Lectures on the Physics of Extreme States of Matter

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Contents

A word to the reader

You are holding a course of lectures from the ‘Higher School of Physics’ series of ROSATOM State Corporation.

The Higher School of Physics is the initiative of ROSATOM, aimed at training and educating scientists of a new generation in the field of theoretical and experimental physics, as well as at attracting talented young people to science and innovation spheres.

The books of this series have been prepared by leading scientists of the Russian Academy of Sciences and industry research centers and contain information about the most topical areas of theoretical and experimental physics.

I hope these books will become handbooks for students and postgraduates of specialized disciplines, young scientists and all employees of the nuclear industry, interested in improving their scientific and technical skills.

For ROSATOM, the matter of honor and professional maturity is to breathe fresh energy into nuclear power engineering and industry: to cultivate a galaxy of physicists of the future, who will become generators of innovative ideas and drivers of the world nuclear industry.

V A Pershukov,
Deputy Director General for Innovation Management,
ROSATOM State Corporation

From the editorial board

The successful history of the nuclear project, which was of key importance for the stability of our country for many decades was the result of the work of a huge team of scientists, engineers and workers. The task of forging an atomic shield was solved in a country destroyed by war, at the cost of incredible efforts, without a developed instrument-making infrastructure, in the absence of necessary unique materials and the corresponding industry. Paying tribute to all participants of the project, particular mention should be made of the decisive contribution of scientists. Bright representatives of physical, chemical, and materials sciences found solutions to the most complicated problems that were on the way to creating nuclear weapons. We proudly remember I V Kurchatov, Yu B Khariton, I E Tamm, A D Sakharov, K I Shchelkin, D A Frank-Kamenetsky, V L Ginzburg, E I Zababakhin and many other prominent scientists who led their colleagues and students. Success was determined by the talent and a broad knowledge of the leaders. Even today, their successors and disciples successfully work in our industry, including civil and defense spheres.

Modern problems of the development of science and technology also call for scientific leaders—custodians of the traditions initiated by previous generations. The upbringing of such leaders is the main concern of ROSATOM. That is why an idea arose to found the Higher School of Physics for young employees of ROSATOM institutes. The main task of the Higher School of Physics is to broaden the horizons of young people—students of the School by organizing four two-week modules on the basis of the largest scientific centers of ROSATOM, during which leading Russian scientists deliver lectures that represent different fields of physics and related sciences.

The selection of the courses and lecturers is made by the Scientific Council of the School. The Council includes well-known scientists from All-Russian Scientific Research Institute of Technical Physics (Snezhinsk), All-Russian Scientific Research Institute of Experimental Physics (Sarov), Troitsk Institute for Innovation and Fusion Research (Troitsk), and Institute of Physics and Power Engineering (Obninsk). Each course consists of six lectures; two courses are read each week; and the number of students is no more than 20 people, which creates prerequisites for direct contact of the lecturer with the audience.

It is important that students attend the courses only twice a year for two weeks. Young employees, who showed their qualities as researchers and leaders, are selected to join the School by the heads of the institutes.

The present series has been prepared on the basis of the lecture materials of the Higher School of Physics. The Scientific Council of the School expresses the hope that the series will appeal to a wide readership who wish to become acquainted with a brief summary of selected chapters of modern physics.

V P Smirnov,
Academician of the Russian Academy of Sciences,
Chairman of the Scientific Council of the Higher School of Physics of ROSATOM State Corporation,
Chairman of the Editorial Board of the series

Author's preface

This book is based on the lectures delivered by the author at the Higher School of Physics founded by ROSATOM State Corporation, as well as on plenary, review and invited papers presented at scientific conferences and symposia.

I am grateful for the opportunity to acquaint students of the School with the current state and prospects for the development of the physics of extreme states of matter, with the advantages and limitations of various experimental methods of generation and diagnostics, and with the results achieved.

In this course, the author has made an attempt to systematize, summarize and present, from a single point of view, theoretical and experimental material relating to this new field of science. In addition to the extensive scientific literature, the author has used a large number of original papers, reports and abstracts that are not widely available to a wide audience.

In view of the vastness and dissimilarity of the material, the presentation is mainly of a fact-finding nature, referring the reader to relevant reviews and monographs. Therefore, many interesting astrophysical, laser and nuclear physics problems, as well as technical applications, are presented briefly, sometimes even schematically. The author, of course, did not set a goal to include everything that is known today about extreme states of matter. The emphasis is laid particularly on those issues that seem most interesting to the author and on which he and his colleagues had to work directly.

After the Introduction, the first lecture addresses the classification of states of matter at high energy densities. The general view of the phase diagram, dimensionless parameters and physical conditions corresponding to terrestrial and astrophysical objects are discussed.

The means for generating extreme states available to the experimenters are outlined in the second lecture.

The use of lasers to produce and diagnose states with high energy densities is considered in the third lecture.

The fourth lecture discusses the problems of the physics of extreme states of matter in collisions of heavy ions accelerated to sublight velocities, which are accompanied by the formation of superdense nuclear matter, i.e. compressed baryonic matter and quark–gluon plasma.

The problems relating to the description of the thermodynamics of a highly compressed electromagnetic plasma are addressed in the fifth lecture.

The book concludes with a discussion of the most characteristic astrophysical objects and phenomena associated with the implementation of extreme energy densities in the Universe under the action of gravity and thermonuclear energy release.

I hope that the book will be useful to a wide circle of scientists, postgraduates and students of natural-science specialties, providing access to original works and allowing them to unravel fascinating problems of modern physics of extreme states of matter.

The author will be grateful to readers for their critical comments, suggestions and amendments that are inevitable in presenting such a rapidly developing field as the physics of extreme states.

