COSMIC PLASMA PHYSICS

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COSMIC PLASMA PHYSICS

by

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Preface

This book is addressed to young people without a background in plasma physics; it grew from the lectures given many times in the Faculty of General and Applied Physics at the Moscow Institute of Physics and Technics (the well known 'fiz-tekh') since 1977. A similar full-year course was also offered to the students of the Astronomical Division of the Faculty of Physics at the Moscow State University over the years after 1990. A considerable amount of new material, related to modern astrophysics, has been added to the lectures. So the contents of the book can hardly be presented during a one-year lecture course, without additional seminars.

In fact, just the seminars with the topics '**how to make a cake**' were especially pleasant for the author and useful for students. In part, the text of the book retains the imprint of the seminar form, implying a more lively dialogue with the reader and more visual representation of individual notions and statements. At the same time, the author's desire is that these digressions from the academic language of the monograph will not harm the rigour of presentation of this textbook's subject – the physical and mathematical introduction to cosmic plasma physics.

The idea of the book is not typical for the majority of textbooks on cosmic plasma physics. Its idea is

> the consecutive consideration of physical principles, starting from the most general ones, and of simplifying assumptions which give us a simpler description of plasma under cosmic conditions.

Thus I would recommend the students to read the book straight through each chapter to see the central line of the cosmic plasma physics, its **classic fundamentals**. In so doing, the boundaries of the domain of applicability of the approximation at hand will be outlined from the viewpoint of physics rather than of many possible astronomical applications. After that, as an aid to detailed understanding, please return with pencil and paper to work out the missing steps (if any) in the formal mathematics.

On the basis of such an approach the student interested in modern astrophysics, its **current practice**, will find the answers to two key questions: (1) what approximation is the best one (the simplest but sufficient) for description of a phenomenon in cosmic plasma; (2) how to build an adequate model for the phenomenon, for example, a solar flare. Practice is really important for understanding the theory of cosmic plasma. Related exercises (problems and answers supplemented to each chapter) to improve skill do not thwart the theory but serve to better understanding of cosmic plasma physics.

As for the applications, preference evidently is given to physical processes in the solar plasma. Why? – Much attention to solar plasma physics is conditioned by the possibility of the all-round observational test of theoretical models. This statement primarily relates to the processes in the solar atmosphere. For instance, flares on the Sun, in contrast to those on other stars as well as a lot of other analogous phenomena in the Universe, *can be seen* in their development, i.e. we can obtain a sequence of images during the flare's evolution, not only in the optical and radio ranges but also in the ultraviolet, soft and hard X-ray ranges.

This book is mainly intended for students who have mastered a course of general physics and have some initial knowledge of theoretical physics. For beginning students, who may not know in which subfields of space physics they wish to specialize, I believe

> it is better to cover a lot of fundamental theories thoroughly than to dig deeply into any particular astrophysical subject or object,

even a very interesting one, for example black holes. Astronomers, or astrophysicists, of the future will need tools that allow them to explore in many different directions. Moreover, astronomy of the future will be, more than hitherto, *precise science* similar to mathematics, physics or plasma physics.

The beginning graduate students are usually confronted with a confusing amount of work on cosmic plasma physics published in a widely dispersed literature. Knowing this difficulty, the author has tried as far as possible to represent the material in a self-contained form which does not require the reading of additional literature. However, there is an extensive bibliography in the end of the book, allowing one to find the original works. In many cases, particularly where a paper in Russian is involved, the author has aimed to give the full bibliographic description of the work, including its title, etc.

Furthermore, the book contains recommendations as to introductory (unavoidable) reading needed to refresh the memory about a particular fact, as well as to additional (futher) reading to refine one's understanding of the subject. Separate **remarks of an historical character** are included in many places. It is sometimes simpler to explain the interrelation of discoveries by representing the subject in its development. It is the author's opinion that the outstanding discoveries in cosmic plasma physics are by no means governed by chance. With the same thought in mind, the author gives preference to original papers on a topic under consideration; it happens in science, as in art, that an original is better than nice-looking modernizations.

The majority of the book's chapters begin from an 'elementary account' and illustrative simple examples but finish with the most modern results of scientific importance. New problems determine the most interesting perspectives of cosmic plasma physics as a new developing science. The author hopes, in this context, that professionals in the field of cosmic plasma physics and adjacent sciences will enjoy reading this book too. Open issues are the focus of our attention in many places where they are. In this way, **perspectives of the cosmic plasma physics** with its many applications will be also of interest for readers.

