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Excerpt
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Extreme environments: What, where, how

1.1 Background, definitions, and assumptions

As far as we know, human beings and other biological organisms exist in the universe only on or near the surface of one rocky planet, where the physical conditions permit the existence of self-replicating long-chain molecules. These molecules are formed as individual atoms bound together via Coulomb forces. Binding takes place when the individual atoms are close enough together that the outer valence electrons of each atom can experience the potential well of the neighboring atom's nucleus as comparable to the potential well of its own atom's nucleus. In an ionic bond, for example, the atom with lower ionization potential "gives" its electron(s) to the neighboring atom that has higher electron affinity. In a covalent bond, the valence electrons of each atom simultaneously fill the valence bands of both atoms in the bond.

Nonetheless, whatever the exact nature of the molecular bond, in the bound molecular system, these valence electrons, in some sense, "belong" to both atoms simultaneously, with their exact positions with respect to the neighboring atomic nuclei known only to the accuracy allowed by the quantum-mechanical uncertainty principle. Thus, the binding energy of a typical di-atomic molecular bond is comparable to the binding energy of the valence electrons to the atom. The electron binding energy is typically a few electron volts (eV). One electron volt is the energy required to move one electron across a potential difference of one volt, equal to 1.6022×10^{-12} erg, a relatively small amount of energy. A typical covalent carbon–carbon molecular bond, for example, has a binding energy of $\sim$4 eV. The covalent carbon–carbon molecular bond forms the basis of all known biological organisms on Earth.

The individual atom that is in a bond with its nearest neighbor is bound to other atoms in the larger molecular structure with much less energy. For example, in graphite, adjacent planes of carbon atoms in the material are bound together by a potential energy of only ~0.05 eV per carbon atom. This energy E corresponds to a temperature $T = E/k \approx 600$ K, which is about twice room temperature, where k is Boltzmann's constant.

Thus, large molecular structures can stay in a stable structural state only at relatively low temperatures and pressures. The surface of the Earth, at an average temperature of ~300 K and an average pressure of 1 atm = 0.1 MPa, is at ideal conditions for the existence of stable large molecular structures. The matter we encounter in our ordinary experience is thus matter that exists largely as neutral atoms arranged in various molecular structures. Such matter could be in a solid state, as in the minerals in the crust of the Earth. It could be in a liquid state, as in the water in the oceans. It could be in a neutral gas state, as in the atmosphere that surrounds us. This is the matter that we encounter in our daily existence, and it is the matter that has been the principal object of study and investigation since before the beginnings of the scientific revolution in the sixteenth century.

Most of the visible matter in the universe, however – from the deep interior of planets to the matter of stars – is at a much higher temperature and/or pressure than the matter of our ordinary experience. Indeed, we do not have to move far in either direction off the surface of the Earth in order to find matter at temperatures and pressures much higher than on the surface. At much higher temperature or pressure, the material will likely be in an entirely different physical state, and will behave differently. At these higher temperatures or pressures, stable large molecular structures necessary for constructing biological organisms cannot exist. However, various exotic states of matter can exist, including states of matter that seem to exist simultaneously as solids and plasmas, that is, charged particles arranged in an ordered lattice structure.

1.1.1 Background

Until very recently in human history we were unable to access matter that is located far from the Earth's surface. We were also unable to create such matter here on the Earth's surface. As a consequence, not much has been known about matter at these high-temperature or high-pressure conditions. Only within the last half-century or so have human beings been able to create physical conditions on the surface of the Earth that are at high-temperature or high-pressure conditions. The invention and development of nuclear weapons in the 1940s originally drove much of the research on matter at these extreme conditions. Much of this research, however, remained classified for a very long time, so research progress was hampered. Several parallel developments, however, have led to a huge expansion in unclassified research into the properties and behavior of matter at extreme conditions, and the emergence of this entirely new discipline of physical science.

