PHENOMENA INVOLVING MAGNETIC VORTEX TUBES

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ABSTRACT. Magnetic vortex tubes (MVTs) on a hierarchy of scales occur universally. On the largest scale they channel bipolar outflows of gas. A pinched region of MVT provides an acceleration mechanism capable of yielding the maximum cosmic ray energies.

A theory for the origin of astrophysical magnetic fields proposed previously (Browne, 1968, 1987) led to the conclusion that all astrophysical magnetic fields are filamentary on small scales. Alignment of the filaments explains large scale order.

Associated with a vortex tube is a current density $\underset{\sim}{j}$ and magnetic field $\underset{\sim}{B}$, both in general helical. If the radial components vanish, then $\underset{\sim}{j} \times \underset{\sim}{B} = (j_\phi B_z - j_z B_\phi)\hat{\underset{\sim}{r}}$, where (r,ϕ,z) are cylindrical polar coordinates. When $j_z B_\phi > j_\phi B_z$ the MVT pinches. In a pinched region charges can be accelerated to ultrarelativistic energies by a mechanism also discussed elsewhere (Browne, 1988a,b). An axial current J flows through an annular channel defined by an electric double layer. Here a radial electric field E_r permits drift of charges axially across lines of azimuthal magnetic field B_ϕ. Two mechanisms can interrupt the current in the annular channel (radius R, thickness Δr_E). In the region of the break of length Δz a displacement current flows, building up a large voltage V across the break. The maximum voltage is attained when all of the energy in B_ϕ has been transferred to E_z. The maximum energy of accelerated particles then is $W = eV = KeB_\phi(R)\Delta z$, where $K \simeq 3-10$.

Vortices are formed during early evolution of a star or galaxy. A rotating gaseous cloud collapses under gravitational forces to an oblate spheroid and then a disc. Contraction toward the axis is arrested by centrifugal force at a radius r^* which increases with z. The development of a bipolar outflow along the generators of the cone $r = r^*(z)$ permits loss of angular momentum by disc fluid, permitting continued contraction in the disc. The inflow of disc mass maintains the vorticity, much as happens at the base of a tornado. Once the vortex has formed, it will precess about an axis defined by the resultant angular momentum of outer fluid should this differ from that of the inner fluid.

Important MVT phenomena include:

(1) The behaviour of solar magnetic flux fibres in assembling into sunspots early in the solar 11 yr cycle and dispersing later as sunspots

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decay can be explained as a vorticity cycle. Suppose that a 22 y torsional oscillation gneerates ocillatory vorticity. As vorticity increases $j_z B_\phi > j_\phi B_z$, so that flux fibres attract magnetically. As vorticity weakens there is reversion to $j_\phi B_z > j_z B_\phi$, causing flux fibres to repel. The polarity of sunspots will alternate with the 22 yr period of the vorticity.

(2) Kilogauss magnetic fields observed in Ap stars also may be an MVT phenomenon. I have argued elsewhere (Browne, 1988a) that the Zeeman-split lines are localized at opposite poles of a precessing MVT. Polar regions alternately come into view and pass behind the stellar limb. An important clue is the existence of two groups of anomalously abundant elements whose spectra show antiphase variations in intensity, Doppler shift, and Zeeman effect. Anomalously abundant elements require resonance line radiation pressure to segregate the elements, and then freedom from mixing. Mild outflows through the cores of an MVT and counter-MVT provide these conditions. One replaces the "rigid rotator model" by a precessing MVT model.

(3) Exactly the same model accounts for the magnetism of AM Her stars ("polars") (Browne, 1988a). Now strong cyclotron sources are present at one or both poles, giving variable circular polarization. Also, X-ray sources may be present at one or both poles. Strong gas outflows are common, and the changing direction of the outflow relative to the line of sight gives a Doppler curve $\pi/2$ out of phase with that due to precession.

