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Introduction

Our terrestrial environment is, for the most part, a benign environment. Even catastrophic natural events such as severe hurricanes, explosive volcanic eruptions, and massive earthquakes are rather tame compared to physical events beyond our rocky planet. The stars and the galaxies have environments far too hostile for our liking.

Even when nature unleashes a violent thunderstorm, the energy may be quite large, but the energy density is not. However, if Thor hurls a thunderbolt our way, we take notice of the explosive release of energy in a small volume and we see firsthand evidence of high-energy density. Generally, we are not aware of everyday instances of high-energy density that are all around us. That is, we don't realize that the energy that holds matter together involves high-energy-density physics.

Early man undoubtedly experienced the violent and often destructive nature of a lightning strike, but had no comprehension of its energy density and plasma physics on display. Not until near the end of the nineteenth century did people realize that larger energy densities existed in nature beyond the uncontrollable lightning events. Early experiments on the structure of atoms suggested far greater energies were responsible for keeping atoms whole. The binding of the electron to the nucleus of the hydrogen atom is 13.6 electronvolts (eV), with even greater binding for higher atomic number elements. In uranium, for example, the outermost electron is bound with an energy of 5.8 eV, while the removal of the last electron requires 132 kilo-electronvolts (keV) to form the bare nucleus. Even greater energies, due to the nuclear force, were later found when nuclear structure experiments were performed; for example, the energy released in the fission of one uranium nucleus is about 180 mega-electronvolts (MeV).

The structure of our surroundings is dictated by Coulomb forces between individual atoms, which in the case of a carbon-carbon molecular bond is about 4 eV. Larger assemblies of carbon atoms are held together by even weaker forces. For example, in graphite, adjacent planes of carbon atoms are bound together by

bonds of about 0.05 eV per carbon atom. For reference, this energy corresponds to a temperature of about 600 Kelvin (K), about twice that of room temperature. By comparison, iron has a melting point of about 1,800 K.¹

Life on Earth is dependent on solar radiation. While the surface (photosphere) of the Sun has a temperature of roughly 5,800 K, the major portion of the radiant energy reaching the surface of the Earth has photon energies in the range 0.06–0.4 eV (wavelengths between 300 and 2,000 nanometers [nm]). It is this matching of photon energy with molecular bonding energies that allows formation of new molecules, and thus the rise of biological structures; that is, the creation of life itself.

The wide distribution of binding/bonding energies is better cast in terms of energy density, which is just another expression for pressure. For example, the covalent bond energy of the hydrogen molecule is a bit less than 5 eV, which corresponds to an internal energy density of about 10^{11} Pascals (Pa) or 1 megabar (Mbar). We would expect that if an assembly of hydrogen molecules is subjected to an external pressure in excess of this internal energy density, the structure of the molecules would be altered. In fact, at these elevated conditions, hydrogen (as well as for all matter) exhibits a new property: the neutrally charged atom becomes ionized. This more energetic state is often referred to as the fourth state of matter, the plasma. Indeed, metals that exhibit a high electrical conductivity have conduction electrons that are loosely bound to individual atoms, and so tend to wander through the lattice. These metals, while solid, exhibit many of the characteristics of plasma.

We are surrounded by plasmas. For example, the radiation from the Sun, which warms us, is produced by plasma; the “neon” advertising signs light up storefronts; the welder’s torch assembles useful structures; light from fluorescent electrical fixtures lets us see in the dark; and so on.

Traditional plasma theory arose from experiments on low-density, high-temperature gases, where ionization had transformed the neutral atoms into negatively charged electrons and positively charged ions. The study of this new form of matter focused on the “individual” behavior of the constituent particles. But for higher-density plasma, this approach is nearly impossible because of the extreme complexity of the dynamics of ions and electrons in close proximity to one another. It is far more advantageous to treat the plasma as two fluids: one for the free electrons and one for the heavy ions. This is the basic approach for describing high-energy-density matter.

Consider air at its normal density, about 10^{-3} grams per cubic centimeter ($\text{g}\cdot\text{cm}^{-3}$), at a pressure of 1 Mbar. At this pressure, the temperature is about 10 keV ($\sim 10^8$ K).

¹ This reference is a bit careless about equating energy to a temperature. The examples are basically “single-particle” energies, while temperature implies averaging energies over some distribution function.