One important development has been the design and construction of various machines and devices that can concentrate energy in a controlled way so as to allow experimental investigation of matter at extreme conditions. These devices include high-power optical lasers, free-electron lasers, particle accelerators, and pulsed-power machines. In parallel, there has been much activity in the development of new diagnostic instrumentation that can measure physical processes on ever-shorter time scales, and in very hostile conditions of temperature and/or pressure. Even though a lot of this research originally grew out of nuclear weapons programs, almost all the research on experimental machines and diagnostics is and has been unclassified, so research on matter at extreme conditions inevitably opened. We will say more about these experimental devices later in this chapter, although the experimental aspects of this emerging area of research are not the focus of this book.

One important thing about these experimental investigations, though, is that they have opened a window on physical processes that are different from the physical processes that define the properties and behavior of the matter of our ordinary experience. As a result, much theoretical work over the past several decades has expanded our understanding of the physical processes in matter at extreme conditions.

Even more important is the interplay of several complex physical processes, which present significant challenges in mathematical modeling. A parallel development over the past few decades has been the development of high-speed, high-performance computers, along with numerical and computational techniques and computer codes that can simulate the interplay of the complex physical processes in matter at high temperature and pressure. Indeed, it is the strong synergism between experiment, theory, and computation – and their parallel development – that has led to the major advances in this new area of physics.

As more and more students become actively involved in this emerging area of physics research, a need has arisen for a thorough and comprehensive text. Recognizing, however, that no single text can adequately cover all three pillars of the field – experiment, theory, and computation – we chose to focus just on theory and computation. Thus, the main objective of this book is to fill the need for a text that provides an introduction to the physics of matter at extreme conditions, along with an introduction to the computational techniques required to do numerical simulations of the properties and behavior of matter at extreme conditions.

1.1.2 Definitions

First, however, we clarify the terminology, particularly what we mean by the term “extreme physics.” As this emerging area of physics research has evolved over the past several years, it has generally taken on the name "high-energy-density physics." Indeed, this is the name given to this field of research by the government agency that provides most of the funding for this research in the United States, the US Department of Energy. It is also the title of a textbook by Paul Drake that was published in 2006, the first attempt at treating this emerging area of physics in a comprehensive way since the publication of the first Russian edition of *Physics of Shock Waves and High-Temperature Hydrodynamic Phenomena* by Yacov Zel'dovich and Yuri Raizer in 1963 (the first English edition appeared in 1967). The Zel'dovich and Raizer monograph remains, in our opinion, the most comprehensive book in existence on high-energy-density physics, but it is out of date, since it was written before the advent of modern experimental and computational capabilities and before the new understandings about the properties and behavior of matter at extreme conditions. This remains true for the second edition which appeared in 2002, even with the addition of some new material. Drake's book brings things up-to-date, but there is little coverage of computational techniques. We consider gaining some facility with mathematical modeling and computation to be essential to understanding and progress in high-energy-density physics. Our hope is that this book can provide what the student needs to know to gain this facility.

Naming this area of physics "high-energy-density physics," though, begs the question of how high the energy density of the matter must be to qualify as high-energy-density matter. The convention that has emerged in the research community over the past decade is to define high-energy-density matter as having an energy density greater than 100 kJ cm^{-3}, which corresponds to a pressure of 1 Mbar (a million times atmospheric pressure, equal to 100 GPa). This seems an arbitrary boundary, and excludes "warm dense matter," that is, matter that is at pressures less than 1 Mbar but still in a state that is very different from matter at standard temperature and pressure (STP), which is $T = 300$ K and $P = 1$ atm $= 1$ bar $=$ 100 kPa. At STP, as discussed above, electrons are bound in atoms, and possess a negligible electronic specific heat compared to the atomic specific heat $3N_Ak$, where N_A is Avogadro's number, the number of atoms per mole of material.

