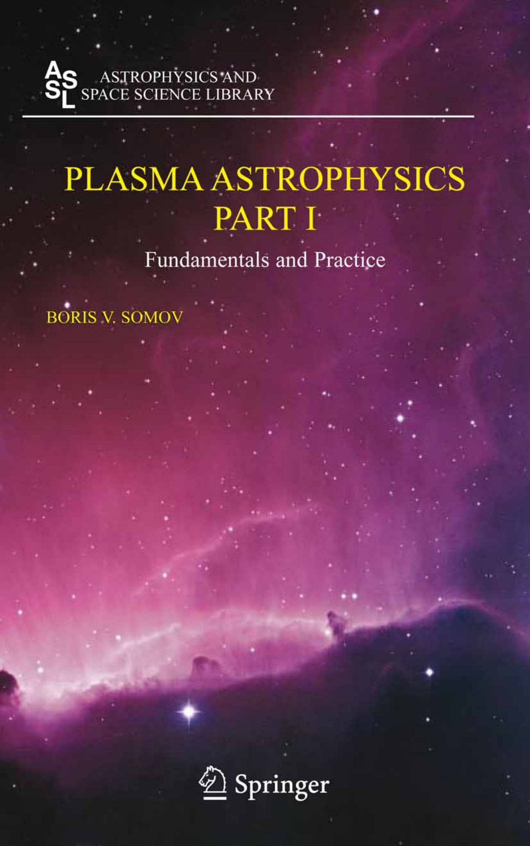

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PLASMA ASTROPHYSICS
PART I

Fundamentals and Practice

BORIS V. SOMOV

Springer

PLASMA ASTROPHYSICS, PART I

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VOLUME 340

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Fundamentals and Practice

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Cover illustration: Interaction of plasma with magnetic fields and light of stars creates many beautiful views of the night sky, like this one shown as the background – a part of the famous nebula IC434 located about 1600 light-years away from Earth and observed by the National Science Foundation's 0.9-meter telescope on Kitt Peak.

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Contents

About This Book

If you want to learn the most fundamental things about plasma astrophysics with the least amount of time – and who doesn't? – this text is for you. This book is addressed to young people, mainly to students, 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 was 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 plasma astrophysics.

There is no unique simple model of a plasma, which encompasses all situations in space. We have to familiarize ourselves with many different models applied to different situations. We need clear guidelines when a model works and when it does not work. Hence **the best strategy** is to develop an intuition about plasma physics, but how to develop it?

The idea of the book is not typical for the majority of textbooks on plasma astrophysics. 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 plasma astrophysics, 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 astrophysical plasma;

(2) how to build an adequate model for the phenomenon, for example, a solar flare or a flare in the corona of an accretion disk.

Practice is really important for the theory of astrophysical plasma. Related exercises (problems and answers supplemented to each chapter) to improve skill do not thwart the theory but serve to better understanding of plasma astrophysics.

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, gamma-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 astrophysics they wish to specialize,

> 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 and 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 and physics.

The beginning graduate students are usually confronted with a confusing amount of work on plasma astrophysics published in a widely dispersed scientific 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 an introductory (unavoidable) reading needed to refresh the memory about a particular fact, as well as to additional (further) 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 plasma astrophysics 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. Anyway,

> knowledge of the history of science and especially of natural science is of great significance for its understanding and development.

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 plasma astrophysics as a new developing science. The author hopes, in this context, that professionals in the field of plasma astrophysics 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 plasma astrophysics** with its many applications will be also of interest for readers. The book can be used as a textbook but has higher potential of modern scientific monograph.

The first volume of the book is unique in covering the basic principles and main practical tools required for understanding and work in plasma astrophysics. The second volume "Plasma Astrophysics. 2. Reconnection and Flares" (referred in the text as vol. 2) represents the basic physics of the magnetic reconnection phenomenon and the flares of electromagnetic origin in space plasmas in the solar system, relativistic objects, accretion disks, their coronae.

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Moscow, 2006 Boris V. Somov

Plasma Astrophysics
History and Neighbours

Plasma astrophysics 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. 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 plasma astrophysics. 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 (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 astrophysics is also important.

From the physical viewpoint,

> plasma astrophysics is a part of plasma theory related in the first place to the dynamics of a low-resistivity 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 recreating the process in the laboratory. The ideas of astro- and geophysics dominate here, as before. At present time, they mainly come from many space experiments and fine astronomical ground-based observations. From this viewpoint, plasma astrophysics belongs to experimental science.

Electric currents and, therefore, magnetic fields are easily generated in the astrophysical plasma owing to its low resistivity. The energy of magnetic fields is accumulated in plasma, and the sudden release of this energy – an original electrodynamical ‘burst’ or ‘explosion’ – takes place under definite but quite general conditions. It is accompanied by fast directed plasma ejections (jets), 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, in the Earth’s magnetosphere as magnetic storms and substorms, in coronae of accretion disks of cosmic X-ray sources, in nuclei of active galaxies and quasars. The second volume of this book is devouted to the physics of *magnetic reconnection and flares* generated by reconnection in plasma in the solar system, single and double stars, relativistic objects, and other astrophysical objects.

