces neutron-rich isotopes prior to neutron drip occurring.

neutron magic number:
See closed neutron shells.

neutron number:
The number of neutrons in a specified nucleus. The neutron number is usually represented by the symbol N and is equal to the difference between the mass number A and the atomic number Z, so $N = A - Z$.

neutron star:
A stellar-mass object supported against gravitational collapse by the degeneracy pressure of neutrons. A neutron star is expected to form in the final stages of the life of a massive star; at extremely high densities and pressures it becomes energetically favourable for protons and electrons to merge (inverse beta-decay). Neutron stars have radii of order ~ 10 km and densities comparable to those of atomic nuclei (~ 10^{17} kg m^{-3}). There is an upper limit on the mass that can be supported by neutron degeneracy pressure, known as the Oppenheimer-Volkoff limit (analogous to the Chandrasekhar mass for a white dwarf), of about 2.5 solar masses. Pulsars are rapidly rotating magnetized neutron stars.

newton:
The SI unit of force, represented by the symbol N, and defined by the relation 1 N = 1 kg m s^{-2}. An unbalanced force of magnitude 1 N will cause a particle of mass 1 kg to accelerate at 1 m s^{-2} in the direction of the force.

Newtonian mechanics:
This is a branch of physics which attempts to explain the motion of objects in terms of the forces acting on them. It is based on Newton's laws of motion and incorporates other important principles, such as the laws of conservation of energy, conservation of linear momentum, and conservation of angular momentum.

Newton's first law of motion:
A law stating that a body remains at rest or in a state of uniform motion unless it is acted on by an unbalanced force. Newton's first law presupposes the use of an inertial frame of reference. Given that such a frame is used, the law implies that a particle moving along the x-axis, that is free from any unbalanced force, will obey the uniform motion equations: $s_x = u_x t$, $v_x = u_x$ and $a_x = 0$.

Newton's law of universal gravitation:
See law of universal gravitation.

Newton's second law of motion:

A law stating that an unbalanced force acting on a body of fixed mass will cause that body to accelerate in the direction of the unbalanced force, and that the magnitude of the force is equal to the product of the mass and the magnitude of the acceleration: $\boldsymbol{F} = m\boldsymbol{a}$.

Newton's second law presupposes the use of an inertial frame of reference. Given that such a frame is used, the law implies that a particle of mass m subject to an unbalanced force with component F_x in the x-direction will obey the equation $F_x = ma_x$. For a system of particles, or an extended body, the law implies that the resultant external force is equal to the total mass times the acceleration of the centre of mass.

Newton's second law may be expressed in terms of momentum as follows. The resultant force acting on a body is equal to the rate of change of the body's momentum: $\boldsymbol{F} = \mathrm{d}\boldsymbol{p}/\mathrm{d}t$. For a system of particles or an extended body this implies that the total external force is equal to the rate of change of the total linear momentum.

Newton's theorem:
A theorem stating that the gravitational effect of any spherically symmetric body, outside its own surface, is identical to that of a single particle, with the same mass as the body, located at the centre of the body.

Newton's third law of motion:
A law stating that if body A exerts a force on body B, then body B exerts a force on body A, and that these two forces are equal in magnitude but act in opposite directions. In vector notation, the law implies that $\boldsymbol{F}_{AB} = -\boldsymbol{F}_{BA}$, where $\boldsymbol{F}_{AB}$ is the force on A due to B, and $\boldsymbol{F}_{BA}$ is the force on B due to A. Such a pair of forces is sometimes called a Newton's third-law pair.

N galaxy:
(Nuclear galaxy) A galaxy with a stellar-like nucleus identified by Morgan in 1958.

Several of these have subsequently turned out to be Seyfert galaxies or BLRGs.

NLR:
See narrow-line region

noble gas:
The elements He, Ne, Ar, Kr, Xe whose atoms have filled electron shells and which consequently are chemically inert. These elements occupy the far right column of the periodic table.

Noether's theorem:
The fact that symmetries in the Lagrangian of a system imply conservation laws.

non-Euclidian geometry:
Geometry in which none of the results of Euclidian geometry is necessarily true,

non-Gaussian:
A distribution which does not take the form of a Gaussian distribution.

non-relativistic particle:

A particle whose speed is significantly less than the speed of light, $v << c$.

non-thermal:

A term used to describe either a distribution of particles whose energies cannot be described by a Maxwell-Boltzmann energy distribution, or the spectrum of radiation from such a distribution of particles. For example, the energetic electrons that produce synchrotron emission in radio galaxies have a distribution of energies given by a power law distribution,

$$N(E) \propto E^{-\alpha}$$

where $N(E)\,dE$ is the number density of particles with energies in the range E to $E + dE$. This is clearly not a Maxwell-Boltzmann distribution – it has no well-defined temperature – and accordingly, both the electrons themselves and the synchrotron radiation from the electron population are described as non-thermal. See thermal radiation.

non-thermal spectrum:
A spectrum produced by a non-thermal process, such as synchrotron radiation.

norm:

In describing geodesic motion, if a curve is specified by the coordinate functions $x^\rho(\lambda)$, then the components of the tangent vector to the curve at the point specified by λ are $t^\rho(\lambda) = d\,x^\rho(\lambda)/d\lambda$.The 'length' of this tangent vector may be defined as $\Sigma_{\alpha,\beta} t^\alpha t^\beta$ and is called the norm.

In the case of an affinely parameterized geodesic, this norm will be the same at all points. For time-like geodesics, the norm is always positive; for null geodesic, the norm is zero; for space-like geodesics, the norm is negative.

normal distribution:
See Gaussian distribution.

nova:
A sudden, dramatic brightening of a star in a binary system. Novae are divided into the categories of dwarf nova and classical nova; both are thought to be the results of accretion involving a white dwarf, though the underlying physical processes are quite different. See cataclysmic variable.

nova-like variable:
A member of a subgroup of cataclysmic variables with stable accretion discs. Spectroscopically they appear similar to dwarf novae in outburst.

nova shell:
The outermost shell of an accreting white dwarf that is ejected from the system as a result of a classical nova outburst.

NSE:
See nuclear statistical equilibrium.

nuclear binding energy:
See binding energy.

nuclear bulge:
The central region of a *galaxy*.

nuclear fusion:
A processes in which two nuclei 'fuse' together to form a heavier nucleus. If the nucleus produced has mass number $A \leq 56$ (e.g. ^{56}Fe) or thereabouts, the process is likely to be exothermic, i.e. it will release energy. Fusion is crucial in stars for both energy release and for the production of the lighter elements, from helium up to iron

(Fe), from primordial hydrogen. Fusion reactions are also the basis for the energy released in hydrogen bombs.

nuclear reaction:

A process in which an atomic nucleus interacts with another nucleus or some other kind of particle (such as a neutron or a photon) to produce one or more nuclei or to excite the original nucleus in some way.

Nuclear reactions are often indicted by showing the symbols representing the incoming and outgoing particles in brackets, sandwiched between the initial and final nuclei. For example, the capture of an alpha-particle by a silicon nucleus to produce a sulphur nucleus with the emission of a gamma-ray is represented by

$$^{28}_{14}\mathrm{Si}(\alpha,\gamma)^{32}_{16}\mathrm{S}$$

nuclear resonance:

A strong enhancement in a fusion cross-section over a narrow energy range caused by the existence of excited states of the product nucleus. Resonances can be extremely important for overall fusion rates, for example in the penultimate stage of the triple-alpha reaction, $^{8}\mathrm{Be} +^{4}\mathrm{He} \leftrightarrow^{12}\mathrm{C}^{*}$.

nuclear statistical equilibrium:

A state in which the relative rates of different nuclear reaction processes become independent of time, with the consequence that the numbers of different nuclei produced by those reactions have a fixed ratio. During silicon burning, α-capture (α, γ) and photodisintegration (γ, α) reactions are in equilibrium. The result is that the production of the most stable nuclei, i.e. those with the lowest binding energy per nucleon, is preferred. The equilibrium distribution has a peak in abundance around ^{56}Ni, which β^+-decays to ^{56}Fe, accounting for the iron peak nuclei.

nucleon:
A term used to mean either a proton or a neutron.

nucleosynthesis:

The formation of heavy nuclei by nuclear reactions.

'Primordial' nucleosynthesis is thought to have taken place in the very early life of the Universe, according to the Big Bang cosmological model; this formed mostly helium and deuterium, together with a much smaller amount of lithium and beryllium. The agreement of the predictions of this model with the observed abundances of deuterium and lithium provides one of the key foundations of Big Bang cosmology.

However, the epoch of primordial nucleosynthesis did not last long enough to produce the heavier elements, such as carbon, nitrogen, oxygen and silicon. These are the results of 'stellar nucleosynthesis', and are formed principally in helium-burning stars. The first heavy element to be synthesized this way is carbon, in the isotope ^{12}C, formed from the fusion of three helium nuclei (the triple-alpha process); then successive additions of helium produce ^{16}O, ^{20}Ne and so on up to iron (^{56}Fe) and the other iron peak nuclei.

Nucleosynthesis by fusion cannot proceed further, because energy input is required to make heavier elements; however, neutron capture, either slowly through the s-process or rapidly, e.g. in supernovae, by the r-process, can allow the synthesis of much more massive nuclei. The heavy elements produced in stars are returned to the interstellar medium through mass loss from stars, including supernovae, and increase the observed metallicity of the interstellar gas and of subsequent generations of stars (see population I, population II).

nucleus:

(1) The positively charged core of an atom, which accounts for nearly all of its mass. A nucleus consists of one or more protons and a number of neutrons. See also atomic number, mass number and neutron number.

(2) The central regions of a galaxy, see for example active galactic nuclei.

nu eff nu:

The quantity given by frequency (nu, v) multiplied by spectral flux density (eff nu, Fv). It is often plotted against frequency to present a spectral flux distribution in a way which emphasises the power output of an astronomical source across a wide range of frequencies. See lambda eff lambda.

null curve:
A curve for which the line element is zero at every point.

null geodesic:
A geodesic that is a null curve. Consequently, it cannot be defined as the shortest distance between the end points of the curve. However, the definition as a curve along which the tangent always points in the same direction is still valid.

number count:
A relationship of the form dN/d$S \propto S^{-\alpha}$ used to describe the number of stars dN in a flux interval dS.

number density:
The number of particles per unit volume, usually represented by the symbol n. The SI unit of number density is m^{-3}.

number fraction:
The number of particles per unit volume of a given type divided by the total number of particles per unit volume. See also mass fraction.

numerical modeling:
A technique of using a computer program to solve a set of equations. In the case of orbital dynamics, the positions and velocities of each body in the system are input, and used to calculate the forces on each other body. The positions and velocities of each body are then incremented over a small time-step, using these forces, and then the whole process is repeated.

Nyquist frequency:
The highest frequency available in a set of measurements made at discrete times. Given by $1/2\Delta T$ where ΔT is the time resolution of the measurements.

O

obscured broad-line region:
An obscured region in Seyfert 2 galaxies. Unified models suppose that Seyfert 2 galaxies contain a broad-line region, similar to that responsible for the broad emission lines seen in the spectra of Seyfert 1 galaxies, but that it is obscured by a dusty torus. Infrared observations of some Seyfert 2 galaxies reveal the existence of an obscured broad-line region by the detection of broad infrared lines.

obscured quasar:
The infrared spectrum of an ultraluminous infrared galaxy sometimes reveals the presence of broad infrared lines. These ULIGs are therefore suggested to harbour obscured quasars, in the same way that many Seyfert 2 galaxies harbour obscured broad-line regions as seen in Seyfert 1 galaxies.

obscuring torus:
The torus of dusty material believed to encircle AGN and to be responsible for hiding the broad-line region when the AGN is viewed from certain orientations.

observable universe:
The region bounded by the particle horizon, which currently lies at a proper distance of about 46 billion light-years or 15 Gpc.

observer:
An individual dedicated to using a particular frame of reference for recording events.

off-band image:
An image of an astronomical object obtained through a filter whose bandpass is centred on a line free region of the spectral continuum, adjacent to the particular emission line for which an on-band image has been obtained.

OGLE:
The Optical Gravitational Lens Experiment. A Polish survey for microlensing events in the Galactic bulge and Magellanic clouds aimed at detecting dark matter, but with the side effect of discovery several exoplanets.

Olbers' paradox:

The apparent paradox posed by the question, if the Universe is infinite, then every line of sight should end on a star, so why isn't the night sky as bright as the Sun?

It is solved by the realization that the Universe is only finitely old and that the Universe comprises a curved, expanding spacetime.

on-band image:
An image of an astronomical object obtained through a filter whose bandpass is centred on a particular emission line. An emission line image is obtained by subtracting an off-band image from an on-band image.

ON cycle:
See oxygen-nitrogen cycle.

ONeMg white dwarf:

A white dwarf composed chiefly of oxygen, neon and magnesium, formed from the core of a star whose initial mass was between $8M_{\odot}$ and $11M_{\odot}$. They will have masses in the range $1.2M_{\odot}$ to $1.4M_{\odot}$.

onion-skin structure:
The layered structure of a massive star near the end of its life, comprising zones of progressively more advanced nuclear burning towards the core where the temperature is higher.

Oort cloud:
The presumed reservoir of comets existing in the outer reaches of the Solar System.

opacity:

A quantity used to describe the ability of a material to block electromagnetic radiation. It is usually given the symbol κ and is expressed as an absorption cross-section per unit mass (SI units of $m^2 kg^{-1}$). Opacity is caused by a variety of physical processes, including bound-bound atomic transitions, bound-free transitions, free-free interactions and electron scattering. In stars with temperatures comparable to that of the Sun, a combination of bound-free and free-free interactions is most important, and this gives rise to a Kramers opacity. See also optical depth.

open cluster:
A loose cluster of stars, containing between a few tens and a few thousands of stars. Open clusters are not strongly gravitationally bound together (unlike globular clusters) and are expected to disperse with time due to the random motions of the component stars and the differential rotation of the Galaxy. Open clusters therefore typically contain relatively young, population I stars whose association is a result of having been formed from the same interstellar gas cloud.

open hypersurface:
A hypersurface with curvature parameter k=-1.

open universe:
A universe, in the Big Bang cosmological model, in which the density is not high enough to halt the expansion of the universe. An open universe will expand forever. Compare with closed universe.

Oppenheimer-Volkoff limit:
The theoretical upper limit to the mass of a neutron star, about $2.5M_{\odot}$. contrast with Chandrasekhar limit.

opposition:
When referring to planets in the solar system, opposition corresponds to the situation when a planet is on the far side of the Sun to the Earth, i.e. at superior conjunction with respect to our line of sight.

optical depth:

A quantity used to describe the transparency of a region of space containing obscuring material to electromagnetic radiation of a certain wavelength. If a region of space has an optical depth t at a given wavelength, then the measured flux of light that has passed through that region is reduced by a factor exp(-t) compared with what would be expected if there were no obscuration. The medium is transparent if t = 0; if t is much less than 1 the medium is said to be optically thin (almost all photons are unabsorbed) while if t is much greater than one it is optically thick (almost all photons are absorbed). The optical depth of a region can be related to its opacity by

$$\tau = \int \kappa(z)\rho(z)\mathrm{d}z$$

where κ is the opacity at the wavelength of interest, ρ is the density, and the integral is carried out along the line of sight through the region.

optical flash:
A short lived flare in optical light observed following some gamma-ray bursts. In some cases, optical flashes can reach naked-eye magnitudes.

optical interferometer:
See interferometer.

optically thick:
See optical depth.

optically thin:
See optical depth.

optically violent variable:
A member of a subset of blazars. See OVV quasar.

optical/X-ray spectral index:

The ratio of the flux in the X-ray band to that in the optical band, defined as:

$$\alpha_{\mathrm{ox}} = -0.384 \log \left[\frac{F_\nu(2\ \mathrm{keV})}{F_\nu(2500\ \mathring{A})} \right]$$

For AGN it is typically found that $a_{\mathrm{ox}} \sim 1.4$.

orbital angular momentum:
Angular momentum associated with the orbital motion of a system such as the two component stars in a binary. The total angular momentum of a binary is in general larger than the orbital angular momentum, as there is also spin angular momentum due to the rotation of the stars.

orbital angular momentum quantum number:

A quantum number, conventionally represented by the symbol l, that characterizes the magnitude L of the orbital angular momentum of an electron in an atom:

$$L = \sqrt{l(l+1)}\hbar$$

The quantum number l can take integer values from 0 to n - 1, where n is the principal quantum number.

orbital light curve:
The variation in light received from an astronomical body as it undergoes an orbit around another body. The phrase is most often used to refer to the light from a star in a binary, whereas the equivalent variation in light from a planetary body in a similar orbit would be referred to as a phase curve.

orbital magnetic quantum number:

A quantum number, conventionally represented by the symbol m_l, that determines the z-component, L_z, of the orbital angular momentum of an electron in an atom:

$$L_z = m_l\hbar$$

The quantum number m_l can take the values m_l = 0, ±1, ±2, … ±l, where l is the orbital angular momentum quantum number.

orbital parameters:
The semi-major axis a, eccentricity e, true anomaly θ, and longitude of periastron ω, used to characterise any orbit.

orbital phase:
The fraction of an orbit at a given instant of time, expressed as either an angle (between 0° and 360° or between 0 and 2π radians) or a number (between 0 and 1).

orbital resonance:
See mean motion orbital resonance; secular resonance; Kozai resonance.

origin:
An arbitrarily chosen reference point from which coordinates are measured in a coordinate system. In one dimension, the origin is the point at which the position coordinate is zero.

orthogonal:
Property of vectors or lines being at right angles to each other.

orthogonality:
Referring to a pair of functions which depend on parameters n and m, such that the integral over the product of the functions is equal to zero unless $n = m$.

OVV:
See OVV quasar.

OVV quasar:
An active galaxy member of a class of quasars that are 'optically violently variable', exhibiting large-amplitude, rapid changes in the optical flux. Together with BL Lac objects they form the group known as blazars.

oxygen burning:

A nuclear fusion process following neon burning in initially massive ($M_{ms} \geq 10 M_{\odot}$) stars in which oxygen nuclei fuse to produce silicon and sulphur.

oxygen-nitrogen cycle:
A nuclear fusion process involving isotopes of oxygen, nitrogen and fluorine that are used as catalysts in the conversion of H to He. The ON cycle runs in conjunction with the carbon-nitrogen cycle if temperatures are high enough. See CNO cycle.

P

Paczynski's approximation:

In a semidetached binary star system, where one of the stars fills its Roche lobe, an approximation for the Roche lobe radius of the donor star is given by a formula due to Paczynski:

$R_{L,2} / a = 0.462(M_2/M)^{1/3}$

where a the orbital separation of the two stars, M_2 is the mass of the donor star and the total mass of the system is $M=M_1+M_2$. The approximation is accurate to within 2% for mass ratios $q<0.8$.

PAH:
See polycyclic aromatic hydrocarbon.

pair production:
See electron–positron pair production.

Palomar Sky Survey:
An optical survey of the northern sky and part of the southern sky carried out with the 48-inch telescope at the Mount Palomar Observatory, California and released in the 1950s. The original observations were in red and blue filters and go down to a limiting apparent magnitude around 21. A second, deeper survey was carried out in the 1980s–90s.

Pan-STARRS:
The Panoramic Survey Telescope and Rapid Response System. An observatory being built in Hawaii to continually monitor the sky in order to detect potentially hazardous near Earth asteroids, as well as other moving or photometrically varying objects.

paraboloid:
The three-dimensional shape obtained by rotating a parabola ($y = kx^2$) around the $x = 0$ axis.

parallax:

The apparent displacement in position of an object when viewed from two widely separated points. In an astronomical context, the rotation of the Earth and its motion about the Sun mean that the position at which we observe astronomical objects changes with time (this is in addition to the effect of the objects' proper motion, which must be taken into account when trying to measure parallax).

The most important form of parallax is the parallax resulting from the Earth's motion around the Sun, which is known as 'annual parallax'. This gives a maximum distance between observations of two Earth–Sun radii, or 'astronomical units'. The maximum apparent angular displacement on the sky of a distant object, due to this annual motion, is then twice the parallax angle π, which is the arctangent of the Sun–Earth distance $\boldsymbol{r}_{AU}$ divided by the distance to the object d.

Because the astronomical unit is very much smaller than the distance to most astronomical objects, the angles involved are usually very small, so a small angle approximation can be used: $\pi = \boldsymbol{r}_{AU}/d$, where π is in radians (but see parsec).

Given the Earth–Sun distance, parallax measurements can be used to determine the distance to any object whose parallax angle can be measured accurately. In the 1990s, this was carried out to high precision for a large number of nearby stars using the Hipparcos satellite. Parallax distance measurements for the nearest stars provide the starting point for more indirect methods of measuring larger distances, for example by calibrating standard candles.

parallax angle:
See parallax.

parallelogram rule:
A graphical method of determining the resultant $\boldsymbol{a} + \boldsymbol{b}$ of two given vectors $\boldsymbol{a}$ and $\boldsymbol{b}$. Any vector can be represented graphically by an arrow, with a length that represents the magnitude of the vector and an orientation that represents the direction of the vector. To construct the arrow representing the resultant $\boldsymbol{a} + \boldsymbol{b}$, first draw an arrow to represent the vector a, then, starting from the same origin, draw a second arrow to represent the vector $\boldsymbol{b}$. Complete the parallelogram by drawing two further sides, one parallel to each of the original two vectors. The resultant $\boldsymbol{a} + \boldsymbol{b}$ will then be represented by an arrow drawn from the origin to the opposite corner of the parallelogram.

parallel transport:
The movement of a vector along a curve, preserving the direction of the original vector throughout each infinitesimal step.

parameter:
A quantity that is constant in a particular case but may vary from one case to another.

parameter degeneracies:
In cosmology, the fact that constraints on one cosmological parameter can correlate with constraints on another.

parameterized curve:
A curve for which the coordinates are functions of a single variable

parent population:
The distribution from which a sub-sample is drawn.

parsec:
A unit of distance, equal to 3.0857×10^{16} m. By definition it is the distance at which the Sun–Earth distance (one astronomical unit, see parallax) would subtend an angle of one arc second. Consequently, if a star has a measured parallax of π arc seconds, then its distance is $d = 1/\pi$ parsecs. This makes the parsec a convenient unit for measuring distances outside the Solar System.

partial derivative:

The result of differentiating a function of two or more variables, treating all but the variable of differentiation as constant. The partial derivative of $f(x, y)$ with respect to x is written

$\frac{\partial f}{\partial x}$

partial differential equation:
A differential equation that involves partial derivatives of a function.

partially degenerate:
See degenerate matter.

partially ionized zone:
The partially ionized region outside of the Strömgren sphere around an AGN which gives rise to enhanced Balmer series emission and can help to explain departures from standard case B recombination line ratios.

particle:

(1) In the context of classical physics a particle is an object that has no spatial extent and can therefore be thought of as existing at a single point in space. It has no size, shape or internal motion though it may have intrinsic properties such as mass and charge, as well as position, velocity and acceleration. Although the concept of a classical particle is an idealization, the centre of mass of an extended body moves just like a particle with the same mass as the body, subject to the combined effect of the external forces acting on the object.