As the density is further decreased, but still has a pressure of 1 Mbar, the temperature becomes hot enough that relativistic plasma is established. This regime, too, is beyond the realm of traditional plasma physics.

Dense plasma also exhibits characteristics of condensed matter. Because of the close proximity of ions, they are highly correlated and form structures not unlike that encountered in the solid state. Thus, high-energy-density physics concepts also draw on the wealth of theory developed in condensed matter physics. While high-energy-density matter is loosely defined as matter with energy density greater than 1 Mbar, recent research has addressed cooler, but still dense, conditions, known as warm dense matter. This book does not explicitly address the physics specific to those environmental conditions, but much of what is discussed is directly applicable to that topic.

1.1 High-Energy-Density on Earth

Perhaps the earliest demonstration of high-energy-density phenomenon in the laboratory was conducted by Martinus van Marum in Amsterdam in 1790. He employed a 1 kilojoule (kJ) capacitive energy store composed of one hundred Leyden jars, which was discharged into a wire 1 meter (m) long, causing its explosion and vaporization. A later, independent discovery in Australia (Pollock and Barraclough, 1905) arose from the radial collapse of a copper tube used at the Hartley Vale kerosene refinery as a lightning conductor; the outcome of the experiment is shown in Figure 1.1. The researchers correctly interpreted the results as being due to the force arising from the lightning's current interacting with its own magnetic field.

By the mid-twentieth century, the power of nuclear weapons had been demonstrated. Based on the exploitation of the energy released in the fission of uranium, the uncontrolled release of energy created energy densities in excess of 10^4 Mbar. Scientists used underground nuclear explosions to explore the physics of matter at extreme conditions. They quickly realized that if this energy source could be controlled, it offered a laboratory source for continuing experiments on the nature of materials at high-energy densities. Thus began the exploration and development



Figure 1.1. A copper tube suffering the effects of a lightning strike
(Credit: Brian James, School of Physics, University of Sydney).

of magnetic fusion energy (MFE) as a possible source of energy production. In the later decades of the twentieth century, technological developments saw the creation of pulsed electrical devices and high-power lasers. These two types of machines made possible the laboratory study of matter at extreme conditions.

Even with the construction of large Z-pinch machines and multiterawatt, short-wavelength optical lasers, it wasn't until well into the 1980s that the instrumentation achieved the spatial and temporal resolutions needed for meaningful experiments to be performed.

With flexible, high-power sources and sophisticated diagnostics available in the laboratory, the ability to address fundamental physics questions about the structure and behavior of matter at extreme conditions became a reality. Not only was the field of fusion research advanced, but important experiments relevant to questions of interest in astrophysics and planetary science caught the attention of researchers worldwide.

1.2 Some Connections to Prior Work

Since the mid-1960s, the “bible” of high-energy-density physics has been the two-volume set by Ya. Zel'dovich and Yu. Raizer (1966), *Physics of Shock Waves and High-Temperature Hydrodynamic Phenomena*. Their work was complemented by an exquisite treatise on radiation hydrodynamics by D. Mihalas and B. Mihalas (1984), *Foundations of Radiation Hydrodynamics*. These two books are augmented by many physics texts on specific topics, including statistical mechanics, electrodynamics, hydrodynamics, equation of state, plasma physics, atomic physics and spectroscopy, and radiative transfer, to name but a few.

It is important to note that many of the topics we will address were first explored by astronomers and astrophysicists in their attempts to explain the structure of the stars and the formation of the galaxies. Much of this work was pioneered by S. Chandrasekhar and other preeminent physicists of the twentieth century.

In the late 1990s and the first years of the twenty-first century, numerous books appeared addressing specific aspects of high-energy-density physics. The first comprehensive work is the textbook by R. P. Drake (2006), appropriately named *High-Energy-Density Physics*, and more recently, my book with J. Colvin, *Extreme Physics* (Colvin & Larsen, 2014). As I proceed into the depths of high-energy-density physics in this book, I will note numerous references to prior work to consult for additional information.