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Moscow, 2000 Boris V. Somov

Introduction
History and Neighbours

Cosmic plasma physics studies electromagnetic processes and phenomena in space, mainly the role of forces of an electromagnetic nature in the dynamics of cosmic matter. Two factors are specific to the latter: its gaseous state and high conductivity. As you know, such a combination is unlikely to be found under natural conditions on earth; the matter is either a non-conducting gas (the case of gas dynamics or hydrodynamics) or a liquid or a solid conductor. By contrast, **plasma is the main state of cosmic matter**. It is precisely the poor knowledge of cosmic phenomena and cosmic plasma properties that explains the retarded development of cosmic electrodynamics. It has been distinguished as an independent branch of physics in the pioneering works of Alfvén (see Alfvén, 1950).

Soon after that, the problem of thermonuclear reactions initiated a great advance in plasma research (e.g., Simon, 1959; Glasstone and Loveberg, 1960; Leontovich, 1960). This branch has been developing rather independently, although being partly 'fed' by astrophysical ideas. They contributed to the growth of plasma physics, for example, the idea of stelarators. Presently, the reverse influence of laboratory plasma physics on cosmic electrodynamics is also important.

From the physical viewpoint,

> cosmic plasma physics is a part of plasma theory related in the first place to the dynamics of a high-conductivity plasma in space.

However it is this part that is the most poorly studied one under laboratory conditions. During the 1930s, scientists began to realize that the Sun and other stars are powered by nuclear fusion and they began to think of re-creating the process in the laboratory. The ideas of astro- and geophysics dominate here, as before. At present time, they mainly come from many

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space experiments and fine astronomical observations. From this viewpoint, physics of cosmic plasma belongs to experimental science.

Magnetic fields are easily generated in the cosmic plasma owing to its high conductivity. The strongest magnets in the Galaxy are presumably the so-called magnetars, the highly magnetized (with the strength of the field of about 10^{15} G) neutron stars formed in the supernova explosions. The energy of magnetic fields is accumulated in cosmic plasma, and the sudden release of this energy – an original electrodynamical 'burst' or 'explosion' – takes place under definite but quite general conditions (Peratt, 1992; Kivelson and Russell, 1995; Rose, 1998). It is accompanied by fast directed plasma ejections, powerful flows of heat and radiation and impulsive acceleration of particles to high energies.

This phenomenon is quite a widespread one. It can be observed in flares on the Sun and other stars (e.g., Haisch, Strong, and Rodonò, 1991), in the Earth's magnetosphere as **magnetic storms** and substorms (Nishida and Nagayama, 1973; Tsurutani *et al.*, 1997; Kokubun and Kamide, 1998; Nagai *et al.*, 1998; Nishida, Baker, and Cowley, 1998), in nuclei of active galaxies and quasars (e.g., Ozernoy and Somov, 1971; Begelman, Blandford and Rees, 1984). However, this process, while being typical of cosmic plasma, can be directly and fully studied on the Sun.

We observe how magnetic fields are generated (strictly speaking, how they come to the surface of the Sun, called the photosphere). We observe the development of **solar flares** and other non-stationary large-scale phenomena, such as coronal transients, coronal mass ejections into the interplanetary medium (e.g., Crooker, Joselyn, and Feynman, 1997), by means of ground observatories (in radio and optical wavelength ranges) and spaceships (practically in the whole electromagnetic spectrum). For example, the *Yohkoh* two telescopes working in soft and hard X-ray bands, respectively, allow us to study the creation and development of non-steady processes in the solar atmosphere (Ichimoto *et al.*, 1992; Tsuneta *et al.*, 1992; Tsuneta, 1993).

The LASCO experiment on board the SOHO satellite makes observations of such events in the solar corona out to 30 solar radii. Moreover, SOHO is equipped with an instrument, the MDI magnetograph, for observing the surface magnetic fields of the Sun. Following SOHO, the satellite TRACE was launched to obtain high spatial resolution X-ray images (see Golub *et al.*, 1999). With the solar maximum approaching, we have an unprecedented opportunity to use the three satellites for coordinated observations.

The link between the solar flares observed and **topology** of the magnetic field in *active* regions, in which these flares occured, was investigated by