(2) In the context of particle physics a particle (also known as an 'elementary particle' in this context) is a piece of matter that is of subnuclear size. Such particles include protons and neutrons, as well as electrons and quarks, and may or may not be truly fundamental constituents of matter.

particle exponent:
The index of the power law distribution describing the relative number of particles with a particular energy, i.e. the quantity *s* in the expression $N(E)\mathrm{d}E = N_0 E^{-s}\mathrm{d}E$.

particle horizon:
The location in spacetime of a signal that travels with the speed of light from the origin of time and space. It currently lies at a proper distance of about 46 billion light-years or 15 Gpc.

Paschen series:
The series of hydrogen spectral lines arising in atomic transitions whose lowest energy level is that with n = 3. Contrast with Balmer series, Lyman series, Brackett series.

passive stellar evolution:
Referring to the phase of evolution of a galaxy during which no star formation takes place. So the change in a galaxy's colours are purely as a result of the evolution of existing stars.

pathlength:
The distance travelled through a medium.

Pauli exclusion principle:

A principle asserting that no two electrons can occupy the same quantum state. Thus, for example, if two electrons in a particular atom have the same values of the principal quantum number *n*, the orbital angular momentum quantum number *l* and the orbital magnetic quantum number m_l, they must also have opposite spin magnetic quantum number, i.e.

$$m_s = +\frac{1}{2}$$

for one, while for the other

$$m_s = -\frac{1}{2}$$

Pauli pressure:
The pressure exerted by a gas of fermions as a direct consequence of Pauli's exclusion principle. When a system of fermions (such as electrons or neutrons) is at a relatively low temperature, the energy levels of the system fill from the ground state upwards. Because of the exclusion principle many particles are forced into quite high energy levels, in spite of the relatively low thermal energy. These particles have a high average translational energy and, by the usual kinetic theory argument, give rise to a large pressure, it is this that constitutes the Pauli pressure. The electrons in a white dwarf star provide an example of this phenomenon: the star is supported against gravitational collapse by the Pauli pressure exerted by its electrons. See also degenerate matter.

P(D) analysis:
The process of constraining the shape of the source count slope by considering the histogram of pixel values in a confusion-limited map. D is the deflection from the mean in the map and P is the probability of that deflection.

peculiar motion:
See peculiar velocity.

peculiar velocity:

The velocity observed between galaxies, e.g. within the Local Group, relative to the large scale expansion of the Universe and therefore not part of the Hubble flow.

pencil-beam survey:
A narrow-field, deep survey, such as the Hubble deep field, covering a long and thin volume of the Universe. See wide-field survey.

Penrose process:
A process by which energy may be extracted from a rotating black hole. If an unstable particle enters the region between the static limit and the outer event horizon of a Kerr black hole, and while there decays to form two other particles, one of the two particles may then enter the black hole. The other decay product may pass out through the static limit and carry away more energy from the black hole than the original particle carried in. As a result, the energy and angular momentum of the black hole are reduced. Compare with Hawking radiation.

perfect fluid:
A fluid that can be completely characterized by its rest frame energy density and isotropic pressure.

periapsis:
See pericentre.

periastron:
The point in the orbit of a binary star (or, more generally, any orbit about a star other than the Sun) at which the orbiting bodies have their minimum separation. Contrast with apastron, at which the bodies have their minimum separation.

periastron precession:
See perihelion precession.

pericentre:

The point in an orbit that lies closest to the centre of mass of the system. In the case of binary stars, the point of minimum separation is called the periastron; in the case of orbits around the sun, this is referred to as the perihelion.

Contrast with apocentre, which is the point in an orbit that lies furthest from the centre of mass of the system.

pericentre precession:
See perihelion precession.

perihelion:
The point in the orbit of a body around the Sun at which the orbiting body has its minimum separation from the Sun. Contrast with aphelion, at which the orbiting body has its maximum separation from the Sun.

perihelion precession:

The movement of the perihelion of a planet in its orbit around the Sun (or in general the movement of the pericentre of an orbiting body around any star, or the movement of the periastron in a binary star). The change in orbital orientation arises from the (Newtonian) gravitational effect of the other planets in the Solar System and the effect of general relativity.

The effect of general relativity is such that, for each orbit, the perihelion (or pericentre, or periastron) advances by an angle $\Delta\phi$ given by $\Delta\phi = 6\pi GM/a(1-e^2)c^2$ where M is the total mass of the system, a is the semi-major axis of the orbit and e is its eccentricity.

period:
The minimum time needed for a repetitive action to recur. If the action can be described by a periodic function $f(t)$, then the period T is the smallest value such that $f(t + T) = f(t)$ for all t. An example is the time $T = 2\pi/\omega$ for a simple harmonic oscillator (described by $x = A \sin(\omega t + \phi)$) to complete one full cycle. Other examples include the period of an elliptical orbit, the period of rotation of a spinning body, and (in the context of waves) the time interval between one part of a wave passing a fixed point and the next identical part of the wave passing the same fixed point.

period distribution:
The distribution function of the period of a certain phenomenon in a certain class of objects (e.g. the orbital period in cataclysmic variables).

periodic table:
An arrangement of all the elements according to their atomic number, starting from hydrogen at the upper-left, increasing from left to right and from top to bottom. Elements are grouped according to chemical properties, which reflect the degree to which each atom's electron shells are filled. Each row ends with a noble gas element which has full electron shells.

permeability of free space:
The physical constant, μ_0 (= $4\pi \times 10^{-7}$ T m A^{-1} = $4\pi \times 10^{-7}$ kg m C^{-2}), that plays a role in determining the magnetic pressure.

permitted line:
An emission line that is permitted by the selection rules governing atomic transitions. See forbidden line.

permitted transition:
Any radiative transition corresponding to a change in quantum numbers that satisfies the relevant selection rules. For an electron in a spherically symmetric atom, these rules require that $\Delta l = \pm 1$ and $\Delta m_l = 0$ or ± 1. Permitted lines in spectra are produced as a result of atomic transitions which give rise to electric dipole radiation. Contrast with forbidden transition.

permittivity of free space:
The physical constant ε_0 (= 8.854×10^{-12} C^2 N^{-1} m^{-2}), that plays a role in determining the magnitude of the electrostatic force.

phase:
A measure of the stage in its cycle that an oscillator has reached at a specified time, or the stage that a wave has reached at a specified time and position. In the case of a simple harmonic oscillator described by $x(t) = A \sin(\omega t + \phi)$, the phase is $\omega t + \phi$, where ω is the angular frequency and ϕ is the phase constant or initial phase. Similarly, in the case of a travelling wave represented by the equation $y(x, t) = A \sin(kx - \omega t + \phi)$, the phase is $(kx - \omega t + \phi)$, where k is the angular wavenumber. Two waves are said to be 'in phase' if their phases are equal at a particular point in space and instant of time; they are said to be 'out of phase' if their phases differ by exactly π at that point and instant.

phase angle:
Used to describe the position of an object in an orbit. The phase angle is zero when the object in question is at superior conjunction (i.e. furthest from the observer) and is 180 degrees when the object is at inferior conjunction (i.e. nearest to the observer).

phase constant:
The constant part of the phase of an oscillation or a wave, usually represented by the symbol ϕ. The phase constant is sometimes called the 'initial phase', since it determines the phase of the oscillation (or wave) at $t = 0$ (and $x = 0$).

phase curve:
The variation in light received from a planetary body as it completes an orbit around a star. Equivalent to an orbital light curve.

phase function:

The flux of light reflected by an astronomical object at a certain phase angle in its orbit, relative to the flux at superior conjunction.

For a planet in orbit around a star, the ratio of the flux at the observer reflected from the planet to the flux observed directly from the star is

$$\frac{f_{P,\lambda}(\alpha)}{f_{*,\lambda}} = \left(\frac{R_P}{a}\right)^2 p_\lambda \Phi_\lambda(\alpha)$$

where R_P is the radius of the planet, a is the orbital separation of the star and planet, p_λ is the wavelength dependent geometric albedo and $\Phi_\lambda(\alpha)$ is the phase function at phase angle α.

phase space:
An imagined multi-dimensional space. For example, the six-dimensional space in which the coordinates of a particle are its three (x,y,z) position coordinates and its three (p_x, p_y, p_z) momentum values.

phase space density:

The density in an imagined multi-dimensional volume of space.

For example, the volume that a galaxy occupies in an imagined six-dimensional space of three spatial dimensions and three velocity axes. It may be estimated by dividing the mass density of the galaxy by the volume of an ellipsoid whose axes are equal to the velocity dispersions in each of the three velocity axes.

phase variation:
The observed change in brightness seen from an astronomical body (e.g. star or planet) as it orbits another body.

phenomenonological law:
A law based on experience with no deeper justification that the fact that it works.

photodisintegration:

The breakup of a nucleus into small parts due to the absorption of a photon - typically a γ-ray - whose energy exceeds the binding energy of the compound nucleus.

photodissociation:
Another word for photodisintegration.

photoionization:

The ionization of an atom by the absorption of a photon. See also bound-free transition.

photoionization equilibrium:
The state in which the photoionization rate equals the recombination rate. See Strömgren radius.

photoionized:
See photoionization.

photolysis:
Decomposition of water by photons.

photon:

A particle of electromagnetic radiation. More properly, a quantum of the electromagnetic field. For monochromatic radiation of frequency v the quantum of energy is, according to Planck's law, $E = hv$ where h is Planck's constant. Each photon of that radiation will carry just one quantum of energy and will also carry momentum $\boldsymbol{p}$ of magnitude $p = h/\lambda$, where λ is the wavelength of the radiation. Viewed as an elementary particle, the photon is the exchange particle for the electromagnetic interaction. It has *spin* 1, no charge, zero mass, and is stable. It is usually represented by the symbol γ.

photon index:

The power law index Γ in the expression often used to describe X-ray spectra from active galaxies, $P_E \propto E^{-\Gamma}$ where P_E is the flux in units of photons per second per keV.

photon sphere:
The distance of 1.5x the Schwarzschild radius from a non-rotating black hole within which a photon is certain to be captured by the black hole.

photosphere:
The effective surface of a star, from which the observed light is emitted. It is a region some hundreds of km thick (for a Sun-like star) over which the stellar material becomes transparent to optical photons (see opacity, optical depth). The solar photosphere is the source of the absorption lines that tell us the chemical composition of the Sun. It is also the region of the Sun that is observed to move in helioseismology.

photospheric radius:

(Of a gamma-ray burst) - the radius at which the fireball becomes transparent to its own radiation. The photospheric radius must be greater than the saturation radius in all observed GRBs. It may be expressed as

$$r_{\mathrm{ph}} \simeq 10^{11}\left(\frac{E_0}{10^{44}\,\mathrm{J}}\right)^{1/2}\left(\frac{300}{\gamma_s}\right)^{1/2}\mathrm{m}$$

where where the Lorentz factor has a maximum value of $\gamma_s = E_0/Mc^2$ and E_0 is the energy of the explosion and M is the mass involved.

physical laws:
Mathematical equations used by physicists to summarize their findings regarding the basic principles that govern the Universe.

pion:

The collective name for three light subatomic particles, the π^+, π^0 and π^-. All three have short lifetimes and can only be observed by their decay products – which include charged particles in the case of the charged pions, but mainly consist of pairs of photons in the case of the π^0.

PIZ:
See partially ionized zone

Planck constant:
The constant h (= 6.626×10^{-34} J s or 4.15×10^{-15} eV Hz^{-1}) introduced by Max Planck to explain the radiation emitted by black bodies. It also appears in Einstein's theory of the photoelectric effect and in the Planck–Einstein formula. In fact, it appears in practically every equation of quantum mechanics but never in those of classical physics.

Planck–Einstein formula:

The formula

$E = hv$

that relates the energy E of a photon of monochromatic electromagnetic radiation to the frequency v of that radiation where $h = 6.63 \times 10^{-34}$ J s is the Planck constant.

Planck energy:

A fundamental energy scale, given by $E_{Pl} = (hc^5/2\pi G)^{1/2} = 1.22 \times 10^{19}$ GeV. See Planck length, Planck mass, Planck time.

Planck function:

The function that describes the distribution of photon energies for a black body spectrum. Black body radiation is continuum radiation, with a characteristic peak wavelength that depends on temperature (see Wien displacement law). The shape of the spectrum can be given in terms of the power emitted per unit area per unit wavelength per unit time per unit solid angle, B_λ by

$$B_\lambda(T)=\left(\frac{2hc^2}{\lambda^5}\right)\frac{1}{\exp\left(\frac{hc}{\lambda kT}\right)-1}$$

or in terms of the power emitted per unit area per unit frequency per unit time per unit solid angle, B_ν by

$$B_\nu(T)=\left(\frac{2h\nu^3}{c^2}\right)\frac{1}{\exp\left(\frac{h\nu}{kT}\right)-1}$$

where T is the temperature, h the Planck constant, c the speed of light, k the Boltzmann constant and λ or ν is the wavelength or frequency of the radiation; B_λ has SI units W m^{-2} m^{-1} sr^{-1} ; B_ν has SI units W m^{-2} Hz^{-1} sr^{-1} .

Planck length:
A fundamental length scale, given by $l_{Pl} = (hG/2\pi c^3)^{1/2} = 1.62 \times 10^{-36}$ m. See Planck energy, Planck mass, Planck time.

Planck mass:

A fundamental mass scale, given by

$$m_{Pl} = (hc/2\pi G)^{1/2} = 2.18 \times 10^{-8} \text{ kg or } 1.22 \times 10^{19} \text{ GeV}/c^2$$

See Planck energy, Planck length, Planck time.

Planck scale:
Quantum effects and gravitational effects become comparable in this regime. See Planck energy, Planck length, Planck mass, Planck time.

Planck time:
A fundamental time scale, given by $t_{Pl} = (hG/2\pi c^5)^{1/2} = 5.39 \times 10^{-44}$ s. See Planck energy, Planck length, Planck mass.

plane of the sky:
The plane perpendicular to our viewpoint on Earth which is a tangent to the celestial sphere at all points.

plane polar coordinates:
See plane polar coordinate system.

plane polar coordinate system:
A coordinate system in which the position of a point in a plane is specified by the ordered pair (r, ϕ) where r is the distance of the point from a selected origin and ϕ is the angular displacement, measured at the origin, of the point from a specified reference line that passes through the origin. They are related to Cartesian coordinates by $x = r \cos \phi$ and $y = r \sin \phi$.

plane-polarized:
Electromagnetic radiation is said to be plane-polarized if it is *polarized* in such a way that its electric field vector oscillates in a single plane.

planet:
According to the definition adopted by the International Astronomical Union in 2006, a planet is a celestial body that is (a) in orbit around the Sun, (b) has sufficient mass for its self-gravity to overcome rigid body forces so that it assumes a hydrostatic equilibrium (nearly round) shape, and (c) has cleared the neighbourhood around its orbit. Contrast with the definition of exoplanet.

planetary nebula:
A shell of material with a mass of a few tenths of a solar mass that has been ejected from a star in the late red giant phase of its evolution (see mass loss). The gas is photoionized by the remaining hot material of the star (possibly by now a white dwarf), and is seen in emission lines (see recombination radiation). Emission lines are seen both from hydrogen and from metals like nitrogen and oxygen. Planetary nebulae are generally ring- or ellipse-shaped (because of the symmetrical ejection from the surface of the star) and are typically a fraction of a parsec in size. Despite their name, they have nothing to do with planets; they are called planetary nebulae because they give the star a disc-like appearance in low-resolution images.

planetary nebulae:
See planetary nebula.

planetary nebula luminosity function:
The number of planetary nebulae per unit volume per unit luminosity. It has a characteristic shape which can be used as a standard candle.

planeticity:
A term loosely used to refer to either the abundance, or prevalence, of stars which host planets, or the probability for hosting planets.

plasma:
A highly ionized gas, that is electrically neutral overall but consists almost entirely of charged particles (electrons and positive ions). Plasma is sometimes described as the fourth phase of matter. On the Earth's surface it is only found in small-scale devices, such as discharge tubes and nuclear reactors. However, on the large scale, plasma is the commonest form of visible matter in the Universe; stars and interstellar space contain large amounts of matter in the plasma state.

plate scale:
The number of arc seconds per pixel in the image plane of a telescope containing a CCD photometer or other imaging detector.

PLATO:
PLAnetary Transits & Oscillations - a proposed ESA satellite designed to discover terrestrial-sized exoplanets transiting bright stars and to characterize the host stars through asteroseismology.

point spread function:

A description of the way in which photons detected from a point source of light (such as a distant star) are spread out to form an extended image on a detector. The PSF depends on the characteristics of the optical elements in the telescope and on the atmospheric seeing conditions.

In perfect seeing conditions (or in the absence of an atmopshere to look through) the PSF may be diffraction limited and determined solely by the aperture size of the telescope.

Poisson distribution:
Used to describe the probability of observing N photons over a time interval ΔT from a source with mean intensity I and given by: $P(N,I\Delta T) = (I\Delta T)^N \times \exp(-I\Delta T) / N!$ This distribution has a mean value of $I\Delta T$ and a standard deviation of $(I\Delta T)^{0.5}$.

Poisson noise:
The variation in the number of photons observed from a light source over a given interval and described by the Poisson distribution.

Poisson's equation:
A partial differential equation of the form $\nabla^2\Phi = 4\pi\rho$, where ρ is a function of the coordinates.

Poisson statistics:

A body of statistical mathematics relating to events that do not happen often or which happen at discrete points in time or space. For a system that obeys Poisson statistics, the average deviation in a measurement whose value is N is given by $\sqrt{N}$.

polar:
Also polar system. Same as AM Her stars. See magnetic cataclysmic variable for a definition.

polar coordinate system:
See plane polar coordinate system and spherical polar coordinate system.

polarization:

(1) The property of a transverse wave that implies the existence of a restriction on the direction of the transverse vibrations. Electromagnetic radiation is a transverse wave and so may be polarized.

(2) For a particle, the number of independent orientations of its spin. A fermion with spin ±1/2 has two possible orientations, a neutrino has spin , so has only one orientation and a photon has spin ±1/2 (corresponding to two directions of circular polarization) so has two orientations.

polycyclic aromatic hydrocarbon:
(PAHs) Organic molecules believed to be present in the interstellar medium and responsible for some of the spectral features seen in infrared spectra of dust.

polynomial:
A function that may be written in the form $f(x) = A + Bx + Cx^2 + Dx^3 + \ldots$, where A, B, C, etc. are constants. Special cases of polynomial functions include constants, linear functions, quadratic functions and cubic functions.

polytrope:
See polytropic model

polytropic equation of state:
See polytropic model.

polytropic model:

A model for the structure of a star in which the pressure and density are related by $P \propto \rho^{\gamma}$ everywhere in the star, where γ is the adiabatic index.

population I:
See stellar populations.

population II:
See stellar populations.

population III:
See stellar populations.

population synthesis:
A simulation technique used to derive a population of objects (stars, planets, etc) in a computer model.

position coordinate:
See coordinate.

position probability density:

The quantity obtained by dividing the probability of finding a quantum particle within some infinitesimal volume by that volume. In one dimension, the probability $\mathrm{d}P(x)$ of finding a particle whose wave function is $\Psi(x)$ in the infinitesimal space interval between x and $x + \mathrm{d}x$ is $\mathrm{d}P(x) = |\Psi(x)|^2\,\mathrm{d}x$, so the position probability density is $\mathrm{d}P(x)/\mathrm{d}x = |\Psi(x)|^2$.

position (vector):

The quantity that determines the location of a point relative to the origin of a specified coordinate system.

In one dimension the position of a point can be specified by means of a single coordinate value, x say. The motion of a particle that moves along the x-axis can then be described by expressing its x-coordinate (its instantaneous position) as a function of time.

Position is a vector quantity characterized by a direction as well as a magnitude. In one dimension the sign of a single coordinate value (such as x) suffices to determine the direction relative to the origin, but in two or three dimensions more information is required. This is often provided by expressing the position vector of a point in terms of its Cartesian components. Thus, a point with position coordinates (x, y, z), has the position vector $\boldsymbol{r} = (x, y, z)$. The magnitude of this position vector is the distance between the origin and the specified point, and is given by

$$r = |\mathbf{r}| = \sqrt{x^2 + y^2 + z^2}$$

positron:
The antiparticle of the electron. It is represented by the symbol e^+.

potential:
See electric potential or gravitational potential as appropriate.

potential energy:

The energy that a body possesses by virtue of its position, shape or internal structure. Typical examples are gravitational potential energy and electrostatic potential energy.

A potential energy may be associated with each conservative force that acts on a body or between a system of bodies. The potential energy, E_{POT}, associated with any particular configuration of a system is the work that would be done by the relevant conservative force in going from that configuration to an agreed reference configuration that has been arbitrarily assigned zero potential energy. Because of the arbitrary nature of this reference configuration, only changes in potential energy are physically significant.

The change in potential energy, when a system goes from some initial configuration to some final configuration, is minus the work done by the relevant conservative force during that change. (Note that this is *not* generally equal to the work done by any external forces that bring about the change, since those forces may be non-conservative.)

$$E_{\mathrm{pot}}(\mathrm{final}) - E_{\mathrm{pot}}(\mathrm{initial}) = \Delta E_{\mathrm{pot}} = -W_{\mathrm{cons}}(\mathrm{initial} \to \mathrm{final})$$

potential well:
A region of space in which the potential energy of a particle is lower than in the surrounding region. In classical physics, a particle within the well that has less energy in total than the potential energy it would have in any region immediately adjacent to the well, will be bound and will remain permanently confined within the well. In quantum physics, such a particle may be able to escape from the well, thanks to the phenomenon of tunnelling.

Pound Rebka experiment:
A terrestrial measurement of gravitational redshift published in 1960 by Robert Pound

and Glen Rebka. They measured the gravitational redshift of photons travelling vertically through a distance of 22.5m in a tower at Harvard University. The experiment confirmed the predictions of general relativity to about 10%.

power:

In the context of mechanics, power is the property of a system that measures the rate at which work is done and energy transferred. (Care must be taken to specify whether the energy is transferred to or from the system.) The SI unit of power is the watt (W), where 1 W = 1 J s^1. The instantaneous power delivered by a force ***F*** acting on a body moving with velocity ***v*** is given by

$$P = \frac{dW}{dt} = \boldsymbol{F} \cdot \boldsymbol{v}$$

power density spectrum:
A function that expresses the amplitudes of the various sinusoidal and cosinusoidal components of a time series. Often displayeed as a plot of power (proportional to amplitude squared) against frequency.

power law:

Any mathematical relationship of the form $A \propto B^C$. See power law spectrum.

power-law distribution:

A distribution of particles in which the number or number density of particles is proportional to some numerical property of the particles raised to some power. For example, a power-law distribution in energy has the form

$N(E) = N_0 E^{-p}$

where N(E) dE is the number of particles with energies between E and E + dE, N_0 is a normalizing constant, and $-p$ is the power-law index.

power-law index:

The exponent to which a quantity is raised in a power law relationship, e.g. the quantity C in the expression $A \propto B^C$.

power-law spectrum:

A spectrum in which the spectral flux density can be related to frequency or wavelength by a power law. Synchrotron radiation often has a spectrum that is well approximated by the power law $F_\nu \propto \nu^{-\alpha}$

power spectrum:
See power density spectrum

Poynting vector:

The quantity

$$\boldsymbol{S} = (c/4\pi)\mathcal{E} \times \boldsymbol{B}$$

which quantifies the flux of energy associated with an electromagnetic wave. It points along the direction of propagation of the wave.

p-process:
A nucleosynthesis process capable of producing certain proton-rich nuclei.

precision cosmology:
The idea that the parameters of the standard cosmological model may be measured to a high degree of precision.

