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Vladimir E. Fortov

Extreme States of Matter

High Energy Density Physics

Second Edition

 Springer

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...but thou hast ordered all things in measure and number and weight
The Wisdom of Solomon 11:20



Preface to the First Edition

This book is concerned with the physical properties of matter and the diverse processes that occur in nature at ultrahigh energy densities, which correspond to extreme pressures and temperatures. It is based on the lecture course I hold at the Moscow Institute of Physics and Technology, as well as reviews and invited papers written for scientific conferences and symposia.

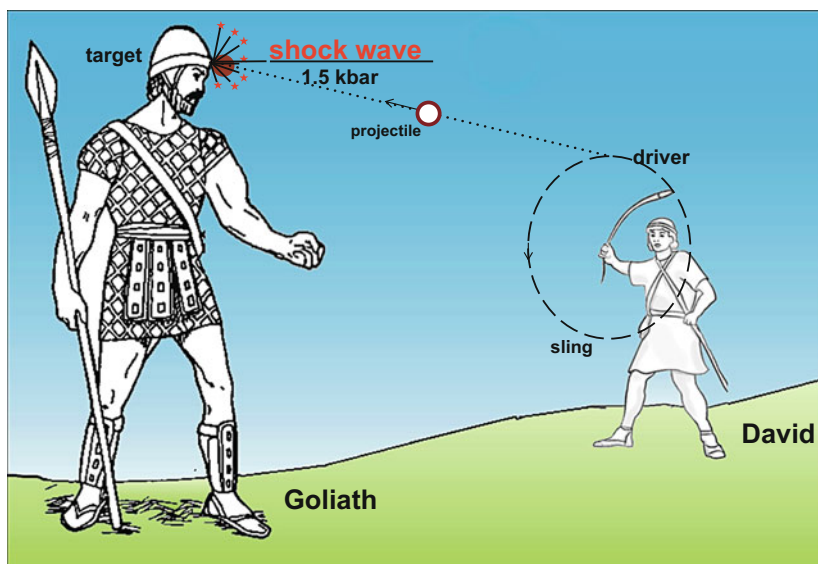


Fig. 1 The battle between David and Goliath [1]

Interest in the physics of extreme states has always been strong, owing to the natural desire of humans to achieve more and to operate with record parameters, as well as owing to the wealth of applications to astrophysics, energy production, and defense. It was indeed military application that fostered the first successful

experiment involving extreme states, which was conducted more than 3000 years ago – during the battle between David and Goliath (Fig. 1). According to the Old Testament [1], the high-velocity impact of a stone, which was shot from David’s sling, on Goliath’s head killed him. It gave rise to a shock wave in Goliath’s head with an amplitude pressure of ≈ 1.5 kbar, which 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 serves as the basis for all subsequent experiments in the area of dynamic high-energy-density physics.

The application of more powerful and highly sophisticated energy cumulation systems – chemical and nuclear explosives, 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 or four orders of magnitude, since the time of David, 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, mainstream high-energy-density physics was closely related to the arrival of the atomic and space era in our civilization. In nuclear charges, the high energy densities generated by intense shock waves serve to initiate chain nuclear reactions in compressed nuclear fuel. In thermonuclear charges and microtargets for controlled fusion, high-energy states are the main instrument for compressing and heating the thermonuclear fuel and initiating thermonuclear reactions in it.

Recently, interest in the science of extreme states has been rekindled as a result of the emergence of new experimental techniques for the generation of high-energy states in terrestrial conditions as well as intriguing new observational astrophysical data obtained by modern-generation ground-based and space telescopes operating at different wavelengths and by unmanned space stations.

Although the limiting pressures in laboratory plasmas so far differ from the maximum astrophysical values by 20–30 orders of magnitude, this gap is rapidly shrinking. The physical processes in a laboratory and in space quite frequently exhibit an amazing diversity and, at the same time, striking similarities, thereby testifying, at the least, to the uniformity of the physical principles of the behavior of matter over an extremely broad range of pressures (42 orders of magnitude) and temperatures (up to 10^{13} K).

However, as pointed out by Voltaire, “. . . in nature this phenomenon is perfectly natural and commonplace. The domains of some rulers in Germany and Italy, which can be circled in about a half hour, when compared with the empires of Turkey, Moscow, or China, give only a faint idea of the remarkable contrasts that are hidden in all of nature” (Voltaire, *Le Micromégas*, Paris 1752) [3].

