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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.

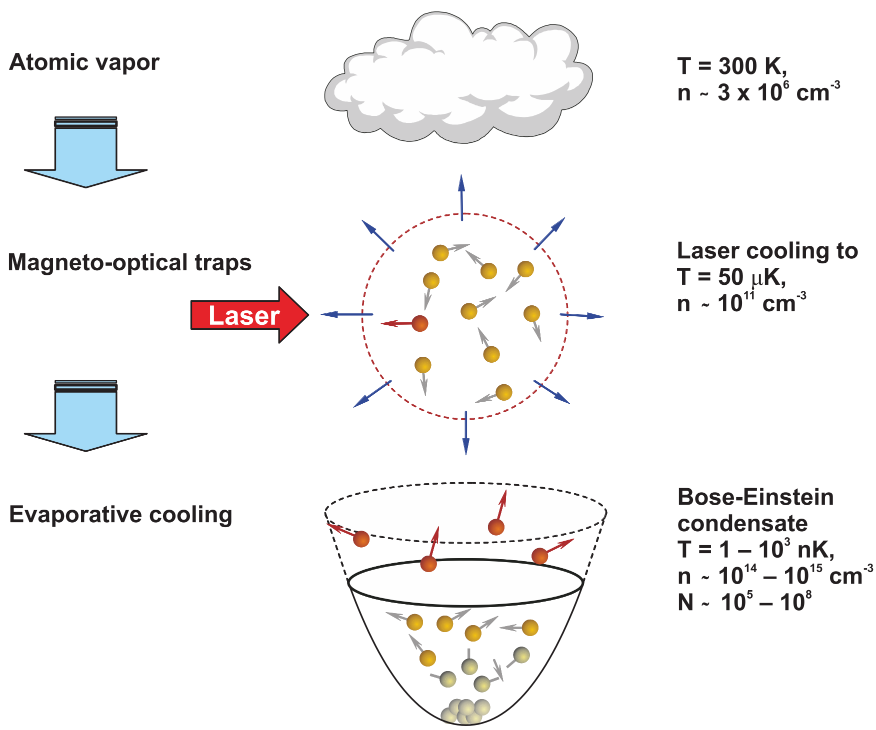

Figure 1.1. Methods for obtaining extremely low temperatures. Reprinted from [5] by permission from Springer. Copyright 2011, Springer.

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

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

the energy

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

the density

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

the force

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

the pressure

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

the charge

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

the power

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

the circular frequency

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

the electric current

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

the voltage

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

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

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

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 ($p \sim T^{3,5}$)	

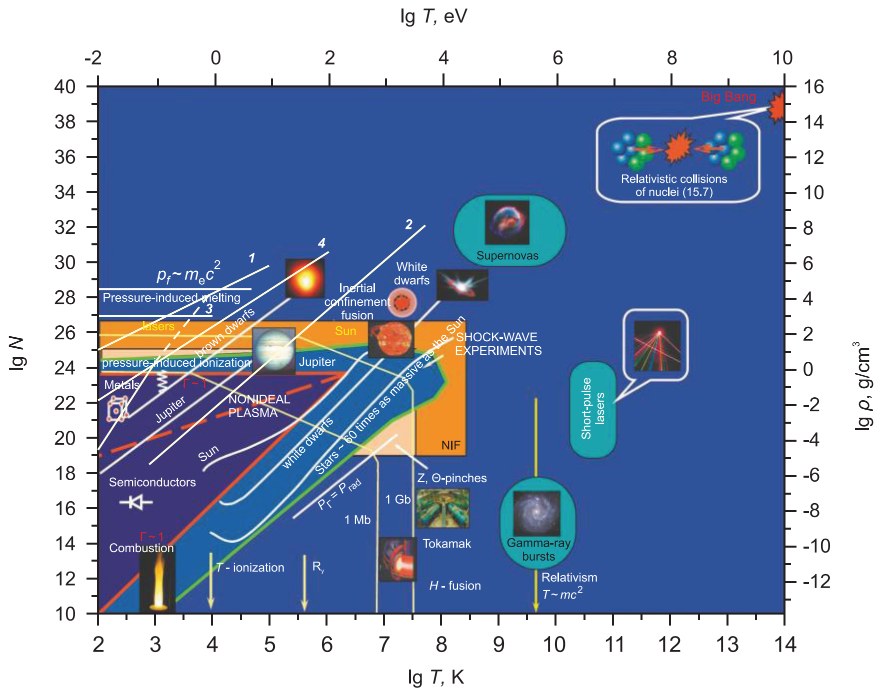

Figure 1.2. Phase diagram of states of matter [9, 11]. Curves *1–4* denote the states of nuclear matter component (neon) [1] on the lg ρ scale: *1*—boundary of the nucleus degeneracy region; *2*—boundary of the ideality region; *3*—melting curve; *4*—boundary of the region in which the lattice may be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