We prefer the term "extreme physics," which we define as the physics of the properties and behavior of matter at temperatures and pressures much greater than STP. In the extreme physics regime, internal energies are much greater than the typical electron binding energies, so atoms have been stripped of some or all their electrons, or they have been compressed together so closely that the electron occupation states are different from those in the isolated atom. In matter at extreme conditions the unbound electrons and ions must often be treated as separate fluids, sometimes with different temperatures, and the electronic specific heat is no longer negligible. Matter at extreme conditions is typically in a plasma state, although, in some instances, the charged particles of the plasma can be in an ordered state and possess some of the characteristics of a solid. The interactions between the plasma electrons and ions define the properties and behavior of the matter.

Extreme physics is thus a much more encompassing term than is high-energy-density physics. Matter at extreme conditions basically includes all visible matter in the universe away from the surfaces of rocky planets, and all matter created by energy-concentrating devices like high-power lasers. We discuss in more detail in the next section the regions in temperature–density space with which we are concerned, and the basic physics that defines the boundaries of these regions. We also discuss where in temperature–density space various natural and laboratory-created extreme states of matter occur.

The student will learn the basic properties of dense plasmas; ionization physics; the physical mechanisms by which laser light is absorbed in matter; the basics of fluid dynamics (hydrodynamics) and shock-wave formation and propagation; shock compression of condensed matter; radiation transport in matter; and the basics of numerical simulation of radiation-hydrodynamics phenomenology.

1.1.3 Assumptions

This text is aimed at the first- or second-year graduate student, but with a judicious choice of what material to cover, could also be useful for advanced undergraduates. The student is assumed to be familiar with the basic concepts of thermodynamics, gas dynamics/fluid mechanics, statistical mechanics, and electricity and magnetism. The student should also have some working knowledge of vector partial differential equations (PDEs). The structure of the text is to start each chapter by deriving the basic equations and discussing the basic physics, and then to proceed rapidly to the final relevant expressions, with student exercises at the end of each chapter. By Chapter 11 the student should have enough basic knowledge of the relevant physics to begin learning how to do numerical computations. The last two chapters – Chapters 11 and 12 – will familiarize the student with numerical simulations and their essential role in extreme physics.

To keep it simple we mainly confine ourselves to motion in one dimension, although we show how to generalize to two and three dimensions. We will also mainly be concerned with dense plasmas that are non-relativistic (that is, plasmas in which the individual particles have velocities much less than the speed of light, c) and non-magnetic (that is, plasmas in which the net magnetic moment $\mu = 0$), but we address magnetic field effects on plasmas in Chapter 10. We will also generally assume that our dense plasmas are isotropic (that is, material properties are not dependent on direction), except that we will discuss non-isotropic elastic properties of shock-compressed solids in Chapters 5 and 6.

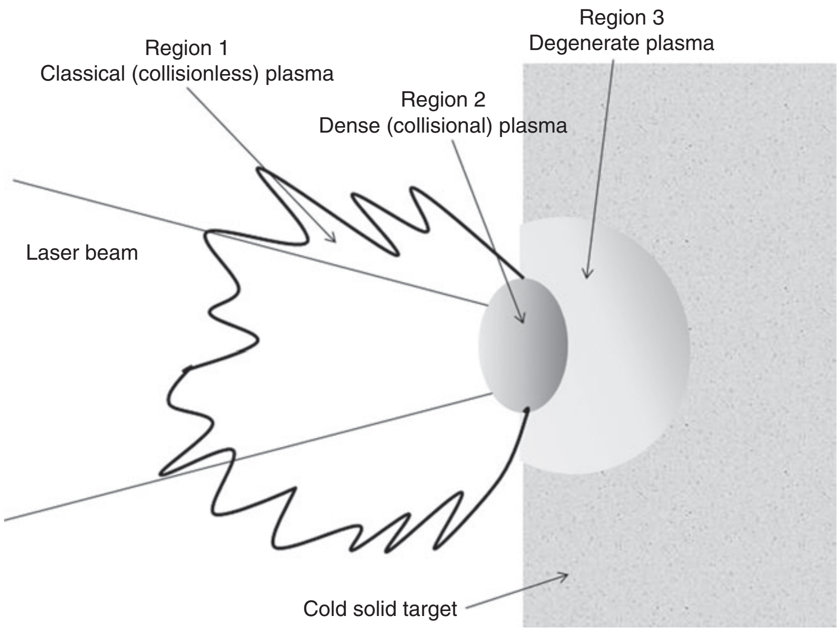

Figure 1.1 The three distinct regions of extreme conditions created by a high-intensity laser beam interacting with solid matter.