It is significant that the range of technical problems related to the physics of extreme states is progressively broadening along with the range of the fundamental ones. These states of matter underlie the operation of pulsed thermonuclear reactors with inertial confinement of the hot plasma, high-power explosive-driven magnetic generators, power installations and rocket propulsors with gas-phase nuclear

reactors, plasmachemical and microwave reactors, plasmatrons, and high-power sources of optical radiation and X-rays. In the energy installations of the future, strongly compressed and heated plasmas will be employed as the working medium, like water vapor in modern thermal power stations.

Extreme states emerge when a substance is subjected to intense shock, detonation, or electroexplosion waves, concentrated laser radiation, electron and ion beams, in powerful chemical and nuclear explosions, in the pulsed vaporization of liners in pinches and magnetic cumulation generators, in the hypersonic motion of bodies in dense planetary atmospheres, in high-velocity impacts, and in many other situations characterized by ultrahigh pressures and temperatures. The physics of near-electrode, contact, and electroexplosion processes in vacuum breakdown is intimately related to the high-energy plasma that defines the operation of high-power pulsed accelerators, microwave radiation generators, and plasma switches.

High energy densities determine the behavior of matter in a vast domain of the phase diagram that occupies the range from a solid and a fluid to a neutral gas, covers the phase boundaries of melting and boiling, and also the metal-dielectric transition domain. The metal-dielectric transition problem has been much explored in experiments involving the multiple (quasi-isentropic) shock-wave compression of dielectrics, their metallization, and the recently discovered plasma phase transitions in the megabar pressure range, as well as dielectrization of strongly compressed simple metals.

Scientific interest in high-energy plasmas has also been rekindled along with pragmatic interest, because the great bulk of matter in the universe is in precisely this exotic state. For about 95% of the mass (neglecting dark matter), according to modern estimates, is the plasma of ordinary and neutron stars, pulsars, black holes, and giant planets of the solar system, as well as the recently discovered hundreds of planets beyond the solar system.

Prior to becoming a star, the matter of the universe experiences the most diverse physical transformations: from quarks and elementary particles to complex molecules and again to atoms and particles; from relativistic energies to absolute zero and again to the state of high-energy-density plasma; from enormous densities to ultrahigh vacuum and again to the densities of atomic nuclei and quarks. And so our fundamental knowledge of the structure, evolution, and history of the universe is directly dependent on our understanding of the behavior of matter in all of its transformations up to ultrahigh energy densities, which forms not only specific physical models, but also the world-outlook of modern natural science because, by steadily increasing the high energy densities attainable by investigations on Earth and in space, we delve into the past, using a “time machine”, looking for the singular conditions of the Big Bang – the instant of the universe’s inception ≈ 1.5 billion years ago.

Today we can clearly see that the study of matter in extreme states is one of the “hottest” and most rapidly developing basic scientific disciplines, situated at the interface between plasma physics, nonlinear optics, condensed-matter physics, nuclear, atomic and molecular physics, relativistic and magnetic hydrodynamics, involving a wealth of compression- and heating-stimulated physical effects and a

constantly widening variety of objects and states in which the plasma nonideality is critically important. Despite the extraordinary diversity of the objects and experimental and astrophysical situations, they all share the common property that high energy densities play a decisive role in their physical behavior.

These circumstances are a permanent steadfast incentive for intensive theoretical and experimental investigations, which have recently resulted in a great body of new and, most important, reliable information about the thermodynamic, structural, gasdynamic, optical, electrophysical, and transport properties of matter under extreme conditions. These specific data are contained in a massive flow of original publications, some of which are not easily accessible to Russian scientists, especially young ones.

This book attempts to systematize, generalize, and set forth from a unified viewpoint the theoretical and experimental material related to this new realm of science, and to show, following Titus Lucretius Carus, “Thus from the mixture of the elements there emerge infinite multitudes of creatures, which are Strange and highly diversified in appearance” (Titus Lucretius Carus) [2]. In it I endeavor to discuss the maximally broad range of problems related to high-energy-density physics. That is why many interesting astrophysical, laser, and nuclear-physical problems as well as technical applications are briefly outlined and the reader is referred to original papers and monographs. In doing this, I did not aim to include everything known about extreme states to date. Emphasis was placed on the issues which appeared to be most interesting to me and which I happened to work on directly. Realizing that the material touched upon in this book will steadily broaden, become defined more precisely, and inevitably become obsolete owing to the extremely rapid development of high-energy-density physics, I would be thankful to readers who send me critical remarks and suggestions.