Press-Schechter model:

A model for the mass function of dark matter, expressed as

$$n(M) \propto \left(\frac{M}{M_*}^{-\alpha-2} \exp\left(-\left(\frac{M}{M_*}\right)^{2\alpha}\right)\right.$$

where M_* is a constant. It provides a good fit to N-body simulations, for reasons that are not entirely understood.

pressure:
A macroscopic property of a system (such as a fluid), defined as the magnitude of the perpendicular force per unit area exerted by the system on a planar surface. In the case of a fluid, the pressure can be determined at any point by introducing pressure detectors that move with the fluid. The SI unit of pressure is the pascal (Pa), where 1 Pa = 1 N m^{-2}.

pressure broadening:
The broadening of spectral lines due to collisions between atoms that modify the energy levels of those atoms. These effects are sensitive to the pressure and temperature of the environment in which they occur.

pressure equilibrium:
The state in which the parts of a system that are in contact have the same pressure. Assuming ideal gas behaviour, this implies that nT is constant (i.e. the product of number density and temperature is constant).

pressure gradient:
The rate of change of pressure with respect to position in a given direction (e.g. dP/dz).

primary:
A term used to denote one component of a binary star. In many (but not all) cases the primary star is the more massive of the two stars.

primary eclipse:
The deeper eclipse in a binary system. For an eclipsing binary star, it is when the fainter star passes in front of the brighter star. For a transiting exoplanet system, it is when the planet passes in front of the star, hence in this case it is also known as a transit.

primary emission:
In active galaxies, the electro-magnetic radiation which is due to particles powered directly by the central black hole, e.g. synchrotron radiation from relativistic particles or thermal emission from an accretion disc. Contrast with secondary emission.

primary minimum:
The deeper of the two minima in the light curve of an eclipsing binary star. Also known as primary eclipse.

principal quantum number:
See quantum numbers.

principle of conservation of angular momentum:
See conservation of angular momentum.

principle of conservation of energy:
See conservation of energy.

principle of conservation of linear momentum:
See conservation of linear momentum.

principle of conservation of mechanical energy:
See conservation of mechanical energy.

principle of conservation of momentum:
See conservation of linear momentum and conservation of angular momentum.

principle of detailed balance:
The principle that an ensemble of atoms or ions in a steady state maintains the relative numbers in each quantum state by the number of transitions from state i to state j exactly equalling the number of transitions from state j to state i, for every possible combination of i and j.

principle of equivalence:
See strong equivalence principle

principle of general covariance:
The principle that physical laws should be expressed in terms of balanced tensor equations that are form invariant under general coordinate transformations.

principle of least action:
The statement that particles in classical mechanics follow paths that minimize the action.

principle of relativity:
Also known as the first postulate of special relativity: The laws of physics can be written in the same form in every inertial frame of reference.

principle of the constancy of the speed of light:
Also known as the second postulate of special relativity: The speed of light in a vacuum has the same constant value c = 3.00 x 10^8 m s^{-1}, in every inertial frame of reference.

principle of universality of free fall:
Another expression for the weak equivalence principle.

probability:
A numerical measure of relative likelihood of the possible outcomes of a process. It is conventional to use a probability of 1 as an indication of certainty. According to this convention, the probability of any particular outcome will be a number between 0 (impossibility) and 1 (inevitability), and will be the fraction of times that outcome is expected to happen in the long run.

probability density:
The probability per unit volume (in three dimensions) of detecting a particle in the vicinity of a given point. If the wave function describing the particle is normalized, the probability density is equal to $|\Psi|^2$, the square of the magnitude of the wave function. For a particle confined to one dimension, the probability density is defined as the probability per unit length of detecting the particle in the vicinity of a given point.

probability wave:
A *wave* (also known as a de Broglie wave) that is associated with a particle in quantum physics. The wavelength of the wave is related to the particle's momentum magnitude p by means of the de Broglie formula ($\lambda_{dB} = h/p$), while the square of the wave's amplitude at any given point is proportional to the probability of detecting the particle in the vicinity of that point. The concept of a probability wave is a crude precursor to the more precise notion of a time-dependent wave function.

product rule:
A method for determining the derivative of a function which is the product of two other functions. If $y = uv$ then $dy/dx = u dv/dx + v du/dx$.

profile asymmetry:
An asymmetry in the emission profile of spectral lines. In the case of AGN narrow-line profiles, the asymmetry can be explained by either net outflow of the narrow-line clouds through a dusty region or by net infall of the narrow-line clouds which are themselves dust-filled.

projected spin-orbit angle:
The spin-orbit angle of a star-planet system projected onto the line of sight to an observer.

propeller system:
A mass transfer binary where the accretor is a rapidly rotating magnetic star. When the accreting matter couples to the magnetic field and hence co-rotates with the accretor it acquires angular momentum at the expense of the accretor and a proportion of the accretion flow is propelled back out into space.

proper coordinates:
See proper distance, proper time.

proper distance:
In Schwarzschild spacetime, two events that happen at the same coordinate time but at infinitessimally separated positions will have a spacetime separation given by the negative quantity:

$(ds)^2 = -(dr)^2/(1 - 2GM/c^2r) - r^2(d\theta)^2 - r^2\sin^2\theta\ (d\phi)^2$

The proper distance between those two events is given by $d\sigma = \sqrt{-(ds)^2}$.

If the two events have the same angular coordinates, the proper radial distance between the two events is $d\sigma = dr/(1 - 2GM/c^2r)^{1/2}$. See also proper time.

In the Robertson-Walker metric, the infinitessimal proper distance element is given by

$(d\sigma)^2 = R^2(t)\ [\ (dr)^2/(1-kr^2) + r^2(d\theta)^2 + r^2\sin^2\theta\ (d\phi)^2\ ]$

where $R(t)$ is the scale factor. The proper distance is related to the comoving coordinate X by

$\sigma(t) = R(t) \sin^{-1} X$ if $k = +1$

$\sigma(t) = R(t)\ X$ if $k = 0$

$\sigma(t) = R(t) \sinh^{-1} X$ if $k = -1$

proper length:
In special relativity, the length of a rod is the distance between its end points at a single time as measured in a given inertial frame of reference. The length of the rod in its own rest frame is referred to as its proper length.

proper motion:
The apparent motion of an astronomical source in the plane of the sky. If the distance to the object is known, the proper motion allows us to deduce a transverse velocity. Because of the large distances to astronomical objects, proper motions are generally very small. The nearby star Barnard's star has the largest proper motion, 10.3 arc seconds per year.

proper motion distance:
The transverse velocity of an object divided by its angular proper motion:

$$d_M = \frac{u}{d\theta/dt}$$

proper radial velocity:
The rate of change of proper distance with respect to cosmic time.

proper time:

In special relativity, the time between two events measured in a frame in which the events happen at the same position. Usually denoted by the symbol $\Delta\tau$.

In general relativity, in Schwarzschild spacetime, two events that occur at the same coordinate position but separated by a coordinate time interval d*t* will, according to a local stationary observer, be separated by a proper time $d\tau = (1 - 2GM/c^2r)^{1/2}\, dt$. See also gravitational time dilation, gravitational redshift, and proper distance.

proplyd:
Another name for a protoplanetary disc; see protoplanet.

proportionality:

A term used to describe a relationship between two quantities, *y* and *x* say, in which altering one of the quantities by a certain factor implies altering the other by the same factor.

If the two quantities are related in such a way that by increasing one of the quantities by a certain factor the other is also increased by the same factor, the two are said to be directly proportional. The existence of such a relationship is indicated by writing $y \propto x$. The direct proportionality of *x* and *y* implies that they are related by an equation of the form $y = kx$, where *k* is a constant, known as the constant of proportionality.

If the two quantities are related in such a way that by increasing one of the quantities by a certain factor the other is decreased by the same factor, the two are said to be inversely proportional. The existence of such a relationship is indicated by saying that *y* is inversely proportional to *x* or by writing $y \propto 1/x$. The inverse proportionality of *x* and *y* implies that they are related by an equation of the form $y = k/x$, where once again *k* is a constant, known as the constant of proportionality.

proton:

A type of elementary particle found in the nucleus of every atom. Protons carry a positive charge $+e$ (= 1.602×10^{-19} C) and have a mass of 1.673×10^{-27} kg (= 938.3 MeV/c^2). The mass of a proton is about 0.1% less than the mass of a neutron and the two particles have similar sizes (about 10^{-15} m). The proton is a stable baryon of *spin* 1/2.

proton-proton chain:
The principal chain of nuclear fusion reactions by which hydrogen burning produces energy in low-mass stars. (The CNO cycle dominates in stars more massive than the Sun.) The proton-proton chain proceeds by several paths, but in all cases the initial reaction involves two protons reacting to form a deuterium nucleus, emitting a positron and neutrino: the deuterium then fuses with another hydrogen atom to give a ^{3}He nucleus, which then by a variety of possible paths becomes a ^{4}He nucleus. Overall, therefore, each cycle converts four protons into one ^{4}He nucleus, releasing energy and neutrinos in the process.

proton-proton chain branches I, II and III:
The three reaction paths that jointly constitute the proton-proton chain, and which diverge once ^{3}He has been synthesized. The most common, branch I, ends in the fusion of two ^{3}He nuclei. Branch II and III fuse ^{3}He and ^{4}He to give ^{7}Be which is processed by two routes.

proton-proton chain reaction:
See proton-proton chain.

protoplanet:
A planet growing by a process of accretion in the protoplanetary disc of a young star or protostar. Small inhomogeneities in the disc are thought to lead to the growth of protoplanets.

protoplanetary disc:
A protoplanetary disc consists of cold gas and dust, and is left over from the material that formed the central protostar. Small inhomogeneities in the disc are thought to lead to the growth of protoplanets. Radiation pressure and the solar wind compete against the gravity of the protoplanets and eventually drive off the remaining material of the protoplanetary disc.

protostar:
The name given to a young star which has collapsed out of its parent gas cloud but which has not yet become hot and dense enough for nuclear reactions to begin. Protostars enter the Hertzsprung-Russell diagram along the Hayashi track and reach the main sequence via the Henyey track. This phase of the star's lifetime is short (10^5–10^7 years, depending on the protostellar mass) compared to its life on the main sequence, and the star is often enshrouded in dust and so hard to study. For these reasons, the details of protostar evolution are poorly known. It is known that some protostars have bipolar outflows (see mass loss) which give rise to observable phenomena such as Herbig–Haro objects.

proximity effect:
The observation that, as we approach the redshift of any quasar, the number of Lyman alpha clouds in that quasar's spectrum decreases. This is caused by the ionizing

radiation from the quasar.

pseudo-forces:
Same as fictitious forces.

pseudo-Riemannian space:
A space for which the line element can be written as $dl^2 = \Sigma_{i,j} g_{ij}\, dx^i\, dx^j$, but the metric coefficients g_{ij} can be positive, negative or zero (null).

pulsar:

A rapidly rotating, highly magnetized neutron star that produces beamed radio (and sometimes optical and X-ray) emission. As the neutron star rotates, the beams sweep around the sky; if they cross our line of sight from the Earth, we see repeated short pulses of radiation, repeating at the rotational period of the neutron star. Pulsar periods range from milliseconds to a few seconds.

The periods of rotation powered pulsars (seen either as isolated radio pulsars or as binary millisecond pulsars) are gradually increasing, as the neutron star's rotational kinetic energy is radiated away and lost to work done on its environment. However, the periods of accretion powered pulsars (in X-ray binaries) are generally decreasing, indicating an increase in angular momentum, as a result of mass transfer from a companion star. A third class of pulsars, known as magnetars, are powered by the decay of the neutron star's enormous magnetic field.

pulsating variable stars:

Stars that vary in luminosity as a result of periodic changes in their radius. Pulsating variable stars include Cepheids, RR Lyrae stars, dwarf Cepheids and δ Scuti stars. Most of these lie in the instability strip in the Hertzsprung-Russell diagram. The pulsations are thought to be driven by a region of changing opacity near the surface of the star, due to the presence of partially ionized helium. When the helium is compressed, it becomes more opaque, storing energy; this then drives an expansion of the outer layers, which expand until gravity pulls them back, while the ionized helium recombines. When the outer layers of the star are pulled back by gravity, the helium is compressed again, and so on. The partially ionized helium thus provides a way of coupling the radiative energy of the star to the kinetic energy needed for an oscillation. If the helium region lies too deep or too close to the surface of the star then oscillations cannot occur.

pure density evolution:
See density evolution.

pure luminosity evolution:
See luminosity evolution.

Pythagoras's theorem:
A mathematical result, concerning the lengths of the sides of a right-angled triangle, which states that: the square of the hypotenuse is equal to the sum of the squares of the other two sides. (The hypotenuse is opposite the right angle and is always the longest side.)

Q

QPOs:
See quasi-periodic oscillations.

QSO:
See quasar.

quantum:

An amount of energy associated with electromagnetic radiation of frequency v, equal to hv where h is the Planck constant. This is the amount of energy carried by a single photon of the radiation.

quantum concentration:

The maximum number density of particles in some material if it is to remain non-degenerate. That is, if the actual number density $n > n_Q$, degeneracy will have set in. $n_{Q,NR} = (2\pi mkT)^{3/2}/h$ for non-relativistic material, and $n_{Q,UR} = 8\pi(kT/hc)^3$ for ultra-relativistic material.

quantum efficiency:
The fraction of photons entering a telescope which are recorded by the detector.

quantum fluctuations:
See Hawking radiation and energy-time uncertainty principle.

quantum gravity:
A hypothetical unification of classical general relativity and quantum physics.

quantum mechanics:
One of the major subdivisions of quantum physics. Quantum mechanics is typically concerned with systems such as nuclei, atoms, molecules and electrons in solids, all of

which have the feature that they may be treated as a finite number of interacting particles. Quantum mechanical problems are often discussed in terms of a wave mechanical formalism which emphasizes the concept of a wave function, satisfying an appropriately formulated Schrödinger equation.

quantum number:
One of the numerical quantities that identify the possible stationary state wave functions of a quantum system. In the case of an electron in an atom, examples include the principal quantum number n, the orbital angular momentum quantum number l, the orbital magnetic quantum number m_l, and the spin angular momentum quantum number s. They are usually integers (apart from spin, s, which, for the electron, is equal to 1/2). The possible values of the quantum numbers (apart from spin) are determined by finding the allowed solutions of Schrödinger's equation.

quantum physics:
One of the major subdivisions of physics that should be compared and contrasted with classical physics. Quantum physics encompasses quantum mechanics and quantum field theory, and covers a host of quantum phenomena. Amongst its characteristic features are indeterminacy and the intrinsic use of probability, along with the appearance of the Planck constant.

quantum state:
The state of a quantum system defined with sufficient precision that it may be associated with a unique wave function. In the case of a stationary state, described by a time-independent wave function, it may be possible to specify the state in terms a unique set of quantum numbers. (If the system is a particle with spin, such as an electron in an atom, the relevant spin magnetic quantum number must be included.) Note that a quantum state is distinct from an energy level, which may correspond to several quantum states, all of which have the same energy, but different wave functions. (Such an energy level is said to be degenerate.)

quantum system:
Any system which is analysed using the formalism of quantum mechanics.

quantum tunnelling:
Also known as barrier penetration. If a particle encounters a potential well with walls of a finite height, the wave function of the particle penetrates some distance into the walls, even when the wave function's energy is below that of the potential energy barrier. (Such behaviour is forbidden in the classical world.) If the barrier is of finite width, and beyond it the particle's energy again exceeds that of the potential barrier, then there is a finite probability that the particle will penetrate the barrier and hence be found on the other side. Particles can penetrate such a barrier in either direction.

quark:
A fundamental constituent of strongly interacting particles such as protons and neutrons. There are six flavours of quark: up, down, charm, strange, top and bottom, each of which has an associated antiparticle.

quasar:

An active galaxy whose defining characteristic is very luminous optical emission from the active nucleus, often exceeding in luminosity all the stars in the host galaxy. Quasars are differentiated from type I Seyfert galaxies by having a blue absolute magnitude greater than a certain threshold value:

$M_B > -21.5 + 5 \log h_0$

(where h_0 is the Hubble constant in units of 100 km^{-1} Mpc^{-1}). This distinction is mostly a historical one; quasars and Seyfert Is share many properties, including strong optical emission from the active nucleus, time-variable continuum flux, large UV flux (the big blue bump, thought to come from an accretion disc), strong broad and narrow emission lines (see broad-line region, narrow-line region) and large, variable X-ray flux. Because of the absolute magnitude criterion in the definition of a quasar, most known quasars are at relatively high redshifts; this is an example of Malmquist bias rather than being intrinsic to the class. Quasars were originally detected by their radio emission, and the term 'quasar' is a contraction of 'quasi-stellar radio source' – 'quasi-stellar' reflects the apparently point-like nature of quasars in early observations due to their strong nuclear optical emission. Quasars of this kind, with strong radio emission, are related to radio galaxies in unified models of active galaxies. However, quasar-like objects without strong radio emission were subsequently discovered. These were originally called quasi-stellar objects or QSOs to differentiate them from quasars. It is now more common to refer to both types of object as quasars, those (about 10%) with strong radio emission being known as radio-loud quasars and those without it being called radio-quiet. The host galaxies of quasars may be of any type, but the most luminous quasars, and all radio-loud quasars, seem to be hosted by elliptical galaxies.

quasar absorption line:
An absorption line in the spectra of *quasars* which is generally much narrower than the emission lines, and at lower *redshift* than the quasar itself. These absorption lines therefore arise in intervening gas along the line of sight to the quasar.

quasar fuzz:
Relatively faint emission from the stars, gas and dust surrounding a *quasar*. It represents the emission from the host galaxy within which the quasar is embedded.

quasar luminosity function:
The luminosity function of quasars. The quasar luminosity function is a monotonically

decreasing function of luminosity (i.e. there are fewer and fewer quasars per unit volume at higher and higher luminosities). The shape of the function is a broken power law, with a steep power law index at high luminosities and a shallow power law index at low luminosities. The position of the change in slope of the power law index changes with the redshift of the quasars concerned.

quasi-periodic oscillations:
Oscillations in the luminosity of an astronomical object that do not have a well-defined period but instead show a range of periods or frequencies. QPOs have been observed in X-ray binaries and cataclysmic variables and in active galactic nuclei. In some sources, the average frequency of the QPO depends on the luminosity of the source, so that flux and period variability are correlated. QPO average frequencies in binary systems range from around 0.01 Hz to 1 kHz. The origin of QPOs is not well understood; a plausible model for some sources is that they come from an interaction between the rotation of the accreting body and the rotation of the accretion disc, and that the QPO frequency is the beat frequency.

quasi-static process:
A process in which the state of a system changes so slowly that it effectively goes from one equilibrium state to another via a succession of intermediate equilibrium states.

quasi-stellar object:
See quasar.

quintessence:
The name given to a postulated fifth fundamental field (in addition to the established four fundamental forces of nature: electromagnetic interaction, gravitational interaction, strong nuclear interaction and weak nuclear interaction). It is one form of dark energy.

R

rad:
The standard abbreviation for *radian*.

radial coordinate:
The coordinate that measures distance from the origin in a polar coordinate system.

radial drift timescale:
Same as viscous time.

radial drift velocity:
See drift velocity.

radial velocity:
The component of the velocity along the observer's line of sight, measured by the Doppler shift, of an astronomical object.

radial velocity curve:
A graph of the radial velocity (the component of the velocity along the observer's line of sight, measured by the Doppler shift) of an astronomical object as a function of time. The radial velocity curves of binary stars give information on the masses of the individual stars in the system (see mass function).

radian:

A unit of angle, common in scientific work. If a circular *arc* of length *r* has a radius *r* measured from a point O, then the angle subtended at O by the end points of the arc is 1 radian. It follows that 2π radians are equivalent to 360°, so 1 radian is equivalent to approximately 57.3°. The standard abbreviation of radian is rad.

radiation:

(1) Specifically, a mechanism of heat transfer in which energy is transferred from one body to another (possibly through a vacuum) by means of light or some other form of electromagnetic radiation.