Vladimir E Fortov,
Academician of the Russian Academy of Sciences

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In preparing the book, I had advice from and stimulating discussions with Yu Balega, N Andreev, S Blinnikov, M Kozintsev, A Sergeev, A Starostin, V Imshennik, I Iosilevskiy, N Kardashev, V Sultanov, B Sharkov, V Griaznov, and V Filinov, for which I am sincerely grateful.

Author biography

Vladimir E Fortov

Vladimir E Fortov is a member of the Russian Academy of Sciences, Head of the Department of Energy, Machinery, Mechanics and Control Processes of RAS.

Professor Fortov is an outstanding scientist who has made significant contribution to the physics of extreme states of matter and high energy densities, nonideal plasmas, shock and detonation waves, thermophysics, chemical physics, space research, and energetics, as well as to several other realms of physics and technology.

Vladimir E Fortov was born in 1946 in Russia, the town of Noginsk, Moscow Region. Fortov graduated from the Aerophysics and Space Research Department of the Moscow Institute of Physics and Technology (MIPT) with distinction in Thermodynamics and Aerodynamics and became a post-graduate student of MIPT. He defended his thesis, entitled ‘Thermophysics of Nuclear Rocket Engines,’ in 1971.

In 1971 Vladimir E Fortov started his research in the area of nonideal plasma physics and the thermophysical properties of extreme states of matter in the Chernogolovka Branch of the Institute of Chemical Physics of the USSR Academy of Sciences. The results of this research formed the basis for his doctoral thesis ‘Nonideal plasma investigations using the dynamic method’.

In parallel with plasma research, Vladimir E Fortov was deeply involved in studies of the mechanics of deformation and damage to materials exposed to high pressures, temperatures, and high deformation rates.

The successful solution to many scientific problems was facilitated by Fortov’s active cooperation with the General Physics Institute (GPI) and the Institute for High Temperatures (IHT) of the USSR Academy of Sciences. In 1994, a group supervised by Professor Fortov made a detailed prediction of the possible observable effects of an extraordinary space event—the collision of Shoemaker–Levy comet with Jupiter in July 1994. The data of subsequent observations carried out by many laboratories in the world confirmed the high accuracy of these predictions. Similar work was performed in 2005 in connection with the Deep Impact Project—a space experiment in which pioneering observations were made of a high-velocity collision of a metal striker with the nucleus of the 9P/Tempel comet.

In recognition of Vladimir E Fortov’s work in the area of thermophysics and thermomechanics of extremely high pressures and temperatures, he was elected a corresponding member of the USSR Academy of Sciences in 1987 and a full member of the Russian Academy of Sciences (RAS) in 1991.

Another impressive line Professor Fortov’s research is highly nonideal dust plasma. He supervised a series of pioneering experimental investigations into the structural and dynamic properties of plasma-dust crystals and liquids over a broad temperature and pressure range. For the first time, plasma crystals and liquids were obtained in a glow discharge, thermal plasmas, UV-radiation plasma, radioactive and cryogenic plasmas; experiments in plasma and crystallization under microgravity conditions were made aboard the Mir space station and the International Space Station (ISS).

Professor Fortov takes an active part in extreme expeditions. Specifically he participated in a cruise aboard the Volk atomic submarine; participated in the High-Latitude Arctic Deep-Sea Expedition to the North Pole; in the framework of the International Polar Year Program he took part in the International Antarctic Expedition to the South Pole and the Pole of Relative Inaccessibility; descended to the depths of Lake Baikal and Lake Leman (Switzerland) and visited the Vostok Polar Station in the Antarctic. Fortov rounded Cape Horn and the Cape of Good Hope on a yacht and crossed the Atlantic Ocean on a sailing yacht. He is keen on alpine skiing, tennis, piloting, and extreme traveling.

In recognition of his scientific and organizational activities, Vladimir E Fortov has been awarded many domestic and international prizes, a UNESCO Medal for his contributions to the development of nanoscience and nanotechnologies is among them. Numerous foreign and international academies and universities welcomed Vladimir E Fortov as their member.

Introduction

The states of matter at extremely high temperatures and densities have always attracted researchers, owing to the possibility of reaching record parameters, advancing to new domains of the phase diagram, and producing in the laboratory the exotic states that gave birth to our Universe through the Big Bang and which now account for the great bulk (90%–95%) of the mass of baryonic (visible) matter—in stellar and interstellar objects, planets, and exoplanets [1–9]. That is why the study of these states of matter—so exotic for us in terrestrial conditions and yet so typical for the rest of the Universe—is of great cognitive importance, forming our modern notions of the surrounding world.

Furthermore, a constant pragmatic incentive for such investigations is the application of highly compressed and heated matter in nuclear, thermonuclear, and pulsed power engineering, high-voltage and high-power electrophysics, for the synthesis of superhard materials, for strengthening and welding materials, for antimeteoritic protection of spacecraft and, of course, for defense. Indeed, the military application fostered the first successful experiment involving extreme states, which was conducted more than 3000 years ago—during the battle between David and Goliath. According to the Old Testament [10], the high-velocity impact of a stone shot from David's sling on Goliath's head killed him. It gave rise to a shock wave with an amplitude pressure of about 1.5 kbar. This pressure was more than twice the strength of Goliath's frontal bone and determined the outcome of the duel, to the great joy of the army and people of Israel. Discovered to be successful at that time, this scheme of action is today the ideological basis for all subsequent experiments in the field of dynamic physics of extreme states of matter.

Since the time of David, the application of more powerful and sophisticated energy cumulation systems—chemical and nuclear high explosives (HE), powder, light-gas, and electrodynamic guns, charged-particle fluxes, laser and x-ray radiation—has enabled the velocity of thrown projectiles to be raised by three to four orders of magnitude, and the pressure in the shock wave, by six to eight orders of magnitude, thereby reaching the megabar–gigabar pressure range and 'nuclear' energy densities in substances.