We use cgs units throughout. As is the custom in this area of physics, we express all temperatures in units of keV. A glossary of symbols, along with unit conversions and constants, is given in Appendix I.

1.2 Elements of the extreme physics environment

1.2.1 Classifications

A high-intensity laser beam, when incident on a piece of solid material, deposits its energy into the material and creates matter that has a wide range of extreme conditions, as illustrated in Figure 1.1. Here, we identify three distinct regions of extreme conditions.

Region 1 contains the ablated material, and is at much higher temperature and much lower density than the initial cold solid material. The material in Region 1 is in a classical plasma state, in which the Coulomb interaction between any two ions is modified by the Coulomb potential of all the other ions. The characteristic range of the modified, or screened, Coulomb potential is given by the ionic Debye length

$$\lambda_D = \sqrt{\frac{kT_i}{4\pi n_i \, (Z^*)^2 \, e^2}}, \tag{1.1}$$

where T_i is the ion temperature, n_i is the ion number density, Z^* is the ion charge state, and e is the electron charge. In the classical plasma, Region 1, the Debye length is large compared to the average distance between the ions,

$$R_0 = \sqrt[3]{\frac{3}{4\pi n_i}}. \tag{1.2}$$

This means that in classical plasma the ion Coulomb potential is well screened, so each ion's electrical repulsion of like charges has little effect on its neighboring ions. Another way of saying this is that the temperature is high enough and the density is low enough that the plasma coupling parameter, the ratio of the ion Coulomb energy to its thermal energy

$$\Gamma = \frac{(Z^* e)^2}{R_0 k T_i}, \tag{1.3}$$

is much less than 1. The plasma is then said to be weakly coupled. The relevant physics operative in this region is discussed in more detail in the next chapter.

The ion charge state $Z^* = n_e/n_i$, where Z^* is a function of electron density, ion density, and temperature. The ion density is the sum of the density of the neutral atoms and the density of the positively charged atoms, $n_i = n_0 + n_+$. Thus, when the atoms are fully ionized, that is, all the bound electrons are free, $n_0 = 0$, $n_i = n_+$, and Z^* is equal to the atomic number. We discuss the physics of ionization, and its dependence on temperature and density, in Chapter 7.

The boundary between Region 1 and Region 2 is where $\Gamma = 1$. Region 2 contains matter that, like in Region 1, is also in a plasma state, but here the plasma ions are no longer weakly coupled. The plasma in this region is dense plasma in which charged particle collisions play a much larger role. The relevant physics operative in this region is also discussed in more detail in the next chapter.

When $\Gamma \gg 1$ the plasma is said to be strongly coupled. Here the plasma is at temperatures higher than in the cold material, but it is in a compressed state, at densities higher than the density of the cold uncompressed material. The ions are distorted by close proximity to their neighbors, with the material resembling a liquid metal.

The electrons become degenerate at sufficiently high density when the quantum-mechanical Pauli exclusion principle alters the occupation of the free electron states. The electron degeneracy parameter is

$$\Psi = \frac{\mu}{kT_e}, \tag{1.4}$$

where μ is the electron chemical potential (not to be confused with the magnetic moment, which is denoted by the same symbol). In regions where $\Psi \ll 1$,