(2) More generally, a term used either as an abbreviation for electromagnetic radiation or when referring to particles emanating from a source (particularly those resulting from the radioactive decay of nuclei).

radiation beaming:
See beaming

radiation (density) constant:
This has a value of $a = 7.565 \times 10^{-16}\ \mathrm{JK^{-4}\ m^{-3}}$. Equivalent to $4\sigma/c$ where σ is the Stefan-Boltzmann constant ($5.671 \times 10^{-8}\ \mathrm{Wm^{-2}\ K^{-4}}$) and c is the speed of light ($2.998 \times 10^{8}\ \mathrm{ms^{-1}}$).

radiation pressure:

Pressure due to the interaction between radiation and matter. Since photons carry momentum, matter that absorbs, reflects or scatters a photon is subject to a force. In special relativity, the momentum of a photon (or other particle with zero rest mass) is given by

$E = pc$

A given flux F (in W m^{-2}) of photons is therefore associated with a radiation pressure

$P_R = F/c$

Radiation pressure is important in the atmospheres of some massive stars and is probably responsible for setting the upper mass limit for stars.

radiative:
A term used to describe a layer in a star or accretion disc where the energy transport is dominated by radiative diffusion.

radiative diffusion:

The process by which radiation leaks out of a star by a series of random walks. The radiative diffusion equation gives

$$\left(\frac{dT}{dr}\right)_{\text{rad}} = -\frac{3\rho(r)\kappa(r)L(r)}{4acT^3(r)4\pi r^2}$$

where $r(r)$ is the density of the star, $\kappa(r)$ the opacity of the star, $L(r)$ the luminosity of the star and $T(r)$ the temperature of the star, each as a function of radius. a is the radiation (density) constant.

radiative mode:
A mechanism by which an AGN can inject energy into the surrounding medium, due to the radio lobes of active galaxies. Contrast with kinetic mode.

radiative transition:
A process in which a quantum system (such as an atom) undergoes a transition from one energy level to another by the emission or absorption of electromagnetic radiation (i.e. a photon).

radiative transport:
The process whereby energy carried by photons is transported through an astronomical object, in particular a star. Radiative transport is the most important energy transport mechanism in stars, although convection can also be important.

radio-far-infrared correlation:
The correlation between the radio emission and far-infrared emission in star-forming galaxies. Far-infrared emission traces the dust-shrouded regions and radio emission traces the total shrouded and unshrouded regions of star formation.

radio galaxy:
Galaxies forming a class of active galaxy that is particularly luminous at radio wavelengths (with luminosities between 10^{35} and 10^{39} W). Radio galaxies generally show extended, double radio structure (see radio source structure). The host galaxy is generally a normal elliptical galaxy as observed in the optical, although some radio galaxies have a bright optical nucleus (N galaxies). Objects with a very strong optical nucleus are normally classed as radio-loud quasars. Low-luminosity radio galaxies often have weak (LINER-type) or absent nuclear emission lines, but more powerful objects show strong narrow emission lines like Type 2 Seyfert galaxies (narrow-line radio galaxies) or broad lines like Type 1 Seyfert galaxies and quasars (broad-line radio galaxies). Radio galaxies are generally considerably weaker X-ray sources than radio-loud quasars. In unified models for radio-loud active galaxies, the X-ray and optical differences between radio galaxies and radio-loud quasars are explained in terms of an obscuring torus close to the nucleus that prevents the broad-line region and the optical and X-ray continuum emission from being seen when the source is observed close to the plane of the sky (a radio galaxy) but allows them to be visible when the source is at small angles to the line of sight (a quasar).

radio galaxy evolution:
The change in the properties of the radio galaxy population with cosmic time. 'Evolution' in cosmological terms means that a class of objects had different properties or was present in different numbers at earlier times, and therefore (since redshift equates to lookback time) at higher redshifts. Like many other active galaxy populations, radio galaxies have evolved in the sense that there appears to be a lower density of them at the present day than there was in the past (say around redshift 1–2) after the change in the overall density of the Universe due to expansion has been accounted for. This is interpreted as showing that the conditions for active galaxies in general, and radio galaxies in particular, were more favourable in the early Universe.

radio interferometry:
A technique of radio astronomy whereby the signals from two radio telescopes are combined to produce an image with an angular resolution corresponding to a single telescope whose diameter is equal to the separation of the two telescopes.

radio loud:
Referring to active galaxies which have significant radio flux.

radio pulsar:
The usual sort of rotation powered pulsar which emits beams of radio waves. See pulsar.

radio quiet:

Referring to active galaxies which have negligible radio flux.

radio source catalogue:
A catalogue of radio sources based on a survey of a region of the sky with a radio telescope. The catalogue will typically list the position and spectral flux density of a large number of radio sources down to some limiting flux value. The 3C, 4C and Parkes (PKS) catalogues are examples of important radio source catalogues.

radio source structure:
The radio-emitting structure of a radio galaxy or radio-loud quasar. These objects generally exhibit two radio-luminous lobes on either side of a radio core that is coincident with the active nucleus; the lobes may be between a few kpc and a few Mpc in size. Some objects also have an observable jet or jets leading into the lobes. In Fanaroff–Riley class I objects the core and jets dominate the emission, while in Fanaroff–Riley class II objects the emission is dominated by the bright ends of the lobes, known as 'hot spots', and the emission from the jets is often weak or invisible. The large-scale structure of the radio source may be determined by the properties of the medium it is propagating into, so that radio sources can be probes of the conditions in intergalactic space.

radio waves:
Electromagnetic radiation with a wave-length greater than around 10^{-1} m or a frequency less than about 3×10^9 Hz.

ram pressure:
A pressure arising from the inertia of gas of density ρ moving with bulk speed v, given by $P_{\mathrm{ram}} = \rho v^2$.

random walk:
A process in which one travelling particle (e.g. a photon) interacts with other particles (e.g. atoms, electrons) such that it has an almost equal chance of travelling in any direction following the encounter.

rank (of a tensor):
The number of indices on a tensor. A four-tensor of rank 1 is known as a four-vector. A mixed tensor with m indices in the 'up' position and n indices in the 'down' position has a contravariant rank of m and a covariant rank of n.

ratio of heat capacities:
The ratio $\gamma = C_P/C_V$ of the heat capacity at constant pressure to the heat capacity at constant volume for a given quantity of a specified substance. Also known as the adiabatic index. For an ideal gas with s effective degrees of freedom, $\gamma = (s + 2)/s$, implying that γ is 1.67 for a monatomic ideal gas (where $s = 3$), 1.40 for a diatomic ideal gas (where $s = 5$) and 1.33 for a triatomic ideal gas (where $s = 6$) under moderate conditions.

Rayleigh Jeans law:
The long wavelength part of the black body spectrum, which can be described by $B_\nu(T) = 2kT\nu^2/c^2$ or $B_\lambda(T) = 2\,ckT/\lambda^4$. See Planck function.

Rayleigh Jeans tail:
See Rayleigh Jeans law.

Rayleigh scattering:
The scattering of radiation by particles with size much less than the wavelength of radiation in question. The Rayleigh scattering cross-section is proportional to wavelength to the power -4.

R-band filter:
A broad band photometric filter used in astronomy spanning the wavelength range from about 550 to 750nm.

recombination:
The process in which a free electron combines with an ion, releasing energy in the form of a photon; the reverse of ionization. Recombination relies on a physical interaction between the electron and the ion, so the speed with which it takes place depends on the density of the plasma in which it occurs. See also case A recombination and case B recombination.

recombination coefficient:
The constant of proportionality in the relationship between the recombination rate (number of recombinations per unit volume per second) and the product of the number densities of ions and electrons.

recombination lines:
Spectral lines (emission lines) which arise when electrons recombine with ions to produce neutral atoms or less ionized species of ion.

recombination radiation:
Radiation produced by the recombination of an electron and an ion. The radiation

produced is a combination of a continuum from the free-bound transition (an electron of any energy recombines with the atom, so a photon of any energy can be produced) and emission lines from bound-bound transitions as the electron decays in energy down to the lowest available energy state.

recombination timescale:
The typical timescale on which electrons and ions recombine to form atoms under specified circumstances.

recycled pulsar:
See millisecond pulsar.

reddened:
Optical emission is said to be reddened if it has been made redder by the effects of wavelength-dependent extinction. See extinction.

reddening:
See extinction.

red edge:
A feature in the near infrared spectrum of a planet due to the reflectance of chlorophyll. It may be a suitable biomarker for exoplanets.

red giant:
Stars which have ceased to burn hydrogen in their cores and started shell hydrogen burning. Shell hydrogen burning causes the outer layers of the stars to expand, making the stars more luminous but reducing their effective temperature. Consequently, red giants occupy a region of the Hertzsprung-Russell diagram above and to the right of their original position on the main sequence. Red giants with enough mass will begin helium burning in their cores and enter the red giant clump or the horizontal branch; once core helium is exhausted, they will begin shell helium burning on the asymptotic giant branch. The most massive stars will end the giant phase as supernovae, while the rest will lose their outer layers in a planetary nebula leaving a degenerate core behind as a white dwarf.

red giant clump star:
See clump red giant star.

red nuggets:
A very numerous population of small, passively-evolving, elliptical galaxies at redshift $z>1$ whose luminosities imply large stellar masses of $>10^{11}$ solar masses.

red sequence:
Part of the distribution of galaxies in the colour-magnitude plane. The red sequence comprises red, passively evolving galaxies. See blue cloud, green valley.

redshift:

A shift of a spectral line to redder (longer) wavelengths. There are three important types of redshift:

(1) Doppler shift – due to the motion of the emitting object away from the observer.

(2) Gravitational redshift – due to strong gravity at the surface of the emitting object.

(3) Cosmological redshift – due to the expansion of the Universe (see the Hubble constant, Big Bang).

Numerically, the redshift z is defined by

$$z = \frac{\Delta\lambda}{\lambda_0}$$

where λ_0 is the original emitted wavelength (the wavelength that the emission line would have in the laboratory) and $\Delta\lambda$ is the difference between the observed and emitted wavelengths.

If the redshift is a small Doppler shift, then $z = v/c$, where v is the speed of recession. For a cosmological redshift, the same formula can be used together with Hubble’s law to infer distances, but only if $z << 1$; otherwise more complex results, depending on the geometry of the Universe, must be applied.

redshift cutoff:
The lobserved limiting redshift (around $z \sim 3$) beyond which the quasar number density appears to drop off quickly.

redshift space distortions:
See fingers of God and Kaiser effect.

reduced images:
Astronomical images which have undergone the process of data reduction to remove systematic artefacts. Processes include bias subtraction, dark current removal and flat-field correction.

reduced mass:

An equivalent mass calculated from the individual masses of a two-component system, m_A and m_B, such that

$m_r = \frac{m_A m_B}{m_A + m_B}$

The reduced mass is always less than the least massive of A or B. It reflects the fact that the more massive particle is not infinite and hence each particle will move in response to the attraction of the other.

reflex orbit:
The orbital motion of a star around the system barycentre caused by the gravitational attraction of planets.

refraction:
The process whereby the direction of propagation of a wave passing from one medium to another, is changed as a result of its change of speed.

refractory material:
A material that retains its strength at high temperatures. Often used generically to refer to rocks in planetary bodies.

reheating:
Referring to the particle generation process in the early Universe that occurs at the end of inflation as the inflaton field decays. During this process, the matter-antimatter asymmetry of the Universe may have been generated.

Reimers law:

A semi-empirical law giving the mass-loss rate for stars as a function of their radius, surface gravity and luminosity. The surface gravity depends on the mass and radius, and the luminosity, temperature and radius are related by $L = 4\pi R^2 \sigma T_{eff}^4$, so Reimers law can be re-expressed in terms of other parameters.

relative atomic mass:
A numerical measure of the mass of a given species of atom, obtained by dividing the mass of the atom *m* by the atomic mass unit; so $M_r = m/1$ amu, where 1 amu is one-twelfth the mass of a carbon-12 atom. The relative atomic mass is a dimensionless quantity.

relative molecular mass:
A numerical measure of the mass of a given species of molecule, obtained by dividing the mass of the molecule *m* by the atomic mass unit; so $M_r = m/1$ amu, where 1 amu is one-twelfth the mass of a carbon-12 atom. The relative molecular mass is a dimensionless quantity.

relativistic beaming:
See Doppler boosting, beaming.

relativistic cosmology:
Study of the universe as a whole based on the underlying principles of general relativity.

relativistic energy:

The total energy of a body according to the special theory of relativity. For a free particle of (rest) mass *m* travelling with speed *v,* the relativistic energy is $E = \gamma(v)mc^2$. The relativistic energy is the sum of its relativistic translational kinetic energy and its mass energy. The total relativistic energy of a particle is also given by the relationship:

$E^2 = p^2c^2 + m^2c^4$

where *p* is the magnitude of the particle's relativistic momentum.

relativistic kinetic energy:
A term used occasionally as an abbreviation of relativistic translational kinetic energy.

relativistic momentum:

The momentum of a body according to the special theory of relativity. For a particle of (rest) mass *m*, travelling with velocity ***v***, the relativistic momentum is

$\mathbf{p} = \frac{m\mathbf{v}}{\sqrt{1-(v^2/c^2)}}$

At speeds which are small compared with the speed of light, *c*, this reduces to the Newtonian expression $\mathbf{p} = m\mathbf{v}$.

relativistic translational kinetic energy:

The translational kinetic energy of a body according to the special theory of relativity. For a particle of relativistic energy *E* and rest energy E_0, the relativistic kinetic energy is $E - E_0$ and is therefore given by $E_K = \gamma(v)mc^2 - mc^2$.

At speeds which are small compared with the speed of light, *c*, this reduces to the Newtonian expression $E_K = mv^2/2$.

relativity:
See special theory of relativity and general theory of relativity.

relativity of simultaneity:
The condition of two events being simultaneous is a relative and not an absolute one. Two events that are simultaneous in one frame of reference are not necessarily simultaneous in every other frame.

remnant:
This is what is leftover at the end of a star's life. Compact remnants are the stellar cores, which become either a white dwarf, neutron star, or black hole. Supernova remnants are the diffuse, hot, ejected envelopes.

replenishment mechanism:
With relation to the broad line region of active galaxies, a means of maintaining the integrity of clouds against processes such as evaporation.

resonant bar detector:
A type of gravitational wave detector, consisting of a large metal bar with sensors to measure tiny movements of the ends.

rest energy:
See mass energy.

rest frame:
A frame of reference in which the system in question is itself at rest.

rest mass:
The mass of a particle as measured by an observer relative to whom the particle is at rest. Associated with a given rest mass is a particular mass energy.

rest wavelength:
The wavelength of a spectral line in a frame of reference in which the material emitting the line is itself at rest.

reverberation mapping:
A method of determining the distance of the broad-line region from the active galactic nucleus by correlating variations in the broad lines and the AGN continuum, measuring, for example, the time delay between a brightening of the continuum and the corresponding brightening of the emission lines.

Reynolds number:

A dimensionless parameter characterizing the relative importance of the viscous force for the dynamics of a fluid flow. The Reynolds number *Re* is the ratio of the rate at which linear momentum is carried through a cross-section of the flow, to the viscous force in the flow. It can be calculated as

$$Re = \frac{\text{density} \times \text{characteristic speed} \times \text{characteristic length}}{\text{viscosity}}$$

If $Re \ll 1$ viscous forces dominate the flow, while if $Re \gg 1$ viscous effects are dynamically unimportant.

Ricci scalar:
See curvature scalar.

Ricci tensor:
The rank 2 tensor $[R_{\alpha\beta}]$ defined in terms of the Riemann tensor by $R_{\alpha\beta} \equiv \Sigma_\gamma R^\gamma{}_{\alpha\beta\gamma}$.

Riemannian geometry:
The geometry of a space for which the line element can be written in terms of the metric tensor as $dl^2 = \Sigma_{i,j}\, g_{i,j}\, dx^i\, dx^j$. The metric coefficients should be positive definite, although physicists often ignore this restriction.

Riemannian space:
See Riemannian geometry.

Riemann tensor:

The tensor given in terms of the metric coefficients by

$$R^l{}_{ijk} \equiv \frac{\partial \Gamma^l{}_{ik}}{\partial x^j} - \frac{\partial \Gamma^l{}_{ij}}{\partial x^k} + \sum_m \Gamma^m{}_{ik} \Gamma^l{}_{mj} - \sum_m \Gamma^m{}_{ij} \Gamma^l{}_{mk}$$

The vanishing of the Riemann tensor is a necessary and sufficient condition for a space to be flat.

right ascension:
One of the two coordinates used to describe positions on the sky (celestial sphere) in the equatorial coordinate system (see also declination). The right ascension of a point describes its angular distance, measured eastwards around the celestial equator, from an essentially arbitrarily chosen reference point (the 'first point of Aries', which is the position of the Sun at the spring equinox). Right ascension is measured in hours, minutes and seconds between 0 and 24 hours; so an object at RA = 6h 0min 0s on the celestial equator is 90° away from the first point of Aries.

right-circularly polarized:
In right-circularly polarized light the plane of the electric field vector rotates anticlockwise about the direction of propagation when viewed from the source towards the destination; in left-circularly polarized light, this rotation is clockwise.

right-hand rule:
A rule for determining the sense in which the vector product $\boldsymbol{a} \times \boldsymbol{b}$ is perpendicular to the vectors $\boldsymbol{a}$ and $\boldsymbol{b}$. The rule is the following: point the flattened palm and fingers of your right hand in the direction of vector $\boldsymbol{a}$. Then, keeping your palm and fingers parallel to $\boldsymbol{a}$, twist your wrist until you can bend your fingers to point in the direction of vector $\boldsymbol{b}$. Your extended thumb will then point in the direction of $\boldsymbol{a} \times \boldsymbol{b}$.

Robertson-Walker metric:

The spacetime metric that underlies all relativistic models that are homogenous and isotropic:

$(\mathrm{d}s)^2 = c^2(\mathrm{d}t)^2 - R^2(t)\ [(\mathrm{d}r)^2/(1-kr^2) + r^2(\mathrm{d}\theta)^2 + r^2\sin^2\theta\ (\mathrm{d}\phi)^2\ ]$

where k is the curvature parameter and $R(t)$ is the scale factor.

Roche limit:

A numerical quantity used to describe the limiting distance within which a small gravitationally bound body can approach a more massive body without being disrupted by differential gravitational forces (tidal forces).

The Roche limit arises because different parts of the smaller body experience different forces due to the gravity of the larger body. When the difference between the forces at either side of the smaller body is greater than the gravitational force holding it together, tidal disruption will start to occur. In the case of a moon orbiting a planet, it is given by

$d_\mathrm{R} = r_\mathrm{moon}\ (2\ m_\mathrm{planet}\ /\ m_\mathrm{moon})^{1/3}$

where r_moon is the radius of the moon, m_moon is the mass of the moon and m_planet is the mass of the planet. Contrast with Hill radius.

Although the Roche limit was originally derived for moons orbiting in the gravitational field of a planet, it also applies, for example, to stars orbiting in the gravitational field of a black hole.

Roche lobe:
The maximum volume available to a star in a binary system. Gravitational and centrifugal forces combine in such a way that the net force is attractive close to a star but repulsive further away. If a star expands such that material enters the region where it is repelled by centrifugal forces, it is said to be overflowing its Roche lobe, and will probably transfer mass to its companion. (See Roche-lobe overflow.)

Roche-lobe filling:
Referring to a star in a binary system that fills its own Roche lobe.

Roche lobe index:

For a Roche-lobe filling star in a binary star system, the exponent or index (represented by the greek letter zeta with a subscript L: ζ_L) in the proportionality between the Roche lobe radius, the star's mass and the total orbital angular momentum of the binary: $R_\mathrm{L} \propto J^2 M^{\zeta_\mathrm{L}}$. It is a function of the mass ratio of the system only.

Using Paczynski's approximation for the Roche lobe radius as a function of mass ratio q, then for conservative mass transfer, the Roche lobe index is $\zeta_\mathrm{L} = 2q - 5/3$.

Roche-lobe overflow:
Mass transfer from a Roche-lobe filling star via the inner Lagrangian point.

Roche lobe radius:
The radius of a sphere that has the same volume as the Roche lobe.

Roche potential:

The effective potential of two point masses that move on circular Keplerian orbits about the centre of mass, as seen in the frame of reference that co-rotates with the binary. The potential is the sum of the gravitational potential of both stars and an additional potential that may be associated with the centrifugal force. We therefore write the force on a test mass as $\boldsymbol{F} = -m\ \nabla\Phi_\mathrm{R}$ where the Roche potential is

$\Phi_\mathrm{R}(\boldsymbol{r}) = -GM_1/|\boldsymbol{r}-\boldsymbol{r}_1| - GM_2/|\boldsymbol{r}-\boldsymbol{r}_2| - ½(\boldsymbol{\omega} \times (\boldsymbol{r} - \boldsymbol{r}_\mathrm{c}))^2$

where M_1 and M_2 are the masses of the two stars, $\boldsymbol{r}_1$ and $\boldsymbol{r}_2$ are the position vectors of the two stars, $\boldsymbol{r}_\mathrm{c}$ is the position vector of the centre of mass of the system and $\boldsymbol{\omega}$ is the angular speed of rotation of the system.

Roche tomography:
An indirect imaging technique that maps the brightness distribution of the surface of the donor star in, for example, a cataclysmic variable from Doppler shift information in spectral lines.

ROSAT:
A German-led X-ray astronomy satellite with contributions from the US and UK, which

operated from 1990-1999. The name comes from Röntgensatellit, which translates as X-ray satellite. It provided a high resolution all-sky survey of around 150,000 objects in the 0.1-2 keV band, and was crucial in determining the line-of-sight absorption to many X-ray binaries.

Rosseland mean opacity:
An average of the frequency-dependent opacity, such that the radiative diffusion equation (see radiative diffusion) in optically thick layers holds.

Rossiter-McLaughlin effect:
A perturbation to the radial velocity curve of a star which is induced by a second object (planet or star) passing in front of the first and consequently blocking surface elements with different Doppler shifts at different times.

Rossi X-ray Timing Explorer:
This X-ray astronomy satellite sacrificed imaging capabilities to achieve the highest possible time resolution: 2.6 μs. As a result RXTE discovered the kHz oscillations from Low Mass X-ray Binaries predicted by theory. It is a NASA mission, launched in 1995 into low Earth orbit (600 km above the surface). The short 90 minute period allows an onboard all sky monitor to keep track of the brightest X-ray sources in the sky, but means that light curves are often broken up, as the Earth eclipses the target.

rotational kinetic energy:

The kinetic energy associated with the rotational motion of a body. For a body rotating with angular speed ω about a fixed axis, the rotational kinetic energy is

$$E_{\text{rot}} = \frac{1}{2} I \omega^2$$

where I is the body's moment of inertia about the axis of rotation.

In the case of a diatomic molecule the rotational energy is associated with rotations of the molecule about axes perpendicular to the line joining the atoms. It does not include translational or vibrational contributions to the energy.

rotation curve:
A graph of the rotation speed plotted against radial distance from the galactic centre for a spiral galaxy or other rotating body. Rotation curves of spirals allow the distribution of mass within the galaxy to be measured. They show that the matter in a spiral galaxy is not strongly centrally concentrated (unlike the stars, which are often concentrated very densely in the nuclear bulge) and provide evidence for dark matter in galaxies.

rotation measure:
See Faraday rotation.

rotation powered pulsar:
The usual sort of radio pulsar, powered by loss of rotational energy. Compare with accretion powered pulsar.

r-process:

The 'rapid' process of neutron-capture reactions, in which neutron capture takes place more quickly than β-decay. The r-process can produce extremely neutron-rich elements, which then β-decay back to stability; this allows the nucleosynthesis of elements that would not be available through the s-process. It is thought to occur in certain supernova explosions, where there is a very high flux of neutrons. Contrast s-process.

RR Lyrae star:
A star that is a member of a class of pulsating variable stars in the instability strip of the Hertzsprung-Russell diagram. RR Lyrae stars are red giants on the horizontal branch, and so have a characteristic absolute magnitude which, together with their distinctive variability, makes them useful standard candles. The period of variability is about 0.5 days.

S

Sachs-Wolfe effect:
As density enhancements in the early Universe grew, after the Universe became transparent to its own radiation, photons emerging from over-dense regions will have a slight gravitational redshift, whilst photons emerging from voids will have a slight gravitational blueshift, with respect to overall spectrum of the cosmic microwave background. This is the Sachs-Wolfe effect.

Sachs-Wolfe plateau:
The observed scale-invariant power spectrum of the cosmic microwave background radiation seen at large angular scales.

Saha ionization equation:

An equation that gives the relative populations of ions and neutral atoms for a system of ions, atoms and free electrons in thermodynamic equilibrium. If the ionization energy is E, then the Saha equation states that

$$\frac{N_+}{N_0} = \frac{A(kT)^{3/2}\exp(-E/kT)}{N_{\text{e}}}$$

where N_+ and N_0 are the number of ionized and neutral atoms, A is a constant, k is the Boltzmann constant, T is the temperature, and N_e is the number density of electrons. The equation can be used to predict the degree of ionization as a function of temperature.