In the 20th century, the mainstream in physics of extreme states of matter was closely related to the entry of our civilization into the atomic and space era. In nuclear charges, extreme states of matter [11] generated by intense shock waves serve to initiate chain nuclear reactions in compressed nuclear fuel, and in thermonuclear charges and microtargets for controlled fusion, high-energy states are the main instrument for compressing and heating thermonuclear fuel and initiating thermonuclear reactions in it.

The research of extreme states of matter, starting in the mid-1950s within the framework of nuclear defense projects [12–16], has received considerable attention with the advent of new devices for generating high energy densities, such as lasers, charged particle beams, high-current Z-pinches, explosive-driven electric–discharge generators of high-power shock waves, multi-stage light-gas guns and diamond anvils. These sophisticated and expensive technical devices have made it possible to advance substantially along the scale of energy densities available for physical experiment and to obtain, in laboratory or quasi-laboratory conditions, the states of the megabar-gigabar pressure range unattainable for the traditional techniques of experimental physics.

Traditionally, energy densities are referred to as 'extreme' [1–4, 8] if they exceed 10^4–10^5 J cm^{-3}, which corresponds to the binding energy of condensed matter (for example, high explosives, hydrogen, or metals) and a pressure level of millions of atmospheres. For comparison, the pressures in the center of the Earth, Jupiter, and the Sun are about 3.6 Mbar, 40 Mbar, and 200 Gbar, respectively.

As a rule, matter in extreme states is in the plasma state—an ionized state arising from thermal- and/or pressure-induced ionization. In astrophysical objects, such compression and heating are caused by gravitational forces and nuclear reactions, and in laboratory conditions—by intense shock waves, which are excited by a wide variety of 'drivers', ranging from two-stage gas guns to lasers and high-current Z-pinches with a power of hundreds of terawatts[1]. However, while the lifetime of extreme states in astrophysical objects varies from milliseconds to billions of years, making it possible to conduct detailed observations and measurements with space probes and orbital and ground-based telescopes of different wavelengths, in terrestrial conditions we have to do with the microsecond–femtosecond–attosecond duration range [2, 3], which calls for the application of ultrafast specific diagnostic techniques.

At present, every large-scale physical facility (megaproject) that generates extremely high pressures and temperatures is enrolled in work programs (frequently international) on the fundamental physics of extreme states of matter, in addition to having practical, applied tasks in impulse energetics or defense. Thus, modern short-pulse laser systems (NIF, NIKE, USA; TRIDENT, LMJ, France; GEKKO-XII, Japan; OMEGA, VULKAN, Great Britain; Iskra-6, Russia; etc) are capable of releasing 1.0–1.8 MJ in a volume of the order of 1 mm^3 in several nanoseconds to produce pressures in the quasi-gigabar range (see tables 1.1 and 2.1).

In addition, the Z-pinch technology is now exhibiting considerable progress: at the Sandia facility (USA), $\approx$1.8 MJ soft x-ray radiation was obtained in the collapse of plasma liners during 5–15 ns in a region measuring about 1 cm^3. Supplemented by experiments with diamond anvils, explosion and electric explosion devices, and light-gas guns in the megabar pressure range, these record-high parameters are now the source of new and sometimes unexpected information about the behavior of highly compressed plasma [3].

Interestingly, in experiments on extreme-state laboratory plasma, even today it is possible to partly reproduce on a small scale many phenomena and processes occurring in astrophysical objects, information about which has become accessible due to the use of ground-based and spaceborne means of observation. These are the data on hydrodynamic mixing and various instabilities, shock-wave phenomena,

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[1] The total power of Earth's electric power plants amounts to about 3.5 TW.

strongly emitting, relativistic and magnetized fluxes and jets, solitons, relativistic phenomena, equations of state, and the composition and spectra of compressed nonideal plasma, as well as the characteristics of interstellar cosmic plasma, dust, and a number of other effects.

Although the limiting pressures of a laboratory plasma are still 20–30 orders of magnitude higher than the maximum astrophysical values, this gap is being rapidly bridged, and the physical processes in a laboratory and in space often demonstrate an astonishing variety and at the same time striking similarities, evidencing at least the uniformity of physical principles of the behavior of matter in an extremely broad range of densities (approximately 42 orders of magnitude) and temperatures (up to 10^{13} K).

The revolutionary discoveries in astronomy of recent decades (neutron stars, pulsars, black holes, wormholes, γ-ray bursts, exoplanets, etc) [4–9] demonstrate new examples of extreme states, the investigation of which is important in order to solve the most fundamental problems of modern astrophysics.

To date, the physics of extreme states of matter has turned into an extensive and rapidly developing branch of modern science that makes use of the most sophisticated means of generation, diagnostic techniques, and numerical simulations using high-power supercomputers. It is no accident that half of the 30 problems of 'the physics minimum at the beginning of the 21st century' proposed by Academician V L Ginzburg [5] are to a greater or lesser degree dedicated to the physics of extreme states of matter.

The physics of extreme states of matter is closely related to several branches of science, including plasma physics and condensed-matter physics, relativistic physics, the physics of lasers and charged-particle beams, nuclear, atomic, and molecular physics, radiative, gas and magnetic hydrodynamics, astrophysics, etc. In this case, a distinguishing feature of the physics of extreme states of matter is an extreme complexity and strong nonlinearity of the physical processes occurring in it, the significance of collective interparticle interaction, and relativity, which makes the investigation of the phenomena in this field a fascinating and absorbing task, which attracts a constantly increasing number of researchers.