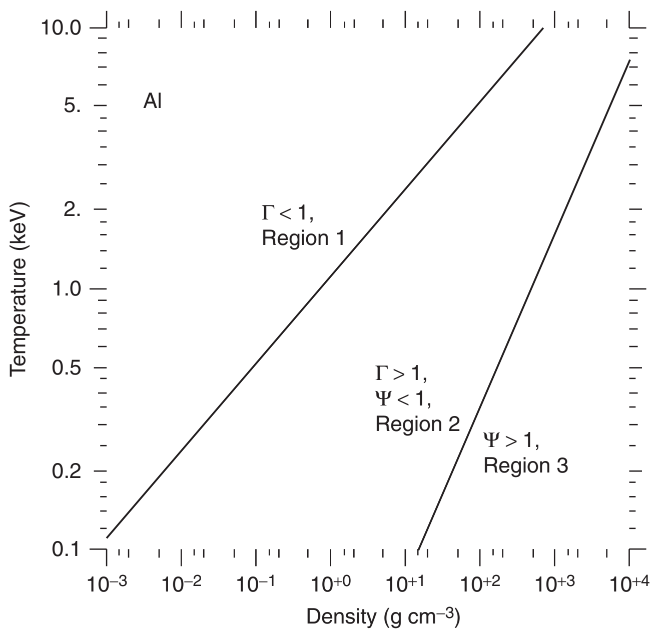

Figure 1.2 The region boundaries in temperature–density space for a fully ionized Al plasma ($Z^* = 13$).

the electrons have an ordinary Maxwell–Boltzmann distribution of energies. In regions where $\Psi \gg 1$, the electrons are fully degenerate, and thus have a Fermi–Dirac distribution of energies. These energy distribution functions are derived and discussed in detail in the next chapter. The boundary between Region 2 and Region 3 is defined as where $\Psi = 1$. The relevant physics operative in these two regions, the regime of dense plasmas, is discussed in more detail in the next chapter. There we show, on the basis of statistical physics, that when $\Psi > 1$ the plasma ion density, in units of cm^{-3}, is

$$n_i > 1.44 \times 10^{26} \frac{T_i^{3/2}}{Z^*}, \tag{1.5}$$

where again T_i is in units of keV.

Note that the region boundaries are strongly dependent on temperature and density. The positions of the region boundaries for a fully ionized aluminum plasma ($Z^* = 13$) are shown in Figure 1.2. In this figure we show the boundaries only for temperatures above 100 eV; to a very good approximation, the plasma is fully ionized above 100 eV, except at very low densities, below about 10^{-3} g cm^{-3}. As we see in Figure 1.2, there is considerable overlap of the regions. For example, a fully ionized Al plasma at density 10^2 g cm^{-3} and temperature 250 eV is both

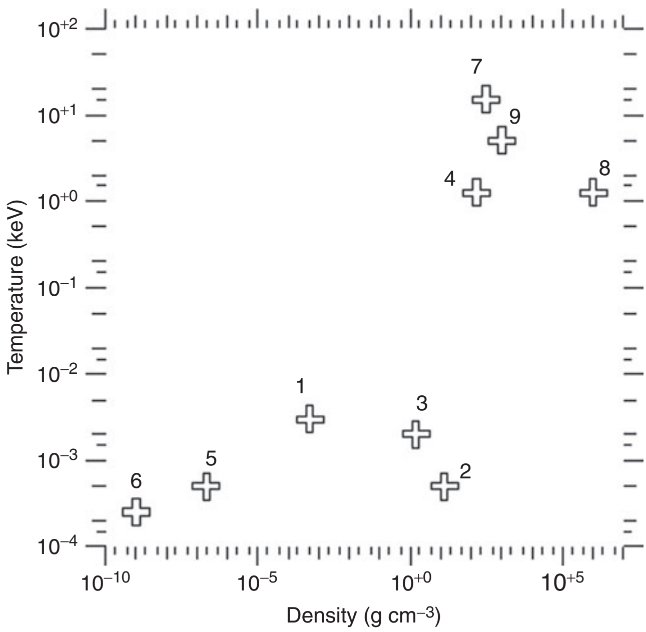

Figure 1.3 The position in temperature–density space of many natural and man-made classical and dense plasmas: 1, lightning discharge; 2, Earth's core; 3, core of a giant gas planet like Jupiter; 4, Sun's core; 5, Sun's surface; 6, surface of a red supergiant star like Betelgeuse; 7, core of Betelgeuse; 8, interior of a white dwarf star; 9, igniting fuel of inertial confinement fusion capsule.

strongly coupled and degenerate, but the same plasma at the same density but twice as hot is strongly coupled and non-degenerate.