Salpeter mass function:
See initial mass function

Salpeter timescale:
Another name for the Eddington timescale.

sample selections:
The means by which a sample of objects is chosen. For example, identifying all U-excess objects is one way to select a sample of quasars using their optical properties; identifying all point-like radio sources brighter than a particular threshold is one way to select a sample of quasars based on their radio properties. Most sample selection techniques are subject to some form of bias.

saturation radius:

The distance from the centre of the explosion in a gamma-ray burst at which the expansion saturates, i.e. the point at which all of the energy of the GRB has been converted into kinetic energy of baryons. It marks the distance at which the expansion ceases to accelerate and the Lorentz factor of the expansion reaches its maximum value.

The saturation radius may be expressed as

$$r_s \simeq \left(\frac{\gamma_s}{300}\right)\left(\frac{\Delta t_{var}}{10\ \mathrm{ms}}\right)\ \mathrm{m}$$

where the Lorentz factor has a maximum value of $\gamma_s \simeq E_0/Mc^2$ and E_0 is the energy of the explosion and M is the mass involved.

scalar:
A quantity that is completely specified by a number, or a number multiplied by an appropriate unit of measurement. Scalar values can be positive, negative or zero. Examples include, distance, speed, mass, electric charge and temperature. Contrast with vector.

scalar field:
A physical quantity to which a definite scalar value can be ascribed at every point throughout some region of space. Examples include the temperature field in a room and the electric potential field between the plates of a capacitor.

scalar product:

A product of two vectors $\boldsymbol{a}$ and $\boldsymbol{b}$, usually written as $\boldsymbol{a} \cdot \boldsymbol{b}$, and sometimes referred to as the 'dot product' of those vectors. Given two vectors $\boldsymbol{a}$ and $\boldsymbol{b}$, which are at an angle θ to each other, where $0° \leq \theta \leq 180°$, their scalar product $\boldsymbol{a} \cdot \boldsymbol{b}$ is defined by the relation

$$\boldsymbol{a} \cdot \boldsymbol{b} = ab \cos \theta$$

Alternatively, if the components of $\boldsymbol{a}$ and $\boldsymbol{b}$ are such that $\boldsymbol{a} = (a_x, a_y, a_z)$ and $\boldsymbol{b} = (b_x, b_y, b_z)$ then the scalar product of $\boldsymbol{a}$ and $\boldsymbol{b}$ is given by

$$\boldsymbol{a} \cdot \boldsymbol{b} = a_x b_x + a_y b_y + a_z b_z$$

scale factor:

A numerical quantity used to describe the expansion of the Universe in Big Bang cosmology; the scale factor gives the relationship between the true distance between two objects and their separation in comoving coordinates (which do not change with time). If we adopt an Earth-centred comoving coordinate system, in which r is the radial distance (we are at $r = 0$) then, in the simple case of a spatially flat Universe, the distance d to an object is given by

$$d = Rr$$

Because the scale factor describes the expansion of the Universe, the ratio of the scale factors when a photon was emitted and when it is observed give us the redshift:

$$(1 + z) = R(\text{observed})/R(\text{emitted})$$

The value of the scale factor is that (1) the equations describing the expansion of the Universe can easily be written in terms of R and its time derivatives and (2) observable cosmological quantities such as the Hubble constant and the deceleration parameter can be described in the same way.

If the scale factor increases with time, the universe is expanding; if the scale factor decreases with time, the universe is contracting. The curvature of constant-t space-like hypersurfaces is equal to the curvature parameter divided by the scale factor.

scale height:
The length scale, for instance in the photosphere of a star, over which the pressure drops by a factor of e (~2.7). Similarly, the length scale from the Galactic plane over which the density of stars drops by this factor.

scale-invariant spectrum:
A power density spectrum with the property that it has the same power per logarithmic interval of wavenumber at all wavenumbers.

scale length:
A typical length scale in a given physical situation.

scattering:
The deflection of the paths of individual particles (such as electrons and photons) by interaction with other particles. Scattering of photons by electrons (Thomson scattering) is particularly important in determining opacity.

scattering medium:
A medium that scatters (see scattering) light.

Schechter function:

A model which fits the luminosity function of many populations of galaxies. Given by

$$\phi(L) = \phi_*\left(\frac{L}{L_*}\right)^{-\alpha}\exp\left(-\frac{L}{L_*}\right)$$

where the normalization ϕ_*, the faint-end slope α and the break luminosity L_* are free parameters.

Schmidt law:
The observation that the star formation rate in galactic discs is proportional to the gas density to some power in the range 1 to 2.

Schrodinger equation:

An equation which describes the spatial and temporal evolution of a particle. The solutions to Schrodinger's equation have wave-like properties, which result in a particle being described by its wave function. The wave function is calculable but not measurable. However, the squared amplitude of the wave function, $|\Psi|^2$, is the position probability density of a particle in a stationary quantum state, i.e. the probability per unit volume that the particle will be found in the neighbouring location.

See also time-dependent Schrodinger equation and time-independent Schrodinger equation.

Schwarzschild black hole:
A non-rotating black hole, the spacetime in the vicinity of which may be described by the Schwarzschild metric.

Schwarzschild coordinates:
Coordinates used in the description of the Schwarzschild solution, namely $x^0=ct$, $x^1 = r$, $x^2 = \theta$, $x^3 = \phi$.

Schwarzschild metric:

The Schwarzschild metric describes the Schwarzschild solution to the Einstein field equations of general relativity. It has 4 non-zero components:

$$[g_{\mu\nu}] = \begin{pmatrix} \left(1-\frac{2GM}{c^2r}\right) & 0 & 0 & 0 \\ 0 & -\frac{1}{\left(1-\frac{2GM}{c^2r}\right)} & 0 & 0 \\ 0 & 0 & -r^2 & 0 \\ 0 & 0 & 0 & -r^2\sin^2\theta \end{pmatrix}$$

The corresponding line element is

$$(\mathrm{d}s)^2 = \left(1-\frac{2GM}{c^2r}\right)c^2\mathrm{d}t^2 - \frac{\mathrm{d}r^2}{\left(1-\frac{2GM}{c^2r}\right)} - r^2\mathrm{d}\theta^2 - r^2\sin^2\theta\,\mathrm{d}\phi^2$$

Schwarzschild radius:
The characteristic radius ($R_S = 2GM/c^2$) in the general relativistic treatment of an isolated non-rotating spherically symmetric body of mass M. A body all of whose mass lies within its Schwarzschild radius is a black hole.

Schwarzschild solution:
The solution of the Einstein field equations of general relativity in the empty region surrounding a non-rotating, spherically symmetric body. It is an example of a vacuum solution to the field equations. The solution is stationary, spherically symmetric, asymptotically flat and singular. See Schwarzschild metric. Compare with Kerr solution.

Schwarzschild spacetime:
A region of spacetime whose properties are described by the Schwarzschild metric.

scientific notation:
The practice of expressing a very large or very small number as another number between 1 and 10 multiplied by ten raised to a certain (positive or negative) power.

scintillation:
Also referred to as twinkling. The rapid irregular variations in brightness of light (or

other electromagnetic radiation) received from stars and other point sources.

SCUBA:
The Submillimetre Common User Bolometer Array, a detector on the JCMT.

S-curve:
The track on a plot of mass accretion rate versus accretion disc surface density followed by a disc as it undergoes a limit cycle behaviour due to the thermal-viscous instability. On the upper branch of the curve, the disc is hot and luminous with a high mass transfer rate and high viscosity; on the lower branch of the curve, the disc is cool and dim with a low mass transfer rate and low viscosity.

SDSS:
See Sloan Digital Sky Survey.

second:
The SI unit of time, represented by the symbol s. The second is one of the seven SI base units, and is defined as 9192 631 770 periods of a certain kind of electromagnetic radiation emitted by caesium-133 atoms.

secondary:
A term used to describe one component of a binary star. In many (but not all) cases the secondary star is the less massive of the two components.

secondary eclipse:
The shallower eclipse in a binary system. For an eclipsing binary star, it is when the fainter star passes behind the brighter star. For a transiting exoplanet system, it is when the planet passes behind the star.

secondary emission:
In active galaxies, the electro-magnetic radiation which is due to re-radiation by gas which receives its energy from primary emission processes, e.g. free-free emission from an ionized gas.

secondary minimum:
The shallower of the two minima in the light curve of an eclipsing binary star. Also known as secondary eclipse.

second derivative:

The derivative of the derivative of a function. Given a function $f(y)$, its second derivative with respect to y is also a function of y, and may be written as

$$\frac{\mathrm{d}^2 f(y)}{\mathrm{d}y^2}$$

secular resonance:
The situation where the orientation of the orbits of two or more bodies changes with time such that the precession is synchronised between the different orbits.

seeing:
The quality of the observing conditions determined by the atmosphere above the telescope. Often quantified by the angular width of the resulting point spread function in arcseconds.

selection effect:
Any effect which causes an observed sample to be unrepresentative of the parent distribution or parent population from which the sample is drawn. See Malmquist bias.

selection function:
A function which expresses the probabilities that an object of a given luminosity may be detected in a volume-limited sample.

selection rules:
Rules that govern whether particular radiative transitions are allowed or forbidden. For example, the allowed changes in the quantum numbers of an electron in an atom are restricted to $\Delta l = \pm1$ and $\Delta m_l = 0$ or ±1. There is no restriction on the change in the value of n.

semi-analytic model:
A model which combines elements of an analytical model (derived from underlying principles) with results from numerical simulations.

semidetached:
A term used to describe a binary system in which one, and only one, of the two stars is overflowing its Roche lobe with the consequence that mass transfer is therefore taking place from one star to the other.

semi-forbidden line:
A non-permitted spectral line which breaks different selection rules to those involved in forbidden lines. Also known as an intercombination line.

semi-latus rectum:

The distance l from the focus of an ellipse to the ellipse itself, in a direction perpendicular to the major axis. In polar coordinates (r,θ), an elliptical orbit may be described by $r = l / (1 + e \cos\theta)$ where e is the eccentricity of the ellipse. In the case of an orbit, θ is the true anomaly of the orbiting body.

semi-major axis:
Half the length of the long axis of an ellipse. Equivalently, it is the mean value of the periastron and apastron distances, and is related to the semi-latus rectum l and eccentricity e of an ellipse by $a = l / (1 - e^2)$.

seminal:
A term used to describe a research paper which opens up a new area and stimulates many other workers to explore it. Seminal papers will have a large number of citations.

Sersic profile:

A generalisation of the de Vaucouleurs' law for the surface brightness profile of an elliptical galaxy as:

$$I(r) = I_0 \exp\left(-(r/r_0)^{1/n}\right)$$

Seyfert 1.5, 1.8, 1.9:
Subclasses of Seyfert galaxies lying between the Seyfert type 1 and Seyfert type 2 classifications. Numerically larger subclasses have weaker broad lines relative to their narrow lines.

Seyfert galaxies:
See Seyfert galaxy.

Seyfert galaxy:
Galaxies forming a class of active galaxy characterized by optical emission from the active nucleus that is bright enough to be noticeable but not so bright as to outshine the stars of the host galaxy (contrast quasar). Type 1 Seyfert galaxies otherwise share many observational features with quasars, including time-variable continuum flux, large UV flux (the big blue bump, thought to come from an accretion disc), strong broad and narrow emission lines (see broad-line region, narrow-line region) and large, variable X-ray flux, and the distinction between Seyfert 1s and quasars is largely one of terminology only. Type 2 Seyfert galaxies exhibit weaker nuclear continuum activity and no or very weak broad emission lines. A number of classes intermediate between the two original types have been defined (Seyfert 1.5, 1.8, 1.9 etc). In unified models for Seyferts, at least some, and possibly all Seyfert 2s are Seyfert 1s seen at a large angle to the line of sight. Seyfert host galaxies are normally, though not exclusively spirals, and of the order of 10% of massive spirals show signs of Seyfert activity, suggesting that a Seyfert phase is common in spiral galaxies.

S-factor:
A factor, usually denoted $S(E)$, appearing in the expression for the fusion cross-section for nuclei with relative energy E, only weakly dependent on energy (except near nuclear resonances), whose size reflects the strength of the interaction between two particles. The S-factor, and hence the fusion rate, is very low for weak interactions, of intermediate size for electromagnetic interactions, and greatest for strong interactions.

Sgr A*:
Sagittarius A*, the compact radio source at the centre of the Milky Way galaxy, believed to represent emission from the vicinity of a supermassive black hole.

Shakura–Sunyaev disc:

A steady-state, optically thick, geometrically thin accretion disc with an alpha-viscosity. The thickness of such as disc is given by $H/r \sim c_s/v_K$ where $c_s$is the sound speed in the disc and v_K is the Keplerian velocity in the disc at radius r.

Shapiro delay:
In gravitational lensing, two different images of a background source would have different path lengths and experience different gravitational potentials, so in general there should be a relative time delay between different images of the same background source.

Shapiro time delay experiment:
A classic test of general relativity, exploiting exceptionally high-powered radar, that was proposed by Irwin Shapiro in 1964. The basic idea of the Shapiro time delay experiment is to record the transit times of radar signals from the Earth to a nearby planet (such as Mercury or Venus) and back. If the planet is just slipping around the back of the Sun then the radar pulse will probe the region close to the Sun where the spacetime metric differs most from that of special relativity.

shear:
A parameter, γ, in the expression for the inverse magnification tensor used to describe gravitational lensing by large scale structure. Shear stretches the shapes of galaxies in a particular direction. See also convergence and cosmic shear.

shear strain:
See strain.

shear stress:

The force per unit area exerted parallel to a surface. If $F_{||}$ denotes the component of a force that is parallel to a surface with area A, then the corresponding shear stress is $\sigma_s = F_{||}/A$.

shear viscosity:
The constant of proportionality between shear stress and shear strain, i.e. the magnitude of shear stress is shear viscosity times the magnitude of shear strain. See also dynamical viscosity.

shell burning:
Nuclear fusion processes occurring inside (post-main-sequence) stars, in which thermonuclear reactions take place in a shell of material surrounding the core. The shell burning generally involves specific nuclei and is initiated at a specific temperature. See shell hydrogen burning for an example.

shell hydrogen burning:
The conversion of hydrogen into helium in a star, occurring as a result of nuclear fusion processes, in a shell of material surrounding a helium core.

shock:

A propagating discontinuous change in the properties of a fluid, such as an astrophysical plasma. Shocks occur whenever there is bulk motion at speeds faster than the speed of sound in the medium (supersonic motion); in this case there is no way for material ahead of the shock front (the leading edge of the shock) to react to the approach of the shock. Material crossing the shock front is heated and compressed, and may also be ionized, leading to increased thermal continuum emission and possibly also line emission from the shocked material.

Shocks may also be involved in the particle acceleration processes that produce the power-law distributions of high-energy electrons responsible for synchrotron emission. Supernovae, gamma-ray bursts, rapidly moving X-ray binaries and pulsars, and expanding radio galaxies all produce shocks.

shock front:
See shock.

SI:
An internationally agreed system of units of measurement. The system employs seven base units (including the metre and the second) and an unlimited number of derived units obtained by combining the base units in various ways. The system also uses certain standard SI multiples and SI submultiples and recognizes a number of standard symbols and abbreviations. (SI is one of those symbols and stands for Systeme International.)

signal-to-noise ratio:
The signal of a particular detection divided by the noise associated with the measurement.

significant figures:
The accurately meaningful digits in the value of a physical quantity. The number of significant figures in a value such as 12 000 may be ambiguous unless the value is expressed in scientific notation, in which case 1.2×10^4 would indicate 2 significant figures, whereas 1.2000×10^4 would indicate 5 significant figures.

silicon burning:
The final advanced stage of nuclear burning in an initially massive ($M_{ms} \geq 10M_0$) star. Photodisintegration releases α-particles from some silicon nuclei, whereupon remaining silicon nuclei capture the liberated α-particles to produce heavier nuclei up to the iron peak. See also nuclear statistical equilibrium.

silicon melting:

Also referred to as silicon burning. The ‘melting’ term reflects the fact that photo-disintegration and α-captures occur in equilibrium.

Silk damping:
See diffusion damping

simultaneous equations:
Two or more equations concerning the same quantities that must be satisfied simultaneously. In general it is possible to solve such equations by rearranging them to eliminate all quantities except the particular quantity of interest. Because each equation gives one extra piece of information, there must be as many equations as there are unknowns.

simultaneous (events):
Two events that occur at the same time in a given frame of reference are said to be simultaneous.

SI multiple:

Any one of a number of standard factors of the form 10^3, 10^6, 10^9, etc. Each is represented by a standard prefix such as kilo, mega, giga, etc.

sine:
See trigonometric functions.

sine curve:
See trigonometric functions.

singular isothermal sphere:
A spherically symmetric distribution of mass whose density and surface density tends to infinity as its characteristic radial distance tends to zero.

singularity:

In the Schwarzschild metric, as the radius approaches the Schwarzschild radius, the metric coefficient g_{11} tends to infinity. This described by saying there is a singularity in the metric. In this case it is a coordinate singularity (a consequence of the Schwarzschild coordinates being used) rather that a physically meaningful gravitational singularity. A coordinate singularity can be removed by an appropriate transformation of coordinates.

The Schwarzschild metric also has a singularity at a radius of zero - this is a gravitational singularity marked by the unlimited growth of invariants related to the curvature, and cannot be removed by any changeof coordinates.

sinusoidal:
A term used to indicate a variation that may be described by a sine function. This also applies to a cosine function since $\cos\theta = \sin(\theta + \pi/2)$.

Sirius:
The brightest star in the sky, after the Sun, with apparent magnitude in the V band of -1.46. It is a visual binary, with a white dwarf companion. The main star (Sirius A) is a main sequence star, somewhat more massive than the Sun, and is bright mainly because it is relatively nearby (about 3 parsec).

SI submultiple:

An SI submultiple is one of a number of standard factors of the form 10^{-3}, 10^{-6}, 10^{-9}, etc. Each is represented by a standard prefix such as milli, micro, nano, etc.

Skumanich law:
A law which states that the rotational angular speed ω of solar-type single stars decreases with stellar age as $\omega \propto t^{-1/2}$.

Sloan Digital Sky Survey:
An optical survey covering about one quarter of the sky and whose initial main science goals relate to mapping the three-dimensional distribution of galaxies and quasars over the survey areas.

slope of a graph:
See gradient of a graph.

slowly-rolling approximation:
The approximation made when neglecting the second-derivative with respect to time of the inflaton field that is responsible for inflation in the early universe.

small-angle approximation:
The expression of the fact that, as an angle θ (measured in radians) approaches zero, the approximations $\sin\theta \approx \tan\theta \approx \theta$ and $\cos\theta \approx 1$ become increasingly more accurate.

small blue bump:
A feature in the spectral energy distribution of some active galaxies that is due to a series of overlapping emission lines.

Small Magellanic Cloud:
A small, irregular satellite galaxy to the Milky Way.

SMC:
See Small Magellanic Cloud.

SMG:
Sub-Millimetre Galaxy. A galaxy detected at submillimetre wavelengths.

snowline:
The distance from a protostar beyond which the protoplanetary disc is cool enough for water, methane and ammonia to condense into solid ice grains.

SNR:
See supernova remnant.

SNU:

See solar neutrino unit.

soft gamma-ray repeater:
A source of low energy gamma-rays which emits strong bursts of gamma-rays at irregular intervals. SGRs are believed to be magnetars, and the bursts of soft gamma-ray emission are thought to be related to the decay and re-arrangement of the strong magnetic field of a neutron star. See also anomalous X-ray pulsar.

softness:
The relative amount of 'soft' to 'hard' (i.e. low energy to high energy) photons in a spectrum. See hardness.

soft X-ray excess:
An excess of emission at low X-ray energies seen in the spectra of some active galaxies. May represent the high energy end of the big blue bump.

soft X-rays:
Low-energy X-rays. The dividing line between soft and hard X-rays will vary according to context, but a typical division is around ~2 keV.

soft X-ray transient:
A binary star containing a neutron star (or black hole) accreting via Roche lobe overflow from a (usually) low mass donor star. They are members of a class of X-ray binaries in which a bright X-ray and (usually) optical outburst lasting a few weeks is followed by a slow decline on a timescale of months, recurring on a timescale of years. As with a dwarf nova, the cause of the phenomenon is a thermal-viscous instability in the accretion disc.

solar neutrino problem:
The fact that the average flux of neutrinos detected from the Sun is significantly less than that predicted by the standard solar model. See neutrino astronomy.

solar neutrino unit:
A non-SI unit used for the measurement of the flux of neutrinos from the Sun. One SNU equals one neutrino-induced event per 10^{36} target atoms in a neutrino detector. The very large number of atoms required reflects the fact that neutrinos interact by the weak nuclear interaction.

solar-type:
Referring to stars of a similar spectral type to the Sun. Often taken to be F, G or K type stars in general.

solar wind:
A gusty flow of energetic charged particles that leave the solar corona and stream out into space. The gravitational force at the surface of the Sun is insufficient to confine these very energetic particles. All stars have these winds, which provide one channel for stellar mass loss. Some stars have very much higher mass loss rates to winds than the Sun.

solid angle:
The three-dimensional analogue of a plane angle, being the vertex subtended at the centre of a sphere by a portion of the surface area of the sphere. Measured in steradians.

sound horizon:
The distance in the Universe that a sound wave could have travelled since the end of inflation.

sound speed:

The speed at which the wavefronts of a sound wave propogate. In an ideal gas, the sound speed c_s is given by $(P/\rho)^{1/2}$ where P is the gas pressure and ρ is its density, or equivalently by $(kT/m)^{1/2}$ where T is the temperature, k is the Boltzmann constant and m is mean molecular mass.

sound wave:
A longitudinal wave with a frequency between about 20 Hz and 20 000 Hz, that might be the direct cause of the phenomenon perceived as sound. Such waves can travel through a gas, liquid or solid.

source count:
See number count.

source count model:
A model which aims to account for the observed number count and redshift distributions of galaxies.

space density:
The number of sources of a particular type per unit volume. It is usually corrected for the effects of the expansion of the Universe if the sources are at cosmological distances.

space-like hypersurface:
A three-dimensional space with geometric properties that are homogenous and isotropic.

space-like separation:

Events with a negative spacetime separation are said to be space-like. Such events are not causally related and there will exist a frame of reference in which the two events happen at the same time but at different places.

See time-like separation and light-like separation.

spacetime:
In special and general relativity, the unification of space and time into a single four-dimensional manifold which allows the coordinates of events to be defined. In general relativity, the paths that objects take under the influence of gravity are a result of the curvature of spacetime.

spacetime diagram:
Also known as a Minkowski diagram, it is a graphical tool to visualize events in Minkowski spacetime. It takes the form of a plot of *ct* against *x* on which each point represents an event. It can be used to show the coordinate systems for two observers moving relative to each other with constant velocity as sets of inclined axes. It allows the space and time coordinates *x* and *t* used by one observer to be converted immediately into the corresponding *x*′ and *t*′ used by the other and vice versa.

spacetime separation:

In Minkowski spacetime, the spacetime separation between two events is given by $(\Delta s)^2 = (c\Delta t)^2 - (\Delta x)^2 - (\Delta y)^2 - (\Delta z)^2$. It is an invariant quantity.