With all these reasons taken into account, the National Research Council of the US National Academies of Sciences formulated a large-scale national program of research [4] in the area of the physics of extreme states of matter and gave it high priority. Similar programs are being vigorously pursued in many developed countries capable of making the unique experimental devices and having qualified personnel in sufficient number.

The physics of extreme states of matter is a rapidly developing realm of modern science and technology, so that the material presented here will be permanently supplemented and improved by new measurements, observations, and models.

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Vladimir E Fortov

Chapter 1

Lecture 1: Matter under extreme conditions: classification of states

The scale of extreme states realized in Nature defies the most vivid imagination. At the bottom of the Mariana Trench (at a depth of 11 km), the water pressure, p, amounts to 1.2 kbar; in the center of the Earth, $p \approx 3.4$ Mbar, $T \approx 0.5$ eV, and the density, $\rho \approx 10$–20 g cm^{-3}; in the center of Jupiter, $p \approx 40$–70 Mbar, $\rho \approx 30$ g cm^{-3}, and $T \approx 2 \times 10^4$ K; in the center of the Sun, $p \approx 240$ Gbar, $T \approx 1.6 \times 10^3$ eV, and $\rho \approx 150$ g cm^{-3}; and in cooling-down stars (white dwarfs), $p \approx 10^{10}$–10^{16} Mbar, $\rho \approx 10^6$–10^9 g cm^{-3}, and $T \approx 10^3$ eV. In targets for controlled fusion with inertial confinement of plasma, $p \approx 200$ Gbar, $\rho \approx 150$–200 g cm^{-3}, $T \approx 10^8$ eV. Neutron stars, which are elements of pulsars, black holes, γ-ray bursts and magnetars, apparently have record-high parameters: $p \approx 10^{19}$ Mbar, $\rho \approx 10^{11}$ g cm^{-3}, and $T \approx 10^4$ eV for the mantle and $p \approx 10^{23}$ Mbar, $\rho \approx 10^{14}$ g cm^{-3}, $T \approx 10^4$ eV for the core at a giant induction of the magnetic field of 10^{11}–10^{16} Gs.

Collisions of heavy nuclei accelerated to relativistic velocities in modern accelerators lead to the emergence of supercompressed quark–gluon plasma states with ultra-extreme parameters $p \approx 10^{30}$ bar, $\rho \approx 10^{15}$–10^{16} g cm^{-3}, and $T \approx 10^{14}$ K, which exceed those realized in extreme astrophysical objects.

The emergence of extreme states in nature is due to the forces of gravity, which are inherently long-ranged and unscreened, unlike Coulomb forces (in electromagnetic plasma). These forces compress and heat the substance either directly or by stimulating exothermic nuclear reactions in massive astrophysical objects and in the early stages of the evolution of the Universe.

What is amazing is not only the breadth of the range of parameters realized in Nature, but also the huge difference in the characteristic times and dimensions. The dimensions of the visible part of the Universe amount to 1.3×10^{19} cm. The impression made by this figure becomes even stronger when it is compared with the time of 10^{-24} s taken by light to traverse a distance equal to about the

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proton size (10^{-13} cm). The theory of relativity and other modern physical models do operate throughout this tremendous range.

As noted above, the lower boundary of the region of extreme states is considered to mean the states of a matter with an energy comparable to a binding energy of condensed matter, 10^4–10^5 J cm^{-2}, which corresponds to the binding energy of valence electrons (of several electron volts) and pressures from about 100 kbar to 1 Mbar. These pressures far exceed the ultimate mechanical strength of materials and make it necessary to take into account their compressibility during hydrodynamic motion under pulsed energy release.

In the domain of low pressures and temperatures, matter exhibits an exceptional diversity of properties and structures that we encounter daily under normal conditions [1].

Physical, chemical, structural, and biological properties of a substance under normal conditions are sharp nonmonotonic functions of the composition. The classification of these 'low-energy' states is complicated and cumbersome. It is determined by the position, details, and occupation features of electronic levels of atoms, ions, and molecules, and finally specifies the amazing richness of the forms and manifestations of organic and inorganic nature on Earth.

Laser and evaporative cooling methods (figure 1.1) enable ultralow (10^{-9} K) ion temperatures to be reached and interesting quantum phenomena such as Bose–Einstein condensation, Rydberg matter, Coulomb condensation, etc to be studied.

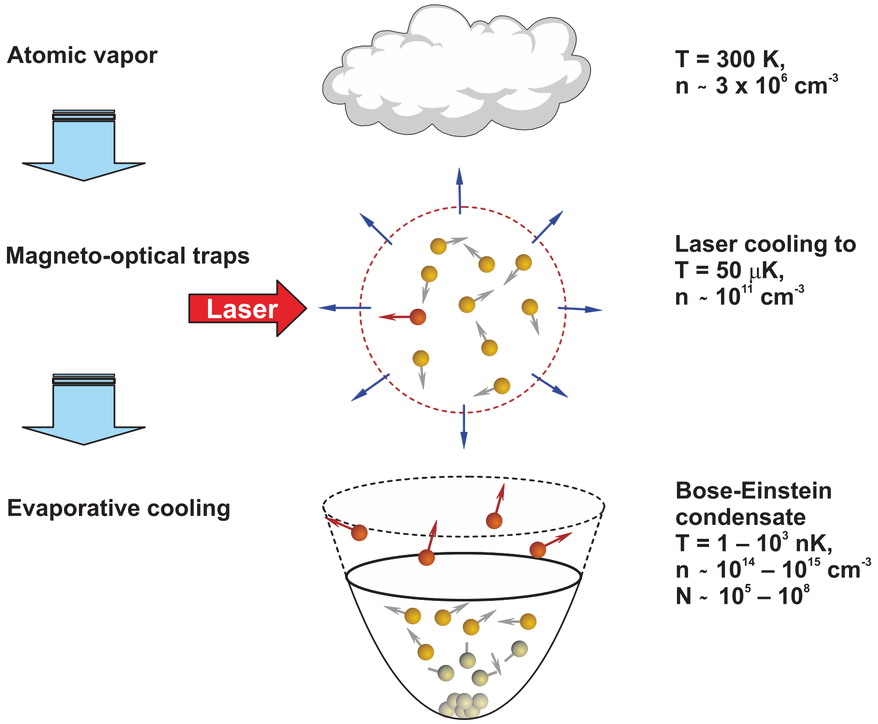

Figure 1.1. Methods for obtaining extremely low temperatures. Reprinted from [5] by permission from Springer. Copyright 2011, Springer.