1.2.2 Environments

The other thing to note about Figure 1.2 is the large range of both temperature and density, spanning many orders of magnitude. This is a reflection of the large range in temperature–density space in which the many natural and man-made classical and dense types of plasma exist, as illustrated in Figure 1.3.

Starting in the lower left-hand side of this figure, we find the plasmas created by natural lightning discharges. These plasmas consist of partially ionized air (largely nitrogen and oxygen) at temperatures of ≈ 3 eV and densities of $< 10^{-3}$ g cm^{-3}.

Moving to the lower center of the diagram, we find planetary interiors. The core of the Earth is a warm dense plasma consisting mostly of iron, at a temperature of ≈ 0.5 eV, a density of ≈ 13 g cm^{-3}, and a pressure of ≈ 3.3–3.6 Mbar. The central core is solid, and the outer core is liquid. The conditions that define the phase boundary are not known. The phase boundary depends on the exact composition of the core, which also is not known.

The cores of the giant gas planets, like Jupiter, consist largely of H and He at a temperature of $\approx$1–3 eV, a density of $\approx$1.5 g cm^{-3}, and a pressure of $\approx$30–45 Mbar. At these conditions, the largely hydrogen core is probably in a liquid metal state. We will say more about this in Chapter 6.

A main-sequence star, like the Sun, inhabits a region near the center of this figure. The surface of the Sun is at a temperature of $\approx$0.5 eV, much the same as the temperature at the center of the Earth, but at a much lower density, $\approx 2 \times 10^{-7}$ g cm^{-3}. The Sun's core is at a temperature of $\approx$1.25 keV, a density of $\approx$150 g cm^{-3}, and a pressure of $\approx$340 Gbar. A more-massive giant star can have a somewhat lower surface temperature than does the Sun (red supergiants like, for example, Betelgeuse, have a surface temperature of $\approx$0.25 eV, comparable to the temperature of the filament of an ordinary light bulb), while the interior is hotter than that of the Sun's interior. The core of a giant star can have a temperature of tens of keV.

Moving toward the upper right-hand side of Figure 1.3 we encounter compact astrophysical objects, like white dwarf stars, that are much denser than main sequence stars. The interior of a typical white dwarf star, below its thin helium envelope, contains the bulk of the star's mass, and consists largely of C at a temperature of $\approx$0.4–2 keV (comparable to the Sun's core temperature) and a density of $\approx 10^6$ g cm^{-3}. Neutron stars are off the figure to the right, with typical densities of $\approx 10^{12}$ g cm^{-3} for hot neutron stars ($T \approx 10^8$ keV), $\approx 10^{14}$ g cm^{-3} for cold neutron stars ($T \approx 10^4$ keV).

Astrophysical objects like planets and stars can maintain such extreme conditions in static equilibrium because the static compression is supplied by gravity. There are, however, astrophysical phenomena that involve classical or dense plasmas not in static equilibrium. Examples are the ejecta of nova and supernova explosions; bi-polar jets created in the disc accretion process; and stellar wind outflows. All of these astrophysical plasmas are not only at extreme conditions, but also moving at high velocity. Astrophysical jets have typical outflow velocities of several hundred kilometers per second. When these flowing plasmas collide with other objects in their path, like interstellar clouds for example, yet other extreme conditions are created in the dynamic collision process. Star formation, for example, takes place as the result of plasma collision processes. Another example is the interaction of the solar wind with the geomagnetic field, which channels the solar wind particles to the polar regions, where collisions with air molecules produce the aurorae. Thus, the universe is a rich potpourri of materials at a wide variety of extreme conditions.

In the laboratory, of course, we cannot use gravity to create dense plasma in static equilibrium. Instead, we create the extreme states of matter dynamically. The various ways to create these plasmas dynamically are reviewed briefly in