Events with a positive spacetime separation are said to be time-like. Such events are causally related and there will exist a frame of reference in which the two events happen at the same place but at different times.

Events with a zero spacetime separation are said to be light-like. Such events are causally related and all observers will agree that they could be linked by a light signal.

Events with a negative spacetime separation are said to be space-like. Such events are not causally related and there will exist a frame of reference in which the two events happen at the same time but at different places.

spaghettification:
In the case of an astronaut falling feet first towards a non-rotating black hole, the geodesic deviation stretches the astronaut in the radial direction and causes compression in the transverse directions. This is referred to as spaghettification.

sparse sampling:
In conducting a survey of objects, the process of sampling only a random subset of objects, rather than a complete sample.

spatially resolve:
The ability to distinguish spatial detail in an image. Quantified in terms of angular resolution.

special relativity:
See special theory of relativity.

special theory of relativity:
The theory, proposed by Albert Einstein in 1905, based on the principle that the laws of physics should not favour one inertial observer over another. The theory is essentially concerned with the relationship between observations made by (inertial) observers who are in uniform relative motion. The theory is ‘special’ in that it only applies in an inertial frame of reference, that is, one which is not accelerating and which is not subject to gravitational forces (the effects of which are locally equivalent, according to Einstein’s general theory of relativity).

specific heat capacity:
The heat capacity per unit mass of a specified substance. In other words, the energy per unit mass and per unit temperature rise needed to raise the temperature of a sample of a specified substance under specified conditions (such as constant pressure or constant volume). Specific heat capacity is measured in units of $\mathrm{J\ K^{-1}\ kg^{-1}}$, and is often referred to simply as ‘specific heat’.

speckle imaging:
A technique used to evade some of the limits on angular resolution for ground-based optical telescopes imposed by the Earth’s atmosphere. It involves taking very short exposures, thereby ‘freezing’ the turbulent atmospheric structure responsible for the blurring of images as seen from the ground in longer exposures. By analysis of a large number of these images, each containing the same region of sky but affected by different atmospheric conditions, the effects of turbulence can be removed and a high-resolution picture of the region of interest can be built up.

spectra:
The plural of spectrum.

spectral:

Relating to properties of a system as a function of wavelength, frequency or photon energy.

spectral classification:

A classification used together with the luminosity classification to give the overall type of a star. The spectral classification of a star is essentially an indication of its effective temperature (the temperature of the photosphere) and therefore reflects its position on the horizontal axis of the Hertzsprung-Russell diagram. Stars are classified by their colour and by the absorption lines observed in their atmospheres. The majority of stars can be divided into seven spectral types, O, B, A, F, G, K and M (remembered by generations of astronomers using the mnemonic 'oh, be a fine girl/guy, kiss me'). These correspond to stellar properties as follows:

Type	Temperature/colour	Spectral lines
O	hottest blue stars	ionized helium lines
B	hot blue stars	neutral helium lines
A	blue/white stars	hydrogen lines dominant, *metal* lines present
F	white stars	metal lines stronger, hydrogen lines weaker
G	yellow stars	ionized calcium dominant, metal lines stronger
K	orange stars	neutral metals dominant, molecular lines observed
M	red stars	molecular lines dominant

spectral energy distribution:
The flux density observed from a star or galaxy expressed as a function of (or graphically plotted against) the frequency or wavelength (or photon energy) of the emission.

spectral excess:
Any region of a spectral energy distribution which displays a larger flux density than expected on the basis of a particular model.

spectral flux density:
A quantity used to describe the flux (energy received per unit area per unit time) per unit frequency, or wavelength from an astronomical object. The SI units are W m^{-2} Hz^{-1} or W m^{-2} m^{-1}, but non-SI units (e.g. ergs s^{-1} cm^{-2} $Å^{-1}$) are in common use. Spectral flux density, often referred to just as 'flux density', has the advantage that it is not necessary to know the filter or bandwidth used to make the observation in order to interpret the results. It is widely used in radio astronomy, where the bandwidth is always small compared to the available range in frequency. Radio astronomers express it using a special derived unit, the jansky (Jy) where 1 Jy = 1×10^{-26} W m^{-2} Hz^{-1}.

spectral index:
If a spectrum is represented as a power law of the form $\nu^{-\alpha}$, then α is referred to as the spectral index.

spectral line:
A narrow line seen in the spectrum of a substance. The lines correspond to those particular wavelengths of electromagnetic radiation that may be absorbed or emitted by atoms or molecules of the substance as a result of transitions occurring between energy levels.

spectral resolution:
Used to describe the performance of a spectrograph. Given by the wavelength divided by the width of the resolution element at that wavelength.

spectral softening:
The phenomenon whereby a spectrum becomes 'softer' with time, i.e. the proportion of lower energy photons to higher energy photons in the spectrum increases.

spectral type:
Referring to the type of spectrum a star displays. See spectral classification.

spectroscopic binaries:
See binary star.

spectroscopic binary:
A star whose spectrum shows evidence for two stellar components that are orbitting around each other. See binary star.

spectrum:

(1) In the context of the electromagnetic radiation emitted by atoms or molecules, a spectrum is any detailed representation of the way in which the intensity of the radiation is distributed with respect to wavelength or frequency or photon energy. A spectrum may be obtained experimentally, as a band of light, using a spectrometer or some similar instrument. Alternatively the spectrum may be presented as a graph.

(2) In more general contexts, the term spectrum may be used to refer to any spread or

distribution of one quantity with respect to another.

speed:

(1) In the context of kinematics, the speed of a specified body is the magnitude of the (instantaneous) velocity of that body. The SI unit of speed is the metre per second ($m\ s^{-1}$).

(2) In the context of waves, the speed of a travelling wave is the product of the wavelength λ and frequency f of the wave, so $v = f\lambda$. (This also represents the speed at which a point of constant phase travels in the direction of propagation of the wave, and may therefore be referred to as the 'phase speed' of the wave.) The speed of light in a vacuum is represented by the symbol c and has a value of $2.998 \times 10^8\ m\ s^{-1}$.

speed of light:
The speed at which all electromagnetic radiation propagate. In a vacuum it is represented by the symbol c and has a value $2.998 \times 10^8 m\ s^{-1}$ (to 3 significant figures). In other media, the speed of light is less than c, and is often different for different frequencies of radiation, so giving rise to the phenomenon of dispersion. Einstein's special theory of relativity is based on the postulate that the speed of light (in a vacuum) has the same constant value in every inertial frame of reference. Causality in Einstein's theory relies on the fact that the speed of light in a vacuum is the maximum speed at which a signal can travel.

spherical coordinates:
See spherical polar coordinate system.

spherical harmonics:
The angular portion of the solutions to Laplace's equation, $\nabla^2\psi = 0$.

spherical polar coordinates:
See spherical polar coordinate system.

spherical polar coordinate system:
A coordinate system in which the position of a point is given by the three coordinates (r, θ, ϕ) where r is the distance from the origin, θ is the angle that the position vector $\boldsymbol{r}$ of the point makes to the z-axis, and ϕ is the angle between the x-axis and the projection of $\boldsymbol{r}$ on to the xy-plane. This coordinate system is particularly useful for systems that exhibit spherical symmetry, since the quantities associated with that system depend only on r and not on θ or ϕ. The coordinates are related to Cartesian coordinates x, y and z by $x = r \sin\theta \cos\phi$, $y = r \sin\theta \sin\phi$, $z = r \cos\theta$.

spin:
See spin angular momentum quantum number.

spin angular momentum quantum number:

A quantum number, conventionally represented by the symbol s, that characterizes the magnitude S of the intrinsic angular momentum of a particle:

$$S = \sqrt{s(s+1)}\hbar$$

The spin angular momentum quantum number is often referred to as simply the spin; hence the electron is said to have spin 1/2, and the photon spin 1. Spin is an inherently quantum property.

spin magnetic quantum number:

A quantum number, conventionally represented by the symbol m_s, that determines the z-component, S_z, of the intrinsic angular momentum of a particle: $S_z = m_s\hbar$

For a particle with spin s=1/2 (such as an electron) m_s can take only two values, +1/2 or -1/2; for a particle with spin 1 (such as a photon), m_s can take the values, ±1 or 0.

spin modulation:
The variation of a signal (e.g. the X-ray flux) with the rotational (spin) period of a rotating body (e.g. a rotating white dwarf).

spin-orbit angle:
The angle between the spin axis of a star and the orbital angular momentum vector of an orbiting body, such as a planet.

spiral galaxies:
See spiral galaxy.

spiral galaxy:
A galaxy that shows a gas-rich disc with active star formation, which often has observable spiral arms, usually surrounding a galactic bulge containing mainly older stars, and in turn surrounded by a low-density halo. Our Milky Way is an example of a spiral galaxy.

s-process:

The 'slow' process of neutron-capture reactions, in which there is time for the newly synthesized element to β-decay back to a stable (or long-lived) isotope between each neutron capture event. This has the effect that the s-process cannot increase the atomic number beyond the highest-atomic number element with at least one stable isotope, bismuth (Z = 83) even though long-lived isotopes with higher atomic numbers exist. These must instead be synthesized by the r-process. The trajectory taken in atomic number and mass number (on the chart of nuclides) by a nucleus undergoing the s-process is called the s-process pathway. The s-process is thought to take place in the late stages of massive star evolution, where free neutrons are produced as a by-product of fusion reactions.

s-process pathway:
The path taken by the s-process on the chart of nuclides.

stacking analysis:
A widely used technique in observational cosmology whereby images of separate objects are averaged together in order to detect the average signal from the population of objects.

standard candle:
An astronomical object with a known luminosity or absolute magnitude. Such objects are of great importance in astronomy; if their flux or apparent magnitude can be determined, then their distance can be calculated, together with the distance of any other objects associated with them. In Galactic astronomy, certain types of star with fixed positions on the Hertzsprung-Russell diagram can be used as standard candles: RR Lyrae stars are a good example. Standard candles to determine the distance to distant galaxies are harder to find; attempts to use quasars or other active galaxies as standard candles have failed because of the wide ranges in their luminosities. Type 1A supernovae are an important standard candle at high redshifts.

standard configuration:
The simplest possible arrangement of two inertial frames of reference with constant velocity relative to each other. The axes of the first inertial frame of reference are all parallel to the corresponding axes of the second frame. The origins of the two frames coincide at $t = t' = 0$, and the origin of the second frame moves along the x-axis of the first frame in the positive direction. The two frames of reference maintain the same relative orientation while moving.

standard rod:
An object with a known, fixed length.

star:
A luminous gaseous body that is gravitationally bound and that is capable, or was capable in the past, of sustaining itself against gravitational collapse by thermonuclear reactions. Until the very late stages of their evolution, stars are composed mostly of hydrogen and helium, which are the most abundant elements in the Universe (see nucleosynthesis). The fundamental properties of a star are its mass, age and composition; these in turn determine (via the stellar structure equations) directly observable parameters such as luminosity and temperature, which give us the position in an evolutionary sequence that can be mapped out on the Hertzsprung-Russell diagram. The lower limit on stellar masses (below which hydrogen burning is never initiated) is 0.08 times the mass of the Sun; the most massive observed stars contain around 100 solar masses. There is a much larger range in stellar luminosities, a factor around 10^{10}.

starburst:
See starburst galaxy.

starburst galaxies:
See starburst galaxy.

starburst galaxy:
A galaxy that is currently undergoing an episode of star formation at significantly more than the average rate. The production of a large number of massive stars can dramatically increase the galaxy’s bolometric luminosity (see, for example, IRAS galaxy). The starburst is generally spread through a large (kiloparsec-scale) region of the galaxy, which clearly differentiates starburst galaxies from active galaxies. What triggers the star formation is unclear, but in some cases it is associated with galaxy–galaxy gravitational interactions.

star formation:
The process of formation of stars from cold interstellar gas. Observational signatures of recent star formation include infrared emission from protostars, hot, blue stars (which are short-lived and therefore necessarily recently formed), HII regions illuminated by hot stars and young supernova remnants.

starspot:
A darker, cooler region on the surface of a star caused by strong magnetic fields which inhibit convection and therefore energy transport to the surface. Our Sun exhibits comparatively weak sunspots; in some stars a significant fraction of the star’s surface is affected. A greater coverage of starspots than the Sun’s appears to be associated with lower stellar masses, higher spin rates and higher magnetic fields.

static limit:
The surface of infinite redshift in the Kerr solution for a rotating black hole. See Kerr metric.

static (metric):
A metric, like the Schwarzschild metric, whose line element is unchanged if *t* is replaced by -*t*, (i.e. nothing is rotating).

stationary (metric):
A metric, like the Schwarzschild metric, whose coefficients do not depend on time.

stationary state:
A quantum state in which the probabilities of all the possible outcomes of measurements are independent of time. Although such states may be described by time-dependent wave functions, they are, for most purposes, adequately described by a time-independent wave function. In practice, such states are often specified in terms of the values of the quantum numbers that characterize that state. A typical example would be the state of the hydrogen atom specified by the quantum numbers $n = 2$, $l = 1$, $m_l = -1$.

statistical equilibrium:
The condition that the number of atoms or ions in a particular quantum state remains constant.

statistical fluctuations:
Deviations from one measurement to another, due to the intrinsic random variability inherent in the system under study.

steady state:
Time-independent. If a system is in a steady state the time derivative of any quantity that describes a property of the system must be identical to zero.

steady-state disc:
An accretion disc undergoing time-independent accretion, i.e. the disc appears the same at all times.

Stefan-Boltzmann constant:
The constant $\sigma = 5.6715 \times 10^{-8}\ \mathrm{W\ m^{-2}\ K^{-4}}$ which appears in the Stefan-Boltzmann law.

Stefan-Boltzmann law:

The relationship $F = \sigma T^4$ which describes the flux of electromagnetic radiation escaping from a surface that emits as a black body, where σ is the Stefan-Boltzmann constant.

Stellar populations:

There are two basic stellar populations: Population I and Population II, into which stars in galaxies can be divided. Population I stars are young, metal-rich stars inhabiting the galactic disc of spiral galaxies, and associated with gas, dust and recent star formation; population II stars are old, metal-poor stars that are found in the halo and galactic bulge of spirals, and throughout ellipticals. Population I stars are thus effectively a signature of recent star formation. Their higher metal abundances come from the fact that they were formed after an earlier generation of (no longer existing) massive population II stars had enriched the interstellar medium (see nucleosynthesis).

A hypothetical group of Population III stars must have been formed from primordial hydrogen and helium only, before Population II stars formed. Such stars are postulated to have been extremely massive and short-lived.

stellar structure equations:

The equations that determine the distribution of mass, temperature and energy generation in a star. These can be written as four differential equations in terms of the radius *r*, the pressure *P*, the mass within a given radius M(*r*), the density *ρ*, the luminosity at a given radius *L*, the specific emissivity (luminosity generated per unit mass) *ε*, the temperature *T* (related to pressure and density by the ideal gas law) and the opacity *κ* :

$$\frac{\mathrm{d}P(r)}{\mathrm{d}r} = -\frac{Gm(r)\rho(r)}{r^2}$$ (the equation of hydrostatic equilibrium)

$$\frac{\mathrm{d}m(r)}{\mathrm{d}r} = 4\pi r^2 \rho(r)$$ (the definition of enclosed mass, or the equation of mass continuity)

$$\frac{\mathrm{d}T(r)}{\mathrm{d}r} = -\frac{3\kappa(r)\rho(r)L(r)}{(4\pi r^2)(16\sigma)T^3(r)}$$ (the radiative transport equation).

$$\frac{\mathrm{d}L(r)}{\mathrm{d}r} = 4\pi r^2 \epsilon(r)$$ (the energy generation equation)

Solving these equations also involves some assumptions about energy generation and transport and chemical composition, but in principle they can be used as part of a computer model to study the structure of stars.

steradian:

The SI unit of solid angle, being that subtended at the centre of a sphere by an area equal to the radius of the sphere squared. Consequently a sphere encompasses 4π steradians. The SI symbol for steradians is sr.

stochastic noise:
Used to refer to random variations in the brightness of an astronomical object.

strain:
A quantity used to measure the deformation caused by the application of stress. In the case of shear stress in a fluid the corresponding strain - shear strain – is the gradient $\partial v/\partial z$ of the fluid flow velocity v perpendicular to the flow direction of the fluid.

strange quark:
A quark with electric charge -e/3. Along with the charm quark, a member of the second generation of quarks.

stratosphere:
A layer in the Earth's atmopshere lying at altitudes of between 10km and 50km.

stress:
A quantity used to measure the force applied over the surface of a body, per unit area of the surface. Since both force and surface orientation are associated with directions, there are a number of ways in which these directions can be taken into account when defining stress; this leads to the consideration of a number of different components of stress in the general case. In the simplest cases 'normal stress' may be identified with the magnitude of the normal (i.e. perpendicular to the surface) component of force per unit area, and this can be further identified with pressure. Another simple case is that of sheer stress in which the stress component is identified with the magnitude of the tangential component of force per unit area.

string theory:
A candidate for an explanation of superunification and a theory of quantum gravity.

Stromgren depth:
Equivalent to the Stromgren radius.

Stromgren radius:
The distance from an ionizing source of radiation at which photoionization equilibrium exists, i.e. the ionization rate equals the recombination rate. The ionized region within the Stromgren radius is the Stromgren sphere.

Stromgren sphere:
An ionized bubble or region surrounding a luminous object, caused by the ionizing radiation emitted by the object.

strong anthropic principle:
The assertion that the Universe must be suitable for the formation of intelligent life.

strong equivalence principle:
The statement that: "The physical behaviour within a local spacetime region resulting from a concentration of mass cannot be distinguished by *any* experiment from the physical behaviour within a local spacetime region resulting from an appropriate uniform acceleration."

strong nuclear force:
See fundamental forces.

strong nuclear interaction:
Another name for the strong nuclear force; see fundamental forces.

sublimation:
A change of state from solid to gas.

sublimation radius:
The minimum distance from an AGN (or other luminous source) at which dust grains can exist without sublimating (i.e. changing from the solid to gaseous state).

submillimetre astronomy:
Radio astronomy carried out at wavelengths between 0.3 and 1 mm (between 300 GHz and 1 THz). It is important because of the large number of molecular emission lines in these frequency range.

submillimetre break:
The location in the continuum spectrum of radio-quiet AGN at which the spectrum begins to decrease rapidly towards low energies.

submillimetre galaxies:
Galaxies selected on the basis of their submillimetre wavelength emission. They are far-infrared-luminous high-redshift galaxies.

sub-stellar point:
The position on a planet where the centre of its parent star's disc appears exactly

overhead.

subtend:

A term used to describe the relation between two points (or an arc connecting those points) and the angle between those points as measured at a third point. A circular arc of radius R and arc length s_{arc} is said to subtend an angle (measured in radians) of $\alpha = s_{arc}/R$ at the centre of the circle of which it is part. More generally, any two points A and B may be said to subtend an angle α at a third point C if α is the angular displacement of A from B, as measured at C.

sum rule:
A method for determining the derivative of a function which is the sum of two (or more) other functions. If $y = u \pm v$ then $dy/dx = du/dx \pm dv/dx$.

Sun:
The nearest star to the Earth. It is a main sequence star of spectral type G2V. It has a mass of 1.99×10^{30} kg, a radius of 6.96×10^{8} m and a luminosity of 3.83×10^{26} W. Its effective surface temperature is 5780 K.

Sunyaev-Zel'dovich effect:
When cosmic microwave background photons pass through a foreground galaxy cluster, they may undergo inverse Compton scattering by high energy electrons in the gas through which they pass. The photons in the Rayleigh-Jeans regime (long wavelengths) are supressed, but those on the other side of the black body peak (short wavelengths) are enhanced. The characteristic wavelength-dependent supression and enhancement is known as the Sunyaev-Zel'dovich effect.

supercluster:
A cluster of clusters of galaxies.

super-Earth:
An exoplanet with a mass that is a few times that of the Earth. (also sometimes known as mini-Neptune.)

super-Eddington accretion:
An accretion rate above the Eddington limit.

superior conjunction:
The point in an orbit of a planet around a star when the star lies directly between the planet and the observer. See inferior conjunction.

superluminal jet source:
An X-ray binary or active galaxy displaying a jet that appears to expand with speeds greater than the speed of light. See also superluminal motion.

superluminal motion:
The apparent faster-than-light motion exhibited by some superluminal jet sources. The observed motion is due to material emitted at a small angle to the line of sight at a speed which is less than the speed of light.

supermassive:
A term used to describe black holes, implying that they have very much more mass than would be expected from a black hole that originated as the remnant of a single star. Black holes in the centres of galaxies, including those believed to power active galactic nuclei, are thought to have masses in the range 10^{6}–10^{9} solar masses, and so are described as supermassive.

supernova:

A star whose luminosity temporarily increases to very high values (an absolute magnitude of −15 or greater, much greater than would be expected for a classical nova) before fading rapidly on a timescale of weeks to months. Energy is emitted in the form of light but also as a burst of neutrinos and as kinetic energy of ejected material (see supernova remnants). There are several ways in which this can happen.

Type Ia supernovae are thought to occur when accretion onto the surface of a white dwarf in a binary system takes its mass over the Chandrasekhar limit. When this happens, the star can no longer be supported by degeneracy pressure, and so it starts to collapse, igniting runaway thermonuclear reactions between the heavy nuclei in the star (similar, on a much larger scale, to the helium flash). The resulting explosion destroys the star and gives rise to the observed supernova. Type Ia supernovae show no hydrogen lines in their spectra, consistent with an origin in a massive white dwarf; absorption features from heavy elements such as silicon are common. Because all type Ia supernovae have a mass around the Chandrasekhar mass, they have a very similar peak absolute magnitude (–19) and so can be used as standard candles.

Type Ib and Ic supernovae were originally classed with Ia because of the lack of hydrogen features in their spectrum, but now appear to be physically different, and more closely related to type II supernovae, in which a massive star fuses elements all the way to iron (see nucleosynthesis) in its core, so that the core cannot support itself any longer by fusion, or (if its mass is above the Chandrasekhar limit) by degeneracy pressure. In these systems, energy-absorbing (endothermic) processes become important, removing energy from the electrons and nuclei that provide the pressure support. The result is that the star's core collapses on approximately the free-fall timescale (milliseconds) to form a neutron star; energy liberated in the collapse heats and drives off the outer layers. These 'core-collapse' supernovae are much more diverse than type 1a supernovae, since the range of conditions of the star before the explosion is much larger. Types 1b and 1c, for example, have probably lost their hydrogen-rich envelopes by mass transfer before the supernova explosion. Core-collapse supernovae are probably the main site for the r-process of nucleosynthesis.

supernova remnant:
(SNR) The shell of rapidly expanding gas that is left behind after a supernova. A small but significant fraction of the binding energy of the collapsed star is put into the kinetic energy of a significant amount (of the order of a solar mass) of ejected material. This moves very rapidly away from the star, and its supersonic motion causes a shock to develop which heats and compresses the material surrounding the star. Supernova remnants are therefore detected in thermal bremsstrahlung from the shock-heated gas, as well as radio synchrotron radiation from high-energy particles accelerated by the shock and (later in their lives) in recombination emission as the shock-heated material cools and becomes neutral. They typically appear as bright rings surrounding the site of the explosion. A supernova remnant can persist for up to 50 000 years after the original supernova.