There is always a dilemma in preparing a comprehensive work: what to include, what to develop in some detail, what to hint at, and what to ignore. Since this work is the outgrowth of the development of the radiation hydrodynamics simulation code HYADES, I have included those subjects of most interest needed to achieve

that goal. There remain a number of topics that should have been included, but page limitations prevailed. Preparation of the manuscript for this book relied heavily on handwritten notes dating back to the 1980s, many of them rather sketchy. Unfortunately, some attributions have been lost over time and have not been readily relocated; I take full responsibility for this deficiency.

1.3 Outline

High-energy-density physics draws on many physics disciplines, from classical, to quantum, to relativistic topics. Central to high-energy-density physics is the bulk motion of matter and its associated energy content and transport, especially that of radiative transfer. As high-energy-density matter is ionized plasma, the free electrons and ionized atoms (the ions) are given equal importance. As we shall see, thermal radiation is an essential ingredient of high-energy-density matter. This requires that the radiation be treated as a third “fluid,” on an equal footing with the electron and ion fluids, taking account of the mass difference between the photons and material particles.

There is one additional aspect of high-energy-density physics that is not found in traditional plasma physics, and that is electron degeneracy. This condition arises when plasma is at high density and low temperature. Degenerate electrons have a profound effect on nearly all aspects of high-energy-density matter.

There are aspects of the physics that should be treated in addition to those discussed here. The list includes gravity, relativistic effects, etc., but they are of little or no concern in the terrestrial laboratory. Further, I omit any discussion of atomic spectroscopy, fusion applications, and diagnostic instruments and nearly all mention of experimental results.

The objective of this book is to provide a comprehensive collection of the most important physical phenomena encountered in high-energy-density matter. Chapter 2 is a brief summary of the topics that define high-energy-density matter and possible ways to characterize it from matter in other states.

Chapter 3 is a collection of many fundamental physics concepts that are often covered in undergraduate and first-year graduate physics courses. I refer back to this chapter many times throughout the text. The reader well versed in basic physics can skip this chapter; I include it for reference for those individuals who are a bit “rusty.”

The real substance of this book begins with Chapter 4. A most important quantity in high-energy-density plasma is the ionization level, that is, the average number of unbound electrons per ion. In traditional plasma, this is determined by binary collisions among the particles, which are controlled by the temperature. In high-energy-density matter, the close proximity of one atom to another causes a

change in the overlap of electron orbitals. The outermost electrons become pressure ionized even for very low temperatures. Another important ionization mechanism is that due to the radiation field – photoionization. Higher-energy photons can interact with the deeper-lying atomic levels, causing those electrons to be removed from the atom. In fact, the combination of processes leads to time-dependent, nonequilibrium ionization.

Chapter 5 discusses the properties of matter at extreme conditions as characterized by the equation of state (EOS). We are familiar with the EOS for a perfect gas, but this simple model is of limited use in high-energy-density physics because it is an “isolated atom” model. The problem of calculating the internal states of matter (pressure and specific energy) as functions of environmental variables (density and temperature) is exceedingly difficult for strongly coupled plasma. Realistic models need to account for more than just “closest neighbor” atoms; there are several computational approaches that yield sensible results. The basis for some of this work comes from solid-state theory.

Chapter 6 develops the equations of material response. Based on the conservation equations of mass, momentum, and energy, and using an EOS for a particular material, the basic model of gas dynamics is developed. Because we are dealing with high-energy-density matter, shock waves are likely to form. Their behavior is easily found from the hydrodynamic equations. A better approximation includes the effects of viscosity and thermal conductivity, which leads to a picture of the structure within the shock front. A further improvement for modeling the response of “solid” materials is based on an elastic-plastic description of deformation. Finally, we briefly address the complex topic of fluid instabilities. This chapter does not include the effects of the radiation field; that topic is left to Chapter 10.

Chapter 7 discusses the heat flow in high-energy-density matter. For the most part, this conductive transfer of energy is due to the electron fluid. After considering the basics of nonlinear thermal conductivity, I address the thermal and electrical transport coefficients that are determined by density and temperature gradients. Electron degeneracy effects play a significant role in determining the rate of heat flow. The issue is complicated even further by the existence of steep temperature gradients, which result in a nonequilibrium electron velocity distribution, leading to thermal energy transport inhibition.