With increasing energy density (p and T), substances acquire an increasingly universal structure [1–3]. The distinctions between the neighboring elements of the periodic system smooth out and the properties of a substance become progressively smoother functions of its composition. Owing to an increase in energy density, an obvious 'universalization' or simplification of the substance properties occurs. An increase in pressure and temperature ruptures molecular complexes to form atomic states, which then lose outer-shell electrons responsible for the chemical individuality of the substance, due to thermal and/or pressure-induced ionization. Electron shells of atoms and ions restructure to acquire an increasingly regular level occupation and a crystal lattice after a number of polymorphic transformations (this ordinarily takes place for $p < 0.5$ Mbar) transforms to a close-packed body-centered cubic structure common to all substances.

These processes of substance 'simplification' take place at energy densities comparable to the characteristic energies of the aforementioned 'universalization' processes. When the characteristic energy density becomes of the order of the valence shell energies, $e^2/a_0^4 \approx 3 \times 10^{14}$ erg cm^{-3} ($a_0 = \hbar/(me^2) = 5.2 \times 10^{-9}$ cm is the Bohr radius), the order of magnitude of the lower boundary of substance 'universalization', $T \approx 10$ eV, $p \approx 300$ Mbar, is reached. The exact quantitative determination of these boundaries is an important task of the experimental physics of extreme states of matter, especially due to the fact that theory [2, 3] predicts a highly varied behavior of substances in the ultramegabar pressure range (shell effects [2, 3], electron and plasma phase transitions [4–8] and other qualitative phenomena).

The upper boundary of the domain of extreme states is defined by the contemporary level of knowledge about the high-energy-density physics and observational astrophysical data, and is expected to be limited only by our imagination.

The ultra-extreme matter parameters available for modern physical concepts are defined by the so-called Planck quantities, which are combinations of the fundamental constants such as the Planck's constant $\hbar$, the velocity of light c, the gravitational constant G, and the Boltzmann constant k:

the length

$$l_p = \sqrt{\frac{\hbar G}{c^3}} = \frac{\hbar}{m_p c} \approx 1.62 \times 10^{-33}\ \text{cm};$$

the mass (the so-called 'maximon' mass)

$$m_p = \sqrt{\frac{\hbar c}{G}} = 2.18 \times 10^{-5}\ \text{g};$$

the time

$$t_p = \frac{l_p}{c} = \frac{\hbar}{m_p c^2} = \sqrt{\frac{\hbar G}{c^5}} = 5.39 \times 10^{-44}\ \text{s};$$

the temperature

$$T_p = \frac{m_p c^2}{k} = \sqrt{\frac{\hbar c^5}{Gk^2}} = 1.42 \times 10^{32}\ \mathrm{K};$$

the energy

$$W_p = m_p c^2 = \frac{\hbar}{t_p} = \sqrt{\frac{\hbar c^5}{G}} = 1.96 \times 10^{9}\ \mathrm{J};$$

the density

$$\rho_p = \frac{m_p}{l_p^3} = \frac{\hbar t_p}{l_p^5} = \frac{c^5}{\hbar G^2} = 5.16 \times 10^{93}\ \mathrm{g\ cm^{-3}};$$

the force

$$F_p = \frac{W_p}{l_p} = \frac{\hbar}{l_p t_p} = \frac{c^4}{G} = 1.21 \times 10^{44}\ \mathrm{N};$$

the pressure

$$p_p = \frac{F_p}{l_p^2} = \frac{\hbar}{l_p^3 t_p} = \frac{c^7}{\hbar G^2} = 4.63 \times 10^{113}\ \mathrm{Pa};$$

the charge

$$q_p = \sqrt{\hbar c 4\pi\varepsilon_0} = 1.78 \times 10^{-18}\ \mathrm{C};$$

the power

$$P_p = \frac{W_p}{t_p} = \frac{\hbar}{t_p^2} = \frac{c^5}{G} = 3.63 \times 10^{52}\ \mathrm{W};$$

the circular frequency

$$\omega_p = \sqrt{\frac{c^5}{\hbar G}} = 1.85 \times 10^{43}\ \mathrm{s^{-1}};$$

the electric current

$$I_p = \frac{q_p}{t_p} = \sqrt{\frac{c^6 4\pi\varepsilon_0}{G}} = 3.48 \times 10^{25}\ \mathrm{A};$$

the voltage

$$U_p = \frac{W_p}{q_p} = \frac{\hbar}{t_p} = \sqrt{\frac{c^4}{G 4\pi\varepsilon_0}} = 1.05 \times 10^{27}\ \mathrm{V};$$

the impedance

$$Z_p = \frac{U_p}{I_p} = \frac{\hbar}{q_p^2} = \frac{1}{4\pi\varepsilon_0 c} = \frac{Z_0}{4\pi} = 29.98\ \Omega;$$

the electric field strength

$$E_p = \frac{U_p}{l_p} = \frac{1}{G}\sqrt{\frac{c^7}{4\pi\varepsilon_0\hbar}} = 6.4 \times 10^{59}\ \mathrm{W\ cm^{-1}};$$

the magnetic field strength

$$\begin{aligned} H_p &= \frac{1}{G}\sqrt{\frac{c^9 4\pi\varepsilon_0}{\hbar}} = 2.19 \times 10^{60}\ \mathrm{A\ m^{-1}} \\ &= 1.74 \times 10^{62}\ \mathrm{Oe} \end{aligned}$$