It is hoped that this book will be beneficial to a wide readership of scientists, postgraduates, and students in the natural sciences by offering them access to original papers and being a helpful guide through the exciting problems of modern Extreme State Physics.

In the preparation of the manuscript I benefited from the assistance, stimulating discussions, and advice of Yu.Yu. Balega, N.E. Andreev, A.Ya. Faenov, S.I. Blinnikov, M.B. Kozintsova, A.N. Starostin, V.S. Imshennik, I.L. Iosilevskii, N.S. Kardashev, V.G. Sultanov, A.N. Sissiakian, B.Yu. Sharkov, and V.A. Yakovleva, to whom I express my sincere gratitude.

Abramtsevo, Russia
May 2009

Vladimir Fortov

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2. Lucretius: *The Nature of Things*. Penguin, London (2007)
3. Voltaire: *Micromégas and Other Short Fiction*. Penguin, London (2002)

Preface to the Second Edition

Dear reader!

The monograph before you is concerned with the diverse physical phenomena occurring in matter in which there is an extremely high energy density, generating in turn ultrahigh pressures and temperatures.

This second edition results from a thorough revision of the first edition [1], which was published in English in 2011, together with the addition of material from another monograph [2], published in Russian in 2012. All the material included herein has been substantially updated and the subject matter of the book considerably expanded by including recent experimental results as well as new theoretical approaches and models. This is also reflected in the new subtitle, which corresponds to the contents more adequately.

This book will hopefully arouse readers' curiosity and be helpful to scientists, post-graduates, and students interested in this fascinating realm of modern physics, and especially to those who have decided to make this field the subject of their future research activities.

Abramtsevo, Moscow
April 2015

Vladimir E. Fortov

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Contents

1	Introduction	1
	References.....	4
2	Matter Under Extreme Conditions: Classification of States	7
	References.....	20
3	High Energy Densities in Laboratories	23
3.1	Main Lines of Research	23
3.2	Generators of High Energy Densities	27
3.3	Static Methods Using Diamond Anvils	40
3.4	Dynamic Methods	43
3.5	Light-Gas Guns and Chemical Explosions.....	50
3.6	Underground Nuclear Explosions and Quasi-Classical Model of a Substance	56
3.7	High Magnetic Fields	65
3.8	Devices of High-Current Impulse Energetics	74
	References.....	80
4	Extreme States in a Nuclear Explosion	91
4.1	Exothermal Nuclear Reactions	92
4.1.1	Thermonuclear Fusion.....	94
4.1.2	Fission Reaction	107
4.2	High Energy Densities for Explosive Nuclear Reactions.....	119
4.2.1	Explosive Fission Reactions	120
4.2.2	Pulsed Thermonuclear Fusion	125
4.2.3	Hydrodynamic Thermonuclear Fusion	127
4.2.4	Explosive Thermonuclear Fusion	131
4.3	Nuclear Explosions for Studying Extreme States of Matter.....	144
	References.....	160
5	High-Power Lasers in High-Energy-Density Physics	167
5.1	Growth of Laser Radiation Intensity	167
5.2	Physical Effects Under High-Intensity Laser Irradiation	180