SuperWASP:
The Wide Angle Search for Planets. The leading ground-based programme searching for transiting exoplanets. See www.superwasp.org

superwind:
A period of extreme mass loss which occurs during the late stages of evolution of asymptotic giant branch stars, when a substantial fraction of the mass of a star may be ejected.

surface brightness:
A quantity used to describe the flux per unit area on the sky, expressed as, for example, magnitudes per square arc second.

surface density:

A quantity with the SI unit kg m^{-2}, used to measure the mass per unit area in a surface or, more realistically, the total mass contained in a column of specified length and unit cross-sectional area associated with a specified surface. For example, in the context of accretion discs the disc surface density Σ is the vertically integrated (in the direction z perpendicular to the disc mid-plane) mass density ρ of disc material,

$$\Sigma = \int_{-\infty}^{+\infty} \rho \, \mathrm{d}z$$

surface integral:
A multiple integral carried out over two variables, such as r and ϕ in a cylindrical polar coordinate system.

surface mass density:
See surface density.

surface of infinite redshift:
In the Schwarzschild solution for a non-rotating black hole, the surface of infinite redshift coincides with the event horizon.

S-wave:
The sinusoidal feature an emission or absorption line leaves in a phase-resolved spectrum of a binary star, i.e. in a diagram where the emitted flux is shown (e.g. colour-coded) over the orbital phase versus wavelength (or velocity) plane.

synchrotron cooling:
The process whereby energetic electrons lose energy by emitting synchrotron radiation.

synchrotron radiation:

The non-thermal electromagnetic radiation arising as continuum emission from a population of highly energetic charged particles (in practice, electrons or positrons) in a magnetic field. The charged particles must be relativistic; that is, their kinetic energy must greatly exceed their mass energy. In these circumstances, the rotation of the electrons about the magnetic field lines (see cyclotron motion) give rise to radiation at a wide range of frequencies. If there is a power-law distribution of electron energies, then the synchrotron spectrum will also have a power-law form (spectral flux density $F_\nu \propto \nu^{-\alpha}$), where ν is the frequency and α is known as the spectral index. This will be modified at low frequencies in compact sources by synchrotron self-absorption. The frequencies over which synchrotron radiation can be seen depend on the energy range of the electrons. It is most commonly observed at radio frequencies, where the required electron energies are comparatively low (~GeV, depending on the magnetic field strength) but it has been observed all the way up to X-ray frequencies, where TeV electrons are required; it can be identified by its power-law spectrum and strong polarization.

Synchrotron radiation is seen in supernova remnants and is the emission process responsible for the radio emission of radio galaxies.

synchrotron self absorption:

The process whereby synchrotron radiation is absorbed by the same relativistic electrons which are responsible for the emission in the first place. It results in a 'turnover' of the low-frequency part of the synchrotron spectrum, which follows a relationship $F_\nu \propto \nu^{5/2}$.

synchrotron self Compton emission:
The process whereby synchrotron radiation undergoes inverse Compton scattering from the relativistic electrons which are responsible for the original emission. The result is that low-energy photons are upscattered to higher energies.

system:
That part of the Universe which is the subject of an investigation.

systemmatic errors:
Uncertainties arising from artefacts of the device used for recording or measuring the data.

S-Z effect:
See Sunyaev-Zel'dovich effect.

T

tangent:
See trigonometric functions.

tangent vector:
A vector that is a tangent to a curve.

tau lepton:
See tauon.

tauon:

A type of elementary particle, similar to an electron, but with a mass of 1777 MeV/c^2 (about 3477 times that of the electron). Tauons are unstable leptons that may occur with either positive or negative charge, the positive tauon (τ^+) being the antiparticle of the negative tauon (τ^-).

tauon neutrino:

A type of elementary particle that has no known substructure and is therefore regarded as a truly fundamental particle. It is the partner to the tauon in the third generation of leptons. It has no charge, spin 1/2 and a mass of less than 18 MeV/c^2.

taxonomy:
The classification of objects and phenomena, grouping similar examples together in named classes.

Taylor series:

The result of expanding a function $f(x)$ about the point $x = a$ by writing it as

$f(a) + (x-a)f'(a) + (x-a)^2f''(a)/2! + (x-a)^3f'''(a)/3!...$

where $f'(a)$ is the first derivative of f evaluated at $x = a$, and $f''(a)$ is the second derivative of f evaluated at $x = a$, and so on. In the special case where $a = 0$, the expansion is known as the Maclaurin series.

temperature:
An equilibrium property of a macroscopic system, with many overlapping shades of meaning. It is a parameter which determines the direction of heat flow: heat flows from a higher temperature to a lower temperature. It can be more quantitatively measured through the equation of state of an ideal gas, $PV = NkT$, which applies to real gases in the limit of low pressure. The SI unit of temperature is the kelvin (K).

temperature inversion:
In a planetary atmosphere, the phenomenon whereby certain layers of the atmosphere at a higher altitude are at a higher temperature than layers at lower altitude. The effect is seen in the Earth's stratosphere where higher layers are heated due to absorption of radiation from the Sun. This is due to the increased opacity of the high altitude absorber.

temporal:
Relating to properties of a system as a function of time.

tensor:
A multi-component mathematical object whose components transform in well-defined ways under general coordinate transformations.

tesla:

The SI unit of magnetic field strength, represented by the symbol T, and defined by the relation 1 T = 1 kg s^{-2} A^{-1}.

theory of general relativity:
See general theory of relativity.

theory of special relativity:
See special theory of relativity.

thermal bremsstrahlung:
The process of free-free emission from a population of thermal electrons and ions. See thermal radiation.

thermal broadening:
The broadening of spectral lines due to the Doppler shift as a result of the different speeds which atoms in a gas posses by virtue of the temperature of the gas. Higher temperature gases give rise to greater thermal broadening.

thermal cyclotron emission:
The process whereby cyclotron radiation is emitted from a population of electrons whose motions in a magnetic field are simply a result of their temperature. Thermal cyclotron can be seen in magnetic cataclysmic variables. See thermal radiation.

thermal energy:
A term for the sum of the kinetic energies and mutual potential energy of all the basic particles (e.g. molecules) in a system. Not to be confused with heat. See typical thermal energy of a particle.

thermal equilibrium:

In general, the condition of an isolated system in which there is no net flow of heat between any two parts of the system. Such a system may be characterized by a uniform temperature. Thermal equilibrium represents a settled and unchanging state in which macroscopic properties are independent of time. It is one aspect of thermodynamic equilibrium.

A star or accretion disc is in (local) thermal equilibrium if local heating (by nuclear fusion or viscous dissipation) balances local cooling (e.g. radiation) at each point in the star or disc. If a star or disc is thermally stable (see thermal instability) and not in thermal equilibrium, thermal equilibrium is established on a thermal timescale.

thermal instability:
An instability that grows on a thermal timescale.

thermally pulsing asymptotic giant branch:
(TP-AGB) The second phase of asymptotic giant branch evolution during which the helium shell periodically ignites for short intervals, causing thermally driven pulses.

thermal pressure:
Pressure arising from the temperature of a sample of matter such as the pressure in a fixed volume V of ideal gas, containing N particles, at temperature T; $P = NkT/V$ where k is the Boltzmann constant.

thermal radiation:
Radiation from a population of particles (ions and electrons) that are in local thermal equilibrium and have a well-defined temperature (contrast with non-thermal). If the photons are also in thermal equilibrium with the particles, black body radiation is produced; if they are not, the spectrum depends on the emission process. For example, both thermal bremsstrahlung and thermal cyclotron emission are thermal radiation, but they have very different spectra.

thermal spectrum:
A spectrum produced by a thermal radiation process, such as a black body spectrum or a thermal bremsstrahlung spectrum. Contrast with non-thermal.

thermal time:
Characteristic time a system would need to significantly change its thermal energy content, e.g. by cooling through radiation. For a star this is the Kelvin-Helmholtz timescale.

thermal timescale:
See thermal time.

thermal-viscous instability:
An instability in accretion discs due to the presence of partially ionized hydrogen. The instability is an interplay of effects that develop on the thermal timescale and on the viscous timescale. Believed to be responsible for dwarf nova outbursts in cataclysmic variables and for soft X-ray transients.

thermal width:
The width of a spectral line as a result of thermal broadening.

thermodynamic equilibrium:
The condition of a system that is in chemical, mechanical and thermal equilibrium.

thermodynamic temperature scale:
A temperature scale in which the mean energy of particles with that temperature is directly proportional to the temperature. The SI unit of temperature, the kelvin, defines a thermodynamic temperature scale, but others (such as the Celsius and Fahrenheit scales) do not, since their zero point does not correspond to zero energy ('absolute zero').

thermonuclear reaction:
A reaction between atomic nuclei. These reactions are called 'thermonuclear' because they require very high temperatures in order to take place. See proton-proton chain, CNO cycle, triple-alpha process, nucleosynthesis.

thermonuclear runaway:
A series of nuclear reactions in which the increased temperature due to the reactions causes the nuclear reactions to proceed at a faster rate, and hence increase the temperature still further.

thermophiles:
Heat-loving bacteria, found on Earth around black smokers and near hot springs.

thick disc:
The region of the disc of the Galaxy containing the oldest stars. It has a scale height of about 1.5 kpc.

thin disc:
An accretion disc which satisfies the thin disc approximation.

thin disc approximation:
The simplifying assumption that the thickness H of an accretion disc at distance R from the accretor is small compared to R. The thin disc assumptions allows one to treat the vertical and radial structure of the disc separately, and motivates the use of vertically integrated quantities like the surface density to describe the disc.

Thomson scattering:
Same as electron scattering.

Thomson scattering cross-section:
The quantity σ_e (or σ_T) = 6.65×10^{-29} m^2 which quantifies the interaction of low energy photons and electrons.

tidal dissipation parameter:
A parameter which depends on the structure of a body (such as a planet) and determines the rate of energy dissipation as a result of tidal heating.

tidal effects:
See tidal force.

tidal field:
See tidal force.

tidal force:
A force that arises in a non-uniform gravitational field causing neighbouring particles to accelerate differently. If an extended body is placed in a gravitational field, the parts of it that are closer to the gravitating object will feel a stronger force than the parts of it that are further away. The resulting differential force, which tends to pull an extended body apart, is responsible for tides in the Earth–Moon–Sun system, but also for more dramatic effects in stronger gravitational fields (see Roche limit). Its interaction with rotation means that it can also alter a body's rotational period until it is the same as the orbital period, as is the case for the Moon; this is called tidal locking.

tidal locking:
A result of a tidal force such that the rotation rate of an astronomical body becomes synchronised with its orbital rate around another body. The Moon is tidally locked in its orbit around the Earth.

time delay surface:
In gravitational lensing, the imaginary surface in angular position on the sky used to locate where images will form. Gravitationally lensed images arise at stationary points on this surface.

time-dependent Schrodinger equation:
The fundamental equation of quantum mechanics (at least in Schrodinger's wave-mechanical approach to the subject.) The time-dependent Schrodinger equation is a differential equation. Its solution is the time-dependent wave function that provides the fullest possible description of the state of a quantum mechanical system — including its time-evolution, in the absence of a measurement. (Measurements cause the wave function to change abruptly and unpredictably, in a way that is not described by the time-dependent Schrodinger equation.)

time-dependent wave function:
A solution to the time-dependent Schrodinger equation. According to conventional quantum mechanics, the time-dependent wave function describing a particular state provides the fullest possible description of that state.

time dilation:

A phenomenon arising in Einstein's special theory of relativity, often summed up by the statement 'moving clocks run slow'. If the time interval between two ticks of a clock is recorded as $\Delta\tau$ in a frame in which the clock is at rest (i.e. the proper time), then the time interval between the same two ticks, measured from a frame of reference in which the clock is moving at speed V, has the dilated value $\Delta T = \gamma(V)\, \Delta\tau$, where $\gamma(V)$ is the Lorentz factor. Time dilation is a consequence of the Lorentz transformation. See also length contraction.

time-independent Schrodinger equation:

For confined particles, the solutions of the time-dependent Schrodinger equation involve standing waves and it is therefore possible to write the relevant wave functions as a product of a function of space $\psi(r)$ and a function of time $\phi(t)$. Thus $\Psi(r,t) = \psi(r)\phi(t)$. The functions $\psi(r)$ are themselves the solutions of a differential equation – the time-independent Schrodinger equation:

$$\left[-\frac{\hbar\nabla^2}{2m} + V(r)\right]\psi(r) = E\psi(r)$$

time-independent wave function:
A solution to the time-independent Schrodinger equation. Such solutions may be used to describe the stationary states of a quantum system.

time-like separation:

Events with a positive spacetime separation are said to be time-like. Such events are causally related and there will exist a frame of reference in which the two events happen at the same place but at different times.

See light-like separation and space-like separation.

time resolution:
The minimum time interval between readings or measurements.

timescale:
The characteristic duration in time of a physical process.

tip of the red giant branch:
Stars at the tip of the red giant branch are the brightest red giant stars and have I-band magnitudes that are insensitive to age and metallicity and so can be used as a standard candle.

Tolman surface brightness test:

A test to see whether the surface brightness of galaxies decreases as $(1+z)^4$ as predicted if the redshift of galaxies is cosmological in origin.

topology:
Referring to the spatial properties of objects that are maintained whilst the object is deformed.

top quark:
A quark with electric charge $+2e/3$. Along with the bottom quark, a member of the heaviest generation of quarks.

torque:
A vector quantity, usually denoted by $\boldsymbol{\Gamma}$ (or sometimes $\boldsymbol{G}$), that measures the turning effect of a force about a specified point. The torque about a point O due to a force $\boldsymbol{F}$ is given by the vector product $\boldsymbol{\Gamma} = \boldsymbol{r} \times \boldsymbol{F}$, where $\boldsymbol{r}$ is the displacement vector from O to the point of application of $\boldsymbol{F}$. This implies that $\boldsymbol{\Gamma}$ has magnitude $rF \sin\theta$, and that it points in a direction that is perpendicular to $\boldsymbol{r}$ and $\boldsymbol{F}$, as specified by the right-hand rule. The SI unit of torque is the N m.

torus:
A geometrical shape analagous to a ring doughnut. Obscuring material with this shape is believed to exist close to the central engines of *AGN*.

total eclipse of the Sun:
The phenomenon observed on Earth when the Moon passes directly between an observer and the Sun. Since the Moon and Sun have very similar angular sizes, when viewed from the Earth, the former can completely block the light from the latter.

TP-AGB:
See thermally pulsing asymptotic giant branch.

transfer equation:

In the context of astrophysical light curves, an equation linking the output light curve as a function of time (L) to the integral over all isodelay surfaces of the transfer function (Ψ) multiplied by the input light curve (C), i.e.

$$L(t) = \int_{-\infty}^{+\infty} \psi(\tau)C(t-\tau)\mathrm{d}\tau$$

transfer function:
A mathematical expression relating the output of a system to its input. In the context of astrophysical light curves, it relates (say) the light curve of a particular emission line due to reprocessed continuum radiation, to the light curve of the original continuum radiation. Represented by $\Psi(\tau)$.

transformation rules for intervals:
Similar to the Lorentz transformation but with the coordinates x, y, z, t replaced by the intervals between two events Δx, Δy, Δz, Δt.

transit:
The passage of one astronomical body across the face of another.

transit depth:
The fractional reduction in light caused by the transit of a non-radiating astronomical body across the face of one which is radiating.

transition:
A process in which the state of a quantum system changes (see also quantum state and permitted transition). When dealing with confined quantum systems, transitions may be informally referred to as 'quantum leaps' or 'quantum jumps'.

transit timing variations:
Variations in the times of occurrence of a transit of one astronomical body across the face of another. In the case of exoplanets, the transit times can be perturbed by the gravitational influence of other planets, moons or asteroids in the system.

translational kinetic energy:

The kinetic energy associated with the translational motion of a body. For a particle of mass m travelling with speed v, the translational kinetic energy is

$$E_{\mathrm{KE}} = \tfrac{1}{2}mv^2$$

For a rigid body of mass M,

$$E_{\mathrm{KE}} = \tfrac{1}{2}Mv_{\mathrm{CM}}^2$$

where v_{CM} is the speed of the body's centre of mass. In the case of a molecule, the translational energy is associated with motion of the centre of mass of the molecule, and does not include energy associated with molecular vibrations or rotations See also relativistic translational kinetic energy.

transmission spectroscopy:
The measurement of the spectrum of (e.g.) a planetary atmosphere as its moves in front of a source of radiation (such as a star). In this case, transmission of the radiation through the atmosphere of the planet imprints spectral signatures of the atmosphere on the underlying stellar spectrum.

transport phenomenon:
The phenomena whereby energy and linear or angular momentum are transported over macroscopic scales. An example is viscosity.

transverse proximity effect:
Given two quasars which have different redshifts, but which appear close on the sky, it is possible to use the Lyman alpha forest in the spectrum of the more distant quasar to measure the ionization effect of the nearer quasar.

transverse velocity:
A quantity that describes the velocity of a body measured in the plane of the sky, perpendicular to the line of sight. Transverse velocities can give rise to observable *proper motions*.

transverse wave:
A wave composed of oscillations that take place in a direction perpendicular to the direction of propagation of the wave. Contrast with longitudinal wave.

triangle rule:
A graphical method of determining the resultant $\boldsymbol{a} + \boldsymbol{b}$ of two given vectors $\boldsymbol{a}$ and $\boldsymbol{b}$. Any vector can be represented graphically by an arrow, with a length that represents the magnitude of the vector and an orientation that represents the direction of the vector. To construct the arrow representing the resultant $\boldsymbol{a} + \boldsymbol{b}$, first draw an arrow to represent the vector $\boldsymbol{a}$, then, starting from the head of the arrow you have just drawn, draw a second arrow to represent the vector $\boldsymbol{b}$. The resultant $\boldsymbol{a} + \boldsymbol{b}$ will then be represented by an arrow drawn from the tail of the arrow representing $\boldsymbol{a}$ to the head of the arrow representing $\boldsymbol{b}$. The arrows representing $\boldsymbol{a}$, $\boldsymbol{b}$ and $\boldsymbol{a} + \boldsymbol{b}$ will thus form a triangle.

trigonometric functions:

A class of periodic functions that includes the sine, cosine and tangent functions, as well as their inverse functions arcsin, arccos and arctan. The trigonometric functions generalize the corresponding trigonometric ratios, and can be defined by various means. For example, suppose a point P lies on a unit circle whose origin coincides with the origin of a Cartesian coordinate system. If a line from P to the origin is at an angle θ, measured anticlockwise, to the x-axis, then the x-coordinate of P determines the value of the cosine function $\cos\theta$ and the y-coordinate of P determines the value of the sine function $\sin\theta$.

trigonometric parallax:
See parallax.

trigonometric ratios:
Numerical quantities (the most important of which are abbreviated $\sin\theta$, $\cos\theta$ and $\tan\theta$) that are defined in terms of ratios of the side lengths of a right angled triangle that has an interior angle θ. Given such a triangle, in which the hypotenuse (longest side) has length r, the side opposite the angle θ has length y, and the third side, adjacent to the angle θ, has length x; the three basic trigonometric ratios (formally called the sine, cosine and tangent) are defined by $\sin\theta = y/r$, $\cos\theta = x/r$, $\tan\theta = y/x$.

trigonometry:
The branch of mathematics concerned with the study of right-angled triangles, the associated trigonometric ratios and their generalizations.

triple-alpha process:

A thermonuclear reaction in which three helium nuclei fuse to form carbon, using an unstable nucleus of beryllium as an intermediate state:

$3\,^{4}\text{He} \rightarrow {}^{8}\text{Be} + {}^{4}\text{He} \rightarrow {}^{12}\text{C} + \gamma$

This reaction is the initial reaction in the helium burning phase of a star's life. It requires high densities and temperatures around 10^8 K.

triplet:
A spectral line with three components due to fine structure sublevels in one or both of the energy levels involved in an atomic transition.

Trojan:
The name given to a body that orbits around a star on the same trajectory as another planet, but ahead (or behind) in the orbit by 60º. They therefore occupy the Trojan points. The name arises from the groups of asteroids which orbit the sun at these locations in Jupiter's orbit, which are individually named after characters in Homer's Iliad describing events surrounding the battle of Troy.

Trojan points:
The L_4 and L_5 Lagrangian points, and the locations of Trojan asteroids.

tropopause:
The height in an atmosphere at which it becomes optically thin to radiation emerging from lower in the atmosphere.

true anomaly:
An angular parameter θ that describes the position of a body following an elliptical orbit. The distance from the focus of the ellipse to the orbiting body is given by $r = a(1 - e^2)/(1 + e\cos\theta)$ where e is the eccentricity of the ellipse and a is the semi major axis.

T Tauri star:
A member of a class of protostar with masses similar to that of the Sun, named after the prototype star, T Tauri. T Tauri stars have not yet reached the main sequence; they are still contracting and losing significant amounts of mass through a stellar wind (see mass loss) and some of them have bipolar outflows, generating Herbig–Haro objects. They are normally found embedded in gas and dust, presumably because this is the environment in which they formed, and some of this may take the form of a protoplanetary disc.

Tully-Fisher relation:
The observation that the velocity widths of spiral galaxies are correlated with their luminosities in the B-band filter. Contrast with Faber-Jackson relation.

tunnelling:
See quantum tunnelling.

turbulence:
The unsteady and chaotic flow that occurs in fluids at Reynolds numbers of a few thousand or greater.

turbulent eddy:
A packet, bubble or blob of fluid that partakes in the turbulent motion of a turbulent flow or layer. The eddy survives as an entity for a characteristic time, the turnover time, and moves with a characteristic velocity, the turnover velocity.

turn-around time:
In a flat Universe with zero cosmological constant, the time taken for density

perturbations to reach their maximum size.

turnover velocity:
See turbulent eddy.

twin effect:
A thought experiment concerning the phenomenon of time dilation. It involves twins, one of whom travels away from the Earth at high speed and then returns, and one of whom stays at home. Sometimes referred to as the twin paradox, although no paradox exists.

twin paradox:
See twin effect

two phase model:
A model of the broad line region in active galaxies, now no longer widely accepted, in which the BLR clouds represent dense condensations immersed within a hotter, low-density medium.

Type Ia supernova:
See supernova.

Type II supernova:
See supernova.

Type I supernova:
See supernova.

typical thermal energy of a particle:
The typical translational kinetic energy of a molecule in a gas in thermal equilibrium at temperature T. It is approximately equal to kT, where k is the Boltzmann constant.

U

U-band drop-out:
A photometric technique to determine galaxy redshifts by searching for galaxies that are detected in the B-band (and longer wavelengths) but are not detected in the U-band. Such galaxies must have redshift $z>4$, as at this redshift the Lyman-break is shifted into the U-band.