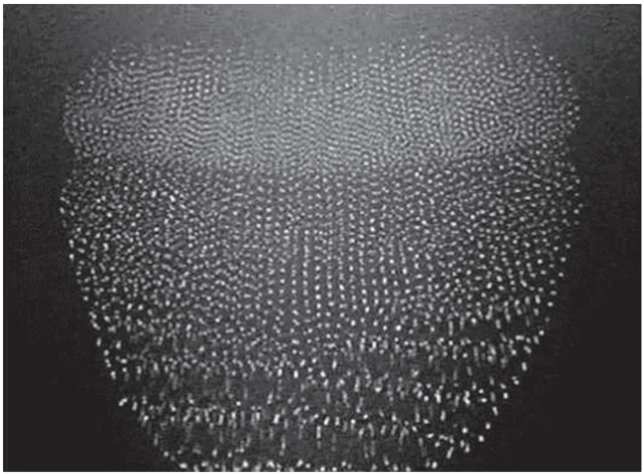

Figure 1.3. Plasma dust crystal and plasma liquid. Reprinted from [5] by permission from Springer. Copyright 2011, Springer.

For a quark–gluon plasma $E_{\mathrm{int}} \sim g^2/r_0$, $r_0 \sim 1/T$, $E_k \sim T$; $\Gamma \approx 300$–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, $\mathrm{Re} \sim Ul/\nu$, 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 $\mathrm{Re} > 10^4$ 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

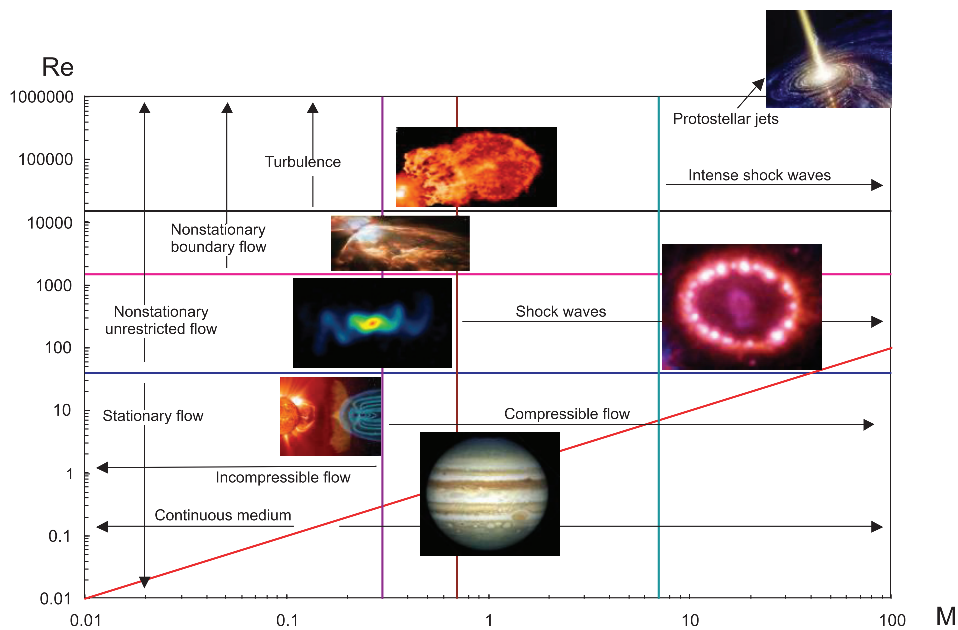

Figure 1.4. Hydrodynamic modes related to the physics of extreme states of matter. Reprinted from [5] by permission from Springer. Copyright 2011, Springer.

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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