(4) X-ray bursters involve MVTs in a different capacity. A degenerate star has a nearly isothermal interior overlain with a skin of normal gas supporting a large temperature gradient. If power generation exceeds surface luminosity for a normal star, there results an increase of temperature gradient and hence of pressure gradient which causes expansion and perhaps pulsation. If power generation exceeds surface luminosity for a degenerate star, there results a slow increase of radiant energy until radiation pressure suffices to "puncture" the skin layer. The puncture occurs in the core of a solar MVT because here there is least mass to lift off due to magnetic pressure. A plug of cool gas in the core of a polar MVT is accelerated outward, exposing to view a hot degenerate sublayer at a shallow depth. The spectrum of a burst at maximum is that of a blackbody with $kT \simeq 3$ keV (Swank et al., 1977). Typical luminosity of say 3×10^{38} erg s^{-1} then implies source radius $\simeq 10$ km. This is not the radius of a neutron star, but of an MVT core. Hard flux en route to the observer must pass through the expanding plug of surface gas whose optical thickness $\tau(t)$ will vary with time t. If acceleration initially compresses the gas, τ increases before it decreases. When $\tau > 1$ hard blackbody flux from the sublayer is reprocessed into softer blackbody flux from the expanding gas. The variations $T(t)$ and $R(t)$ seen in some bursts (Hoffmann et al., 1980) indicate such reprocessing. Following escape of excess heat the "window" to the interior closes, and the stage is set for a repeat performance. Accretion plays no role in this burst mechanism, and binary membership is not a requirement.

(5) Gamma-ray bursts reveal blackbody spectra with $kT \simeq 300$ keV (Mazets et al., 1981). Only one source has been located. It lies within a supernova remnant in the LMC at distance 55 kpc, so the luminosity of this burst is $\simeq 3 \times 10^{44}$ erg s^{-1}. The spectrum is anomalously soft, but this is likely to be a consequence of reprocessing. Such a luminosity with $kT \simeq 300$ keV implies a source of radius 1 km. Since $kT \simeq mc^2$ pair creations in thermal collisions is possible and recombinations via positronium should yield a strong 511 keV two-photon annihilation line. The line will be broad and will be seen with a large redshift due to transverse Doppler effect. Precisely these effects are observed (Mazets et al., 1981). The redshifts observed are such that the line occurs at 340-425 keV (Kluznial, 1989), implying Lorentz factor γ in the range 1.5-1.2. Using $(\gamma-1)mc^2 = kT$ one infers kT in the range 225-102 keV.

(6) The burst mechanism can be applied to cataclysmic outbursts in general, ranging from dwarf novae through novae to even supernovae. The essential difference is that the escaping plug of gas remains optically thick for much longer.

(7) X-ray pulsars radiate over spectral range $10^3 < h\nu < 10^{16}$ eV, the highest energy being detected by air shower techniques. There must exist a mechanism to accelerate electrons to at least 10^{16} eV. The proposed mechanism can do so. Taking $B_\phi(r) = 30$ MG for a magnetic white dwarf, and adopting $\Delta z \simeq R = 10$ km on the basis of the new burster theory, one obtains $W = 10^{17}$ eV, taking $K = 10$. Applying the mechanism to the more degenerate γ-ray burster with $B_\phi(R) = 3\times10^{12}$ G (inferred from cyclotron lines (Mazets et al., 1981)) and $R = 1$ km, one infers $W = 10^{21}$ eV, the maximum cosmic ray energy.

(8) Acceleration in pinched MVTs supplies the ultrarelativistic electrons which delineates the MVT as a synchrotron jet. Without such delineation one relies on linear alignments of sources as indicators of an undetected MVT. Synchrotron jets associated with both compact and extended galactic sources have detailed properties confirming their identification with MVTs. For example, trailing of jets through the intergalactic medium becomes comotion of vortex lines with the fluid. Periodic wiggles suggest precession, as also do rings and recently discovered large luminous arcs.

(9) Differential rotation in a galactic nucleus can distort an axial MVT. In the same way as toroidal flux tubes are produced from axial flux tubes in the Sun, there arises a toroidal magnetic field in galaxies. Differential rotation increasingly stretches a loop of flux tube. However, in the galactic case the loop expands from the nucleus into spiral arm configuration. Assuming that the MVT continues to channel an outflow of gas from the nucleus, the spiral arm distribution of newly formed stars is explained. After formation stars decouple from MVT rotation and may get left behind. A prediction of this model is helical arm magnetic fields which reverse across the equatorial plane (Makarov and Andreassian, this volume), or from outer to inner arm if the plane of the loops is rotated.

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