Chapter 8 is devoted to the development of radiation transport theory. Because photons can have a wide range of mean free paths and are moving at the speed of light, the theory is complex, and we must begin from the basic concepts, then turn to the fundamental issue of how radiation interacts with the electrons by their absorption, emission, and scattering. The full set of radiation transport equations is “impossible” to solve, even with advanced computational resources, so I reduce

the set to several approximations, each of which is relevant under certain conditions. I also find that even in the most basic conditions, certain aspects of the transport theory must include relativistic effects, and that there is a preferred frame of reference for calculating radiation transport. Lastly, I address the topic of view factors.

Chapter 9 focuses on atomic theory and the calculation of the radiative absorption, emission, and scattering coefficients. My approach is to treat the electron quantum mechanically, in the hydrogenic approximation, but the radiation classically. Rate coefficients are also developed for collisional processes that necessarily include electron degeneracy effects.

Chapter 10 begins the discussion of combining the basic hydrodynamic theory with radiation transport theory. This makes for some very interesting situations, and I can only lightly touch the subject; several excellent books on this topic have been published in recent years. I consider a number of situations that might be encountered in the laboratory or in the astrophysical environment, developing the essence of each.

Chapter 11 examines the magnetic fields that are known to play a prominent role in some astrophysical phenomena. They also occur in the laboratory setting, but usually are not given a position of importance. Magnetic fields affect plasma in nearly all aspects, from altering the hydrodynamic response, to modifying the thermal conductivity and associated transport coefficients, and to creating an environment where collisions between magnetic field geometries can cause energetic mass ejections, which, for example, are readily observed in the solar environment. An additional equation describing the diffusion of magnetic fields in plasma is introduced. Further, magnetic fields can be produced by pulsed-power devices to create high-energy-density plasma; the most common configuration is that of the Z-pinch. I discuss some simple models of how the Z-pinch forms as a result of the magnetic pressure created by high-current flow.

The last chapter, Chapter 12, focuses on the interaction of electromagnetic waves with plasma. This topic is the outgrowth of the investigation of atmospheric propagation and heating (absorption) of the ionosphere in the mid-twentieth century. The most important aspect of this topic is oblique incidence of the wave on a stratified planar medium. If the polarization is such that the electric vector lies in the plane of incidence, a number of phenomena can occur at the so-called critical-density point. These include profile modification due to the ponderomotive force and formation of plasma instabilities that can create very energetic electrons. I also consider the spontaneous creation of magnetic fields and the effects of magnetic fields on changing the identity of the electromagnetic wave. I conclude with a brief discussion about very high-intensity electromagnetic waves, which produce relativistic effects.

1.4 Notation, Variables, and Units

As the material presented in this book is drawn from a number of disciplines and different authors, using the notation from those sources results in a less than uniform description. I have made every attempt to keep the notation consistent within this book, yet retain some of the original description. Consequently, the reader will find more than one mathematical symbol is used to describe the same quantity; for example, the radiation energy density is designated both by u_r and E_r . And of course, a specific symbol is used for multiple quantities, such as σ for a cross section, for the electrical conductivity, and for the Stefan-Boltzmann constant. I make clear the particular use as the book progresses.

The mathematical expression of the physics, for the most part, is written as vector differential equations. I assume the reader is familiar with the mathematical symbols used, such as the differential operators: ∇ , $\nabla \cdot$, and $\nabla \times$. Variables appear as scalars, such as ω for frequency; vectors, such as $\mathbf{v}$ for the velocity (with the scalar representation v); and tensors, such as $\underline{P}$ for pressure. I introduce four vectors in Chapter 8, where it is natural to discuss certain aspects of radiation transport with this formalism.

For the most part, I work in a Cartesian coordinate system. Occasionally I find it appropriate to use some other system, such as spherical.

I prefer (and use) the Gaussian cgs (centimeter-gram-second) system of units, with temperatures expressed in keV (thousands of electronvolts), and occasionally eV. At times it is more convenient to use other units common to a specific instance, especially when noting values for real quantities; for example, for the “modest” temperatures of the outer layers of the Sun, I use degrees Kelvin. Another measure employed for measuring pressure and energy density is the megabar (Mbar), which is commonly used in the industry, but is not consistent with the cgs system. And then there is laser intensity, for which the practitioners use the measure watts-cm^{-2} , which is really a flux (the true use of “intensity” implies a solid angle). Also, they measure the laser wavelength in micrometers.