Uhuru:
The first ever X-ray satellite, a NASA mission that was operational from December 1970 to March 1973. It gave us the first catalogues of bright X-ray sources, as shown by the names of many X-ray sources e.g. 4U 1624-490, where 4U refers to the position given in the 4th Uhuru catalogue.

ULIG:
See ultraluminous infrared galaxy.

ULIRG:
See ultraluminous infrared galaxy.

ultraluminous infrared galaxy:
Also known as ULIGs or ULIRGs. An infrared-luminous galaxy with 10^{12} - 10^{13} solar luminosities. See IRAS galaxy.

ultraluminous X-ray source:
(ULX) An X-ray source with a luminosity exceeding around 2×10^{32} W, which is the Eddington limit for a 15 solar mass black hole. Possible explanations of ULXs include: intermediate mass black holes, beaming from systems containing stellar mass black holes, or X-ray binaries with extended sources of emission

ultra-relativistic particle:
A particle whose speed is close to the speed of light, $v \sim c$.

ultraviolet excess:
The phenomenon whereby quasars tend to have a higher proportion of their emission in the ultraviolet (U-band) than stars. This provides a convenient way of separating the two populations, which may visually look alike, on colour–colour diagrams. The UV excess is a consequence of the existence of the big blue bump.

ultraviolet radiation:
Electromagnetic radiation with a wavelength between about 1×10^{-8} m and 4×10^{-7} m or a frequency between about 3×10^{16} Hz and 8×10^{14} Hz.

ULX:
See ultraluminous X-ray source.

unbound particle:
A particle whose total energy E_{TOT} is everywhere greater than its potential energy E_{POT}. If, in addition, E_{POT} is constant, the particle is said to be free.

unified model:
An attempt to explain the various phenomena seen in different classes of AGN in terms of a common underlying physical structure. Differences between classes of AGN are assumed to be due to different viewing angles with respect to a central obscuring torus and different intrinsic radio and/or optical luminosities. See radio galaxy, Seyfert galaxy, quasar, BL Lac object.

uniform acceleration equations:
See constant acceleration equations.

uniformly accelerated motion:
A form of motion in which the acceleration does not change with time. See constant acceleration equations.

uniform motion equations:

The equations that describe the uniform motion of a particle. For a particle moving in one dimension, with initial position x_0, the equations may be written

v_x = constant

$x = x_0 + v_x t$

In terms of vectors, the equations may be written

$\boldsymbol{v} = \boldsymbol{u}$

$\boldsymbol{s} = \boldsymbol{u}t$

where $\boldsymbol{s}$ represents the displacement from the initial position and $\boldsymbol{u}$ is the initial velocity.

unit vector:

A vector of magnitude 1 that serves to indicate a specific direction. Given a displacement vector $\boldsymbol{r}$, the unit vector in the direction of is $\hat{\boldsymbol{r}} = \boldsymbol{r}/r$. (Note that the magnitude of any unit vector is 1, *not* 1 m, nor even 1 unit.)

universal gravitational constant:
The constant $G = 6.673 \times 10^{-11}$ Nm^2 kg^{-2} that appears in Newton's law of universal gravitation.

unpolarized:
A term used to refer to electromagnetic radiation which has no polarization.

unsaturated inverse Compton scattering:
Inverse compton scattering in which the mean number of scatterings experienced by a photon before it escapes is much less than the number required for photons to reach an energy of kT, where T is the temperature of the medium.

unstable mass transfer:
Runaway mass transfer. As a result of the transfer of mass the orbital separation and the donor star's radius change such that the mass transfer rate increases. Thus more mass is transferred, increasing the transfer rate even further, and so on.

up quark:
A quark with electric charge $+2e/3$. Along with the down quark, a member of the lightest generation of quarks.

V

vacuum field equations:
The Einstein field equations in the case where the energy-momentum tensor $T_{\mu\nu}$=0, so $R_{\mu\nu}$- $g_{\mu\nu}R/2 = 0$ where $R_{\mu\nu}$is the Ricci tensor, R is the curvature scalar and $g_{\mu\nu}$ is the metric. These equations may be solved to show that $R = 0$ and $R_{\mu\nu} = 0$ too in this case.

vacuum solutions:
A class of solutions to the Einstein field equations corresponding to empty spacetime.

valley of stability:
The region in the chart of nuclides occupied by stable isotopes. Stable nuclei have lower energies than neighbouring unstable ones. If a three-dimensional graph is plotted showing the nuclear energies as a function of atomic number Z and mass number A, the low energies of the stable nuclei resemble a valley in the diagram.

variability:
The phenomenon whereby the electromagnetic radiation emitted by stars, galaxies or other astronomical objects, changes with time. For instance, quasars display variability in every waveband in both their continuum and emission lines on a variety of timescales.

vector:
A quantity that requires both a magnitude and a direction for its complete specification. Examples include position, displacement, velocity, acceleration, force, torque, angular velocity, momentum, angular momentum, and electric and magnetic

fields. A vector can be represented by an arrow whose length is proportional to the magnitude of the vector and whose direction is the same as that of the vector. Vectors can also be specified by giving their components in a chosen coordinate system. In two dimensions, a vector **v** can be written as $\boldsymbol{v} = (v_x, v_y)$. In three dimensions, three components are required: $\boldsymbol{v} = (v_x, v_y, v_z)$. Contrast with scalar.

vector field:
A quantity to which a definite magnitude and direction can be ascribed at every point throughout some region of space. Physical examples include; electric field, gravitational field and magnetic field.

vector product:

A product of two vectors ***a*** and ***b***, usually written as $\boldsymbol{a} \times \boldsymbol{b}$, and sometimes referred to as the 'cross product' of those vectors. Given two vectors ***a*** and ***b***, which are at an angle θ to each other, where $0° \leq \theta \leq 180°$, their vector product $\boldsymbol{a} \times \boldsymbol{b}$ is a vector of magnitude $ab \sin \theta$ that points in the direction perpendicular to both ***a*** and ***b***, as specified by the right-hand rule.

Alternatively, if the components of ***a*** and ***b*** are such that $\boldsymbol{a} = (a_x, a_y, a_z)$, and $\boldsymbol{b} = (b_x, b_y, b_z)$, then the components of the vector product $\boldsymbol{a} \times \boldsymbol{b}$ are given by

$\boldsymbol{a} \times \boldsymbol{b} = (a_y b_z - a_z b_y, a_z b_x - a_x b_z, a_x b_y - a_y b_x)$

Vega-excess star:
A star like Vega which exhibit an excess of infrared radiation attributed to thermal radiation from circumstellar gas and dust.

velocity:

The (instantaneous) rate of change of the position of a body. For a particle moving in one-dimension along the *x*-axis, the velocity v_x at any time is the rate of change of the particle's position x and is given by the gradient of the particle's position–time graph at the relevant time. This gradient is equal to the derivative of the position with respect to time, so the velocity at time t may be written

$$v_x(t) = \frac{\mathrm{d}x}{\mathrm{d}t}$$

Velocity is a vector quantity, characterized by a direction as well as a magnitude. In one dimension the sign of v_x suffices to indicate the direction, but in two or three dimensions, some other method must be used to indicate direction. This is often achieved by expressing the velocity vector in terms of its (Cartesian) components, as in $\boldsymbol{v} = (v_x, v_y, v_z)$, where

$$\mathbf{v}(t) = \frac{\mathrm{d}\mathbf{r}}{\mathrm{d}t}$$

and $\boldsymbol{r}(t)$ is the position vector.

velocity coordinates:
The *x*-component and the *y*-component of the velocity of a particle or a fluid at a point (x, y) in the *xy*-plane (usually the orbital plane of a binary).

velocity dispersion:
A quantity used to describe the spread in the speeds of sub-components of an astronomical object, for example of an elliptical galaxy (where the sub-components are individual stars) or the broad-line region of an active galaxy (where the sub-components are the broad-line clouds). The velocity dispersion is often measured from the widths of emission lines, which are broadened by the Doppler shift. If the size of the object is known and the distribution of speeds comes from orbits in a gravitational potential, the virial theorem allows the gravitating mass to be estimated. The velocity dispersions of elliptical galaxies and clusters of galaxies provides evidence for dark matter.

velocity gradient:
The rate of change of a component of velocity in a fluid in a chosen direction.

velocity transformation:

In special relativity, the equations relating the velocity ***v*** of an object measured in one frame of reference to its velocity ***v***' measured in another frame of reference which is in standard configuration with the first and moving with respect to it at speed *V*. The transforms are:

$$v'_x = \frac{(v_x - V)}{(1 - v_x V/c^2)}$$

$$v'_y = \frac{v_y}{\gamma(V)(1 - v_x V/c^2)}$$

$$v'_z = \frac{v_z}{\gamma(V)(1 - v_x V/c^2)}$$

where $\gamma(V)$ is the Lorentz factor.

very long baseline interferometry:
An application of radio interferometry whereby two or more radio telescopes separated, typically, by thousands of kilometres, may be combined to produce images with an extremely high angular resolution, which may be as small as milli-arcseconds.

Virgo Cluster:
A relatively nearby rich cluster of galaxies with over 1000 members, about 18 Mpc away.

virialised:
Referring to clusters of galaxies, indicating that they have settled into a stable gravitationally-bound system for which the virial theorem applies.

virial mass:
The mass (M_V) of a cluster of stars or galaxies calculated using the virial theorem ($2E_K + E_{GR} = 0$), and assuming that the kinetic energy is determined by the measured mean-square velocity ($\langle v^2 \rangle$) of the stars or galaxies $E_K = M_V \langle v^2 \rangle$.

virial temperature:
See virial theorem. The temperature of a system when the virial theorem – the balance between thermal and gravitational potential energy – holds.

virial theorem:

The statement that, for a gravitationally bound system in equilibrium, the total kinetic energy is minus one-half the gravitational potential energy: $-E_{GR} = 2E_K$ (where both quantities are long-term time averages). The virial theorem can easily be shown to be true for simple systems (e.g. circular orbits) but is slightly more complex to prove in general.

Equivalently, the volume-averaged pressure needed to support a self-gravitating body in hydrostatic equilibrium is minus one-third of the gravitational potential energy per unit volume.

virtual particles:
See energy-time uncertainty principle.

viscosity:
The phenomenon of internal friction in a fluid, that tends to reduce the relative velocity of two neighbouring layers of the fluid and leads to energy dissipation. It also gives rise to a viscous force when an object moves through a fluid.

viscous diffusion:
The radial drift of matter in an accretion disc, and hence the rate of change of the local surface density of the disc, is a diffusion process driven by viscosity.

viscous dissipation:
The process whereby the mechanical energy of a plasma flow is converted into thermal energy due to viscous friction.

viscous instability:
An instability that grows on a viscous timescale.

viscous time:

The characteristic time for the viscous spreading of a viscous torus in a radial direction (hence also radial drift timescale). The viscous time t_{vis} for an accretion disc ring with radius r and kinematic viscosity v is $t_{vis} \sim r^2/v$, or alternatively $t_{vis} \sim r/v_r$ where v_r is the radial drift velocity.

viscous timescale:
See viscous time.

viscous torque:
The torque exerted on an accretion disc ring by a neighbouring ring due to viscosity.

visible light:
Electromagnetic radiation with a wavelength between about 4×10^{-7} m (400 nm, violet) and 7×10^{-7} m (700 nm, red) or a frequency between about 8×10^{14} Hz and 4×10^{14} Hz.

visual binaries:
See binary star.

visual binary:
See binary star.

visual binary star:
See binary star.

VLA:
The Very Large Array radio telescope in New Mexico, comprising twenty seven 25m dishes arranged in a moveable Y-formation. Each leg of the Y is 21 km long, allowing the array to act as an interferometer with an effective diameter of 36 km and an angular resoultion of 0.05 arseconds.

VLBA:

The Very Long Baseline Array of ten radio telescopes comprising installations across the continental USA, Hawaii and the Virgin Islands. It operates as an interferometer with a maximum baseline of over 10,000 km and can achieve an angular resolution as small as 0.17 milliarcseconds.

void:
The vast non-luminous regions lying between superclusters of galaxies.

Voigt profile:
The effect of convolving a Gaussian absorption profile with a Lorentzian profile. The resulting Voigt profile is a good representation of many absorption lines.

volume:
An amount of space, usually that occupied by a specified substance. The SI unit of volume is the cubic metre (m^3).

volume integral:
A multiple integral carried out over three variables, such as r, θ and ϕ in a spherical polar coordinate system.

volume-limited sample:
A sample which contains all the objects within a particular volume of space.

W

warm dark matter:
Dark matter whose particles have properties that are intermediate between those of cold dark matter and hot dark matter.

warped accretion disc:
An accretion disc that is warped out of its natural plane of symmetry (the disc mid-plane). The resulting shape can be complicated, and the warped regions might be restricted to a certain radial range of the disc.

warped disc:
See warped accretion disc.

water maser:
A naturally ocurring microwave laser produced by water molecules in the interstellar medium.

watt:
The SI unit of power, represented by the symbol W, and defined by the relation 1 W = 1 J s^{-1}.

wave:
A periodic disturbance that may convey energy from one point to another without any particle of the medium through which it travels being permanently displaced. Waves may be standing or travelling, solitary or continuous, and transverse or longitudinal. According to its type, a wave may be characterized by a frequency or wavelength, a plane of polarization and a direction of propagation. The speed of a (travelling) wave is jointly determined by its frequency and wavelength in accordance with the relation $v = f\lambda$.

wave function:
A solution of the time-dependent Schrodinger equation, usually represented by $\Psi(x,t)$ in one dimension, which describes the state of a quantum system. Knowing the wave function makes it possible to predict the possible outcomes of measurements of the system and the probabilities of those outcomes. For systems that are in stationary states, i.e. where the probabilities of the outcomes are not time-dependent, the wave function may be written as the product of a time-dependent part with a spatial part. The spatial part, $\psi(x)$ in one dimension, is correctly referred to as the time-independent wave function, and is a solution of the time-independent Schrodinger equation.

wavelength:
The distance, measured along the direction of propagation of a wave, between successive points that are oscillating in phase. For convenience, wavelength is frequently thought of as the distance between two successive wave crests.

wavelength dependent geometric albedo:
The fraction of starlight which is reflected from a planetary body as a function of wavelength, p_λ. See also albedo.

wavenumber:
Wavenumber is the number of wavelengths per unit distance, so $k = 1/\lambda$.

Often the angular wavenumber is used, where in this case, $k = 2\pi/\lambda$

weak anthropic principle:
The principle of using anthropic arguments to constrain our position in time and space

within a given cosmological model. May be paraphrased by the statement that, if the Universe were not as it currently is, we would not be here to observe it.

weak equivalence principle:
The statement that: "Within a sufficiently localised region of spacetime adjacent to a concentration of mass, the motion of bodies subject to gravitational forces alone cannot be distinguished by any experiment from the motion of bodies within a region of appropriate uniform acceleration."

weak nuclear interaction:
See fundamental forces.

Weber bar:
See resonant bar detector.

Weyl's postulate:
In cosmic spacetime there exists a set of privileged fundamental observers whose worldlines form a smooth bundle of timelike geodesics. These geodesics never meet at any event apart, perhaps, from an initial singularity in the past and/or a final singularity in the future.

white dwarf:
A stellar-mass compact object, with a mass below the Chandrasekhar mass limit (1.4 solar masses) supported against gravitational collapse by the degeneracy pressure of electrons. White dwarfs are the final products of the evolution of low-mass stars, after thermonuclear reactions have ceased and the outer regions of the star have been lost in stellar winds or as a planetary nebula. Since they are small compared to main-sequence stars (with radii of the order of 10^4 km) they are faint (absolute magnitudes between 10 and 15), even though their surface temperatures are high (a few times 10^4 K). They therefore lie at the bottom left of the Hertzsprung-Russell diagram. If left isolated they will gradually cool and contract until they become invisible, but since the luminosity is low, the cooling time is long. White dwarfs in binary systems may meet a different fate: when their companion star moves off the main sequence, mass transfer may take the white dwarf over the Chandrasekhar mass limit. In this case, the white dwarf can end its life as a type Ia supernova.

wide-field survey:
A wide-area, shallow survey, such as the Sloan Digital Sky Survey, covering a wide but nearby volume of the Universe. See pencil-beam survey.

Wien displacement law:

A law relating the wavelength of peak spectral flux density from a black body spectrum to the temperature of the black body. For spectral flux density measured in terms of wavelength, with units W m^{-2} m^{-1}, Wien's law states

$\lambda_{max}T = 2.9 \times 10^{-3}$ mK

It offers a convenient way of finding the expected wavelength of radiation from a system of a particular temperature.

Wien tail:

The short-wavelength part of the black body spectrum, described by

$$B_\nu(T) = (2h\nu^3/c^2)\exp(-h\nu/kT)$$

or

$$B_\lambda(T) = (2hc^2/\lambda^5)\exp(-hc/\lambda kT)$$

WIMP:
Weakly Interacting Massive Particles. A possible class of dark matter particles, which includes the neutralino.

wind accretion:
Accretion from the wind of a stellar companion in a detached binary.

WMAP:
The Wilkinson Microwave Anisotropy Probe. A satellite used to map the cosmic microwave background radiation across the entire sky.

Wolf-Rayet star:
Very massive (> 20 solar mass) main sequence stars that expel mass copiously in strong winds. Their mass loss rate is a billion or so times higher than that of the Sun.

work:

Any quantity of energy that is transferred by non-thermal means. According to one widely used convention, the symbol W is used to represent work that is transferred to a system from its environment. This convention implies that positive values of W tend to increase the internal energy of the system.

The work done by a constant force $\boldsymbol{F}$ on a body that undergoes a displacement $\boldsymbol{s}$ is defined by the scalar product

$W = \boldsymbol{F} \cdot \boldsymbol{s} = Fs \cos\theta$

If the force is not constant, then this product is replaced by the limit of an appropriate sum, which may be expressed as a definite integral. In the case of a force that varies in strength but always acts along the x-axis this integral takes the form

$$W = \int_A^B F_x \mathrm{d}x$$

which may be interpreted as the area under the graph of F_x against x between $x = A$ and $x = B$. In three dimensions the work done depends on the particular path (e.g. between A and B) that the body moves along and can be represented by the line integral

$$W = \int_A^B \mathbf{F} \cdot \mathrm{d}\mathbf{s}$$

The work done on any body by a force is the energy transferred to that body by the force. When a nonzero resultant force acts on a body, the work done by that force is related to the change in the body's translational kinetic energy by the work–energy theorem, according to which

$$W = \Delta E_{\mathrm{KE}} = \tfrac{1}{2}mv^2 - \tfrac{1}{2}mu^2$$

world-line:
A particle's pathway through four-dimensional Minkowski spacetime.

X

xallarap:
In gravitational microlensing, if the lensing signal persists over an appreciable period of time, and the lensed object is a binary, then it may be possible to detect a slight variation in the light curve signal as a result of binary orbital motion of the background source. This is, in some sense, an inverse process to trigonometric parallax measurements using the motion of the Earth around the Sun. Therefore it has been named 'xallarap', which is 'parallax' backwards.

XBONG:
X-ray Bright, Optically Normal Galaxies.

XMM-Newton:
A European-led X-ray astronomy satellite that was launched a few months after Chandra in 1999, and is still currently active. It has three co-aligned X-ray telescopes, and one optical/UV telescope. It is the most sensitive X-ray imaging observatory to date (depending on energy range and source spectrum about five times more sensitive than Chandra), but has poorer spatial resolution than Chandra (5 arcsec rather than 1 arcsec). XMM-Newton is currently the only telescope that can detect sufficient photons for studying the variability and emission from most X-ray binaries outside our Galaxy.

X-ray:
Electromagnetic radiation with a wavelength between around 1×10^{-8} m and 1×10^{-11} m or a frequency between about 3×10^{16} Hz and 3×10^{19} Hz.

X-ray binaries:
See X-ray binary.

X-ray binary:
A binary system which produce strong X-ray emission as a result of mass transfer and accretion. X-ray binaries consist of a normal donor star and a neutron star or black hole. The X-ray emission from these sources is thermal emission from the accretion disc and a corona above it. X-ray binaries are divided into low-mass X-ray binaries and high-mass X-ray binaries according to the mass of the secondary star. There are several other subclasses of X-ray binaries that can be identified observationally. Soft X-ray transients are a class of X-ray binaries in which the X-ray emission occasionally increases by a large factor followed by a slow decline; this is thought to be due to instabilities in the accretion disc. X-ray bursts may also arise in X-ray binary systems. Regularly pulsing X-ray binaries are known as X-ray pulsars. X-ray binaries occasionally have jets, presumably being generated near the accretion disc; as these jets sometimes exhibit apparent superluminal motion the sources are referred to as 'microquasars'.

X-ray burst:
A short flash of bright X-rays, lasting between a few seconds and a minute. There are two types of X-ray burst; type I bursts repeat on timescales of hours or days, while type II consist of a series of bursts repeating on timescales of minutes over a period of several days. Both types of X-ray burst are believed to arise in X-ray binary systems. Type I bursts are thought to be due to thermonuclear burning of material accreted onto the surface of a neutron star; this makes them analogous to classical novae (see cataclysmic variable) and requires that the primary object should be a neutron star rather than a black hole, which has no solid surface. Type II bursts are believed to arise from a rapidly varying mass accretion rate, but this is uncertain.

X-ray corona:
An X-ray emitting, optically thin, very hot and tenuous layer, usually in a low mass X-ray binary.

X-ray dip:
A sudden drop to close to zero in the X-ray intensity observed from an X-ray binary. The dips are confined to a narrow phase interval and occur preferentially just before orbital phase zero.

X-ray irradiation:
The impact of X-rays on an object causing heating and/or other effects. In particular, in cataclysmic variables or X-ray binaries, the heating of the companion star or other structures by X-rays emitted from close to the compact object.

X-ray pulsar:
An X-ray binary exhibiting regular luminosity variations with a period from a few seconds to a few minutes. As is the case for rotation powered pulsars, these pulses are thought to be related to the magnetic field of a neutron star; the magnetic field is believed to channel accreting matter onto the neutron star's magnetic poles (compare polars) giving pulsed emission when the magnetic poles are visible.

X-ray spectral paradox:
The fact that the spectrum of the extragalactic X-ray background is very different to (harder than) the spectrum of a star-forming galaxy or an unobscured quasar, thus posing a problem for its origin.

Y

young stellar object:
An object in an early phase of the star formation process; this includes protostars as well as young main-sequence stars like Vega-excess stars.

YSO:
See young stellar object.

Z

zero-age main-sequence:
The track on the Hertzsprung-Russell diagram traced by newly formed main-sequence stars. Changes to a star's chemical composition cause a star to move slightly to the right of the zero-age main-sequence over the course of its main-sequence lifetime.

Zwicky galaxy:
A galaxy drawn from a catalogue produced from optical survey plates by Fritz Zwicky in the 1960s. His class of 'compact blue galaxies' includes many Seyfert galaxies and some quasars.