Such super-extreme parameters of matter, under which the known laws of physics seem to no longer work, might have been realized at the very beginning of the Big Bang or at the singularity in the collapse of black holes. In the first case, according to the model of the expanding Universe (A Friedman, G Lemaître [9, 10]), the Universe originated from the Planckian area of the order of 10^{-33} cm with ultra-high Planckian physical parameters and expanded to modern sizes of the order of 10^{28} cm over approximately 13.7–14.5 billion years. Here, owing to the gravitational compression of stars to the stage of black holes, singularities—ultrahigh parameters of the Planckian scale arise again. In these domains of singularities, physical models are now proposed according to which our space has more than three dimensions and that ordinary matter is in a three-dimensional manifold—the '3-brane world' [10]—embedded in this many-dimensional space. The capabilities of modern experiments in high-energy-density physics are far from these 'Planck' values and allow the properties of elementary particles to be elucidated up to energies of the order of 0.1–10 TeV and down to distances $\approx 10^{-16}$ cm.

Considering (following paper [1]) the energy range $mc^2 \approx 1$ GeV, which is amenable to a more substantial physical analysis and is nonrelativistic for nucleons, we obtain a boundary temperature of 10^9 eV, an energy density of 10^{37} erg cm^{-2}, and a pressure of about 10^{25} Mbar, although it is highly likely that even more extreme states of matter are realized in the cores of massive pulsars and could be found at early stages of the evolution of the Universe.

While our experimental capabilities are progressing rapidly, of course they are only partly able to encroach upon the region of ultra-extreme astrophysical states. Material strengths radically limit the use of static techniques for investigating high-energy densities, because the overwhelming majority of constructional materials are unable to withstand the pressures in question. The exception is the diamond—a record-holder in hardness ($\sigma_n \approx 500$ kbar); its use in diamond anvils allows a pressure of 3–5 Mbar to be reached in static experiments.

The palm of supremacy now belongs to dynamic techniques [7, 11, 12], which rely on the pulsed cumulation of high-energy densities in substances. The lifetime of such high-energy states is determined by the time of inertial plasma expansion, typically in the range 10^{-10}–10^{-6} s, which calls for the application of sophisticated fast diagnostic techniques. Physical conditions corresponding to the lower bound of states in question are listed in table 1.1 [9, 12, 13].

The phase diagram of the matter, corresponding to high-energy densities, is shown in figure 1.2 [9, 11, 12], which indicates the conditions existing in astrophysical objects as well as in technical and laboratory experimental devices. One can see that, being the most widespread state of matter in nature (95% of the mass of the Universe without dark matter), plasma occupies virtually the entire domain of the phase diagram. In this case, of special difficulty in the physical description of such a medium is the region of the nonideal plasma, where the Coulomb interparticle interaction energy $e^2n^{1/3}$ is comparable to or exceeds the kinetic energy, E_k, of particle motion. In this domain, at $\Gamma = e^2n^{1/3}/E_k > 1$, the effects of plasma nonideality cannot be described within the perturbation theory [1, 12], while the application of computer parameter-free Monte Carlo and molecular dynamics methods [4] is fraught with great difficulties of selection of adequate pseudopotentials and correct inclusion of quantum effects.

Table 1.1. Physical conditions corresponding to high energy densities of 10^4–10^5 J cm^{-3} [9].

Physical conditions	Values of physical parameters
Energy density W	$W \approx 10^4$–10^5 J cm^{-3}
Pressure p	$p \approx 0.1$–1.0 Mbar
Condensed high explosives:	$W \approx 10^4$ J cm^{-3}
pressure	≈ 400 kbar,
temperature	≈ 4000 K,
density	≈ 2.7 g cm^{-3},
detonation velocity	$\approx 9 \times 10^5$ cm s^{-1}
Impact of an aluminum plate on aluminum,	
velocity	$(5$–$13.2) \times 10^5$ cm s^{-1}
Impact of a molybdenum plate on molybdenum,	
velocity	$(3$–$7.5) \times 10^5$ cm s^{-1}
Electromagnetic radiation:	2.6×10^{15}–3×10^{15} W cm^{-2}
laser, intensity q ($W \sim q$)	2×10^2–4×10^2 eV
blackbody temperature T ($p \sim T^4$)	
Electric field strength E ($W \sim E^2$)	0.5×10^9–1.5×10^9 W cm^{-1}
Magnetic field induction B ($W \sim B^2$)	$1{,}6 \times 10^2$–5×10^2 T
Plasma density at temperature $T = 1$ keV	
($p = nkT$)	6×10^{19}–6×10^{20} cm^{-3}
Laser radiation intensity q:	0.86×10^{12}–4×10^{12} W cm^{-2}
for $\lambda = 1$ μm, $W \sim q^{2/3}$	66–75 eV
blackbody temperature T ($p \sim T^{3,5}$)	