5.3	Laser-Induced Shock Waves	190
5.4	Mechanics of Ultrafast Deformations	199
5.4.1	Mechanical Properties in Ultrafast Deformations	199
5.4.2	Dynamic Strength of the Melts and Solid Phases of Metals	206
5.5	Thermodynamics for Ultrashort Pulses	212
5.5.1	Hydrodynamics of Ultrashort Pulses	213
5.5.2	Role of Evaporation	217
5.5.3	Shape of Acoustic Wave Traveling into the Target Interior	218
5.5.4	Melting and Nucleation	221
5.5.5	Newton Rings	223
5.6	Laser-Induced Explosion of Cluster Plasma	227
5.6.1	Models of the Interaction of High-Power Laser Pulses with an Atomic Medium	228
5.6.2	Cluster Ionization in the Field of an Intense Electromagnetic Wave	230
5.6.3	Absorption of Laser Radiation by the Cluster Medium...	232
5.6.4	Cluster Production and Formulation of Experiments	233
5.6.5	Production of Ultrabright X-ray Radiation	236
5.6.6	Production of Fast Electrons in Cluster Plasma	240
5.6.7	Production of High-Energy Ions in Cluster Plasma	241
5.6.8	Conclusions	245
5.7	Spectra of Hollow Ions in Superdense Laser Plasma	246
5.8	High Magnetic Fields	256
	References	258
6	Relativistic Charged Particle Beams	277
6.1	Production of Macroscopic Hot Plasma Volumes	282
6.2	Relativistic Nuclear Collisions	288
6.3	Quark-Gluon Plasma	297
6.4	Viscosity and Interparticle Interaction	328
6.5	Extreme Atomic Physics	338
6.6	Large Hadron Collider	344
6.7	FAIR Project	351
6.7.1	Accelerator Complex	352
6.7.2	Atomic Nuclear Structure, Astrophysics, and Nuclear Reactions with Rare Isotope Beams: NuSTAR (Nuclear STructure, Astrophysics and Reactions)	357
6.7.3	Compressed Baryonic Matter (CBM) Experiment	363
6.7.4	Antiproton Program: PANDA Experiment	365
6.7.5	Electromagnetic Plasma Physics	373
6.7.6	Radiative Study of Materials and Biophysics (BIOMAT)	380

6.8	Heavy-Ion Experiments in the NICA Project	386
	References	393
7	Technical Applications of the Physics of High Energy	
	Densities	403
7.1	Magnetic Confinement Fusion	403
7.2	Laser Inertial Confinement Fusion	414
	7.2.1 Direct-Drive Laser Fusion	414
	7.2.2 Towards Thermonuclear Ignition: NIF Experiments	422
	7.2.3 Fast Ignition	428
7.3	Heavy-Ion Beam Fusion	431
7.4	Laser-Plasma Acceleration of Charged Particles	432
7.5	Synchrotron Sources, Free-Electron Lasers and High-Intensity Sources of Terahertz Radiation Pulses	443
7.6	Plasma in Accelerators	452
	References	453
8	Nuclear Transformations Under Strong Compression	465
8.1	Extreme States of Neutron Stars	466
8.2	Compression: Nuclear Structures	476
8.3	Thomas–Fermi Model	478
8.4	Meson, Pion, and Kaon Condensations	483
8.5	Nucleons and Hyperons Under Supercompression	486
	References	499
9	High Energy Densities in Planets and Stars	505
9.1	Planets and Exoplanets	511
	9.1.1 Planets of the Solar System	511
	9.1.2 Exoplanets	515
	9.1.3 Low-Mass Stars and Substars	522
9.2	Production and Evolution of Single Stars	528
	9.2.1 Origin of Stars	528
	9.2.2 Evolution of Single Stars	535
	9.2.3 Supernova Stars	547
	9.2.4 Collapse of Supermassive Stars ($M > 30\text{--}40 M_{\odot}$)	550
	9.2.5 Brown and White Dwarfs	556
9.3	Superextreme States in the Cosmos	561
	9.3.1 Neutron and Quark Stars	561
	9.3.2 Radio Pulsars	563
	9.3.3 Magnetars	566
	9.3.4 Strange Stars	570
	9.3.5 Black Holes	572
	9.3.6 Quasars	575
	9.3.7 “Wormholes”	581
	References	586

10 High Energy Densities Outside of Compact Astrophysical Objects	591
10.1 Cosmic Jets, Radiative Shock Waves and Molecular Clouds	591
10.1.1 Cosmic Jets	592
10.1.2 Radiative Shock Waves	598
10.1.3 Molecular Clouds	602
10.1.4 Planetary Nebulae	609
10.1.5 “Dark” Matter and “Dark” Energy	616
10.2 Cosmic Rays	637
10.3 Gamma-Ray Bursts	645
10.4 Matter Transformation After the Big Bang	653
10.4.1 Inception of the Universe	659
10.4.2 Inflation	660
10.4.3 Post-Inflationary period	668
10.4.4 Recombination Era	672
10.4.5 Nucleosynthesis	675
10.4.6 Our Time	679
References	692
11 Conclusion	699
Reference	700