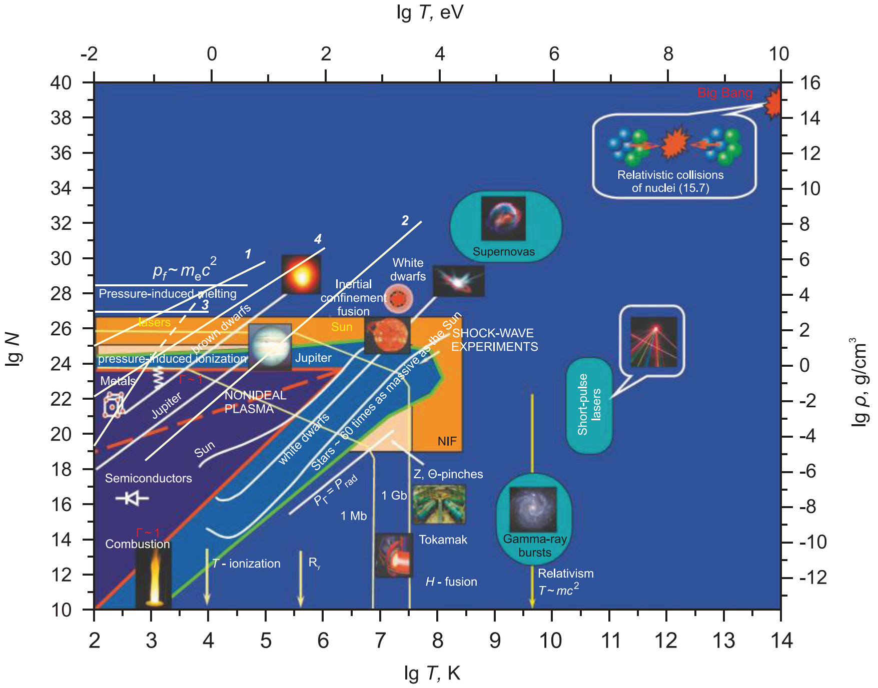

Figure 1.2. Phase diagram of states of matter [9, 11]. Curves *1–4* denote the states of nuclear matter component (neon) [1] on the lg ρ scale: *1*—boundary of the nucleus degeneracy region; *2*—boundary of the ideality region; *3*—melting curve; *4*—boundary of the region in which the lattice may be treated as classical. Reprinted from [5] by permission from Springer. Copyright 2011, Springer.

The effects of electron relativity in the equation of state and transport properties of the plasma, when $m_e c^2 \approx kT$, correspond to $T \approx 0.5$ MeV $\approx 6 \times 10^6$ K. Above this temperature, the matter becomes unstable with respect to spontaneous electron–positron pair production.

Quantum effects are determined by the degeneracy parameter $n\lambda^3$ ($\sqrt{\hbar^2/2mkT}$ is the thermal de Broglie wavelength). For a degenerate plasma, $n\lambda^3 \gg 1$, and the kinetic energy scale is the Fermi energy $E_\mathrm{F} \approx \hbar^2 n^{2/3}/2m$, which increases with increasing plasma density, making it more ideal as it compresses, $n \to \infty$; $\Gamma = me^2/(\hbar^2 n^{1/3}) \to 0$. The relativity condition corresponding to $m_e c^2 \approx E_\mathrm{F} \approx 0.5$ MeV yields a density $\rho \approx 10^6$ g cm^{-3}.

Similar asymptotics also takes place in another limiting case $T \to 0$ of a classical ($n\lambda^3 \ll 1$) plasma, where $E_k \approx kT$, and the plasma become more ideal [$\Gamma \approx e^2 n^{1/3}/(kT)$] upon heating. One can see that the periphery of the phase diagram is occupied by ideal ($\Gamma \ll 1$), Boltzmann ($n\lambda^3 \ll 1$), or degenerate ($n\lambda^3 \gg 1$) plasmas, which are described by the presently available adequate physical models [1, 4, 6, 11, 12].

The electron plasma in metals and semiconductors corresponds to the degenerate case with an interaction energy $E_\mathrm{int} \sim e^2/r_0, |r_0 \sim \hbar|/k_\mathrm{F}$, $E_k \sim k_\mathrm{F}^2/m$; $\Gamma \sim e^2/\hbar v_\mathrm{F} \approx 1$–5, where $v_\mathrm{F} \sim 10^{-2}$–$10^{-3}$ s (s is the speed of light), and the subscript F refers to the parameters at the Fermi limit.

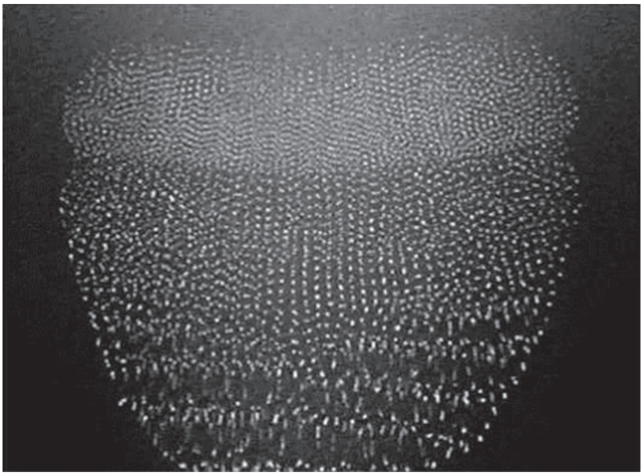

Figure 1.3. Plasma dust crystal and plasma liquid. Reprinted from [5] by permission from Springer. Copyright 2011, Springer.

For a quark–gluon plasma $E_{\text{int}} \sim g^2/r_0$, $r_0 \sim 1/T$, $E_k \sim T$; $\Gamma \approx 300$–400. For an ultracold plasma in traps, $\Gamma \sim (n/10^9)^{1/3}/T_k$. Most challenging for the theory is the vast domain of nonideal plasmas, $\Gamma \geqslant 1$, occupied by numerous technical applications (semiconductor and metal plasma, pulsed energetics, explosions, arcs, electric discharges, etc), where theory predicts qualitatively new physical effects (metallization, 'cool' ionization, dielectrization, plasma phase transitions, etc [11, 12]); the study of these effects requires substantial experimental and theoretical efforts.

Of special interest are plasma phase transitions in strongly nonideal Coulomb systems: crystallization of dust plasmas (figure 1.3) and ions in electrostatic traps and cyclotrons, in electrolytes and colloidal systems, and in two-dimensional electron systems on the surface of liquid helium, as well as exciton condensation in semiconductors, etc. Special mention should be made of the recently discovered phase transition in thermal deuterium plasma quasi-adiabatically compressed to megabar pressures by a series of reverberating shock waves.

The search for qualitatively new effects in the nonideal domain of parameters is a powerful and permanent incentive to investigate substances at high energy densities.

Another characteristic property of a high-energy-density plasma is the collective nature of its behavior and the strong nonlinearity of its response to external energy actions such as shock and electromagnetic waves, solitons, laser radiation, and fast particle fluxes. Thus, the propagation of electromagnetic waves in plasma excites several parametric instabilities (Raman, Thomson, and Brillouin scattering) and is accompanied by self-focusing and filamentation of radiation, by the development of inherently relativistic instabilities, by the generation of fast particles and jets, and—at higher intensities—by the 'boiling' of the vacuum with the electron–positron pair production.

Of special interest under extreme energy actions are transient hydrodynamic phenomena such as instabilities of shock waves and laminar flows, transition to the turbulent mode, turbulent mixing, and dynamics of jets and solitons.

Figure 1.4 borrowed from [9] shows the domains of the dimensionless parameters [Reynolds number, Re $\sim$ Ul/ν, and Mach number, $M = U/c$ (c is the velocity of sound, l is the characteristic size, and ν is the kinematic viscosity)], in which different hydrodynamic phenomena related to the physics of extreme states of matter are realized. The flow modes correspond to astrophysical applications, where Re $> 10^4$ and $M > 0.5$. In the explosion of a type Ia supernova, the Mach number ranges from 0.01 in the region of thermonuclear combustion to 100 in the shock wave arising due to the surface explosion.

All these fascinating and inherently nonlinear phenomena manifest themselves in both astrophysical and laboratory plasmas and, despite the enormous difference in spatial scale, have much in common and make up the subject of 'laboratory astrophysics'.

Laboratory astrophysics allows the states of matter and processes with high energy densities typical of astrophysical objects to be reproduced in microscopic volumes. These are the processes of instability and hydrodynamic mixing; ordinary and magneto-hydrodynamic turbulence; the dynamics of high-power shock, radiating, and soliton waves; expansion waves; magnetically compressed and fast relativistic jets; strongly radiating fluxes, and a number of other interesting and scarcely studied phenomena.

Of considerable interest is the information about the equation of state, composition, optical and transport properties, emission and absorption spectra, cross

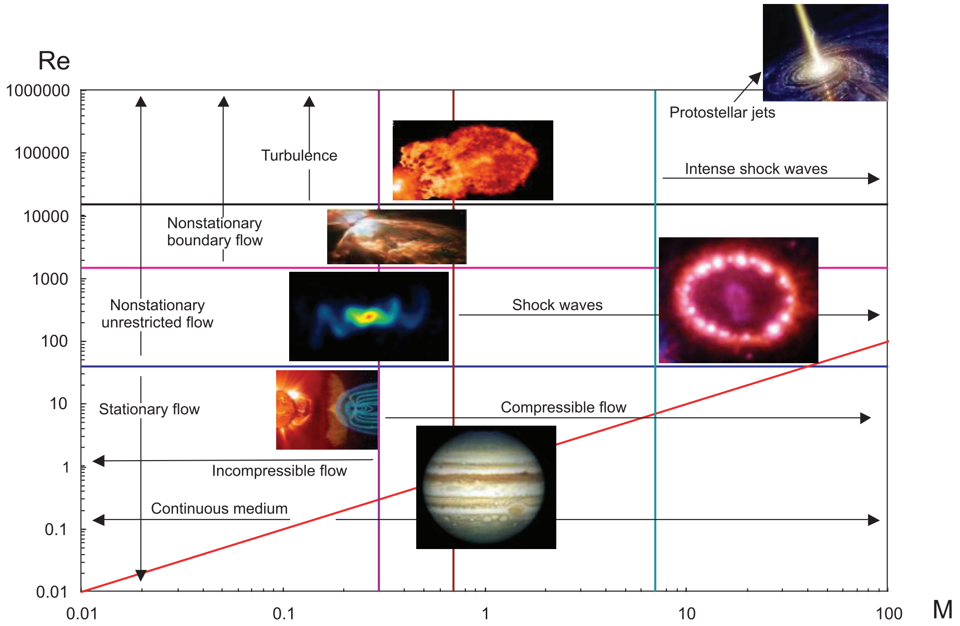

Figure 1.4. Hydrodynamic modes related to the physics of extreme states of matter. Reprinted from [5] by permission from Springer. Copyright 2011, Springer.

sections of elementary processes, radiation thermal conductivity coefficients, and properties of relativistic plasma. This makes it possible to study and model the physical conditions, stationary and pulsed processes in astrophysical objects and phenomena such as giant planets and exoplanets, stellar evolution and supernova explosions, gamma-ray burst structure, substance accretion dynamics in black holes, processes in binary and neutron stars as well as in the radiative motion of molecular interplanetary clouds, collisionless shock wave dynamics, charged-particle acceleration to ultrahigh energies, etc.

Let us now proceed to a more detailed description of the presently developed laboratory (lectures 2–4) and quasi-laboratory (section 2.2.4) methods for generating extreme states of matter.

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