The subject of the first volume of present book is the systematic description of the most important topics of plasma astrophysics. However the aim of the book is not the strict substantiation of the main principals and basic equations of plasma physics; this can be found in many wonderful monographs (Klimontovich, 1986; Schram, 1991; Liboff, 2003). There are also many nice textbooks (Goldston and Rutherford, 1995; Choudhuri, 1998; Parks, 2004) to learn general plasma physics without or with some astrophysical applications.

The primary aim of the book in your hands is rather the solution of a much more modest but still important problem, namely to help the students of astrophysics to understand the interrelation and limits of applicability of different approximations which are used in plasma astrophysics. If, on his/her way, the reader will continously try, following the author, to reproduce all mathematical transformation, he/she finally will soon find the pleasant feeling of real knowledge of the subject and the real desire for constructive work in plasma astrophysics.

The book will help the young reader to master the modern methods of plasma astrophysics and will teach the application of these methods while solving concrete problems in the physics of the Sun and many other astronomical objects. A good working knowledge of plasma astrophysics is essential for the modern astrophysicist.

Chapter 1

Particles and Fields: Exact Self-Consistent Description

There exist two different ways to describe *exactly* the behaviour of a system of charged particles in electromagnetic and gravitational fields. The first description, the Newton set of motion equations, is convenient for a small number of interacting particles. For systems of large numbers of particles, it is more advantageous to deal with the single Liouville equation for an *exact* distribution function.

1.1 Interacting particles and Liouville's theorem

1.1.1 Continuity in phase space

Let us consider a system of N interacting particle. Without much justification (which will be given in Chapter 2), let us introduce the distribution function

$$f = f(\mathbf{r}, \mathbf{v}, t) \tag{1.1}$$

for particles as follows. We consider the six-dimensional (6D) space called *phase space* $X = \{\, \mathbf{r}, \mathbf{v} \}$. The number of particles present in a small volume $dX = d^3\mathbf{r}\, d^3\mathbf{v}$ at a point X (see Figure 1.1) at a moment of time t is defined to be

$$dN(X, t) = f(X, t)\, dX. \tag{1.2}$$

Accordingly, the total number of the particles at this moment is

$$N(t) = \int f(X, t)\, dX \equiv \iint f(\mathbf{r}, \mathbf{v}, t)\, d^3\mathbf{r}\, d^3\mathbf{v}\,. \tag{1.3}$$

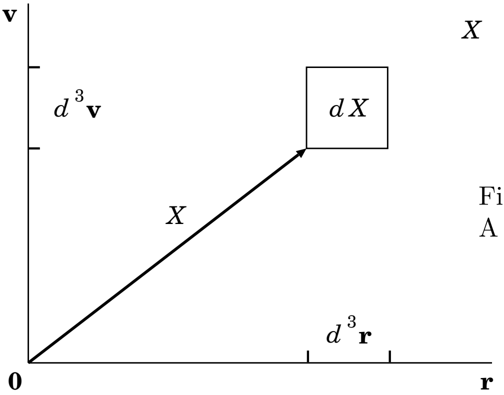

Figure 1.1: The 6D phase space X. A small volume dX at a point X.

If, for definiteness, we use the Cartesian coordinates, then

$$X = \{\, x,\, y,\, z,\, v_x,\, v_y,\, v_z \,\}$$

is a point of the phase space (Figure 1.2) and

$$\dot{X} = \{\, v_x,\, v_y,\, v_z,\, \dot{v}_x,\, \dot{v}_y,\, \dot{v}_z \,\} \tag{1.4}$$

is the velocity of this point in the phase space.

Let us suppose the coordinates and velocities of the particles are changing *continuously* – 'from point to point'. This corresponds to a continuous motion of the particles in phase space and can be expressed by the *continuity equation*:

$$\boxed{\frac{\partial f}{\partial t} + \mathrm{div}_X\,(\dot{X} f) = 0} \tag{1.5}$$

or

$$\frac{\partial f}{\partial t} + \mathrm{div}_{\mathbf{r}}\,(\mathbf{v} f) + \mathrm{div}_{\mathbf{v}}\,(\dot{\mathbf{v}} f) = 0\,.$$

Equation (1.5) expresses the *conservation law* for the particles, since the integration of (1.5) over a volume U enclosed by the surface S in Figure 1.2 gives

$$\frac{\partial}{\partial t}\int\limits_U f\,dX + \int\limits_U \mathrm{div}_X\,(\dot{X} f)\,dX =$$

by virtue of definition (1.2) and the Ostrogradskii-Gauss theorem

$$= \frac{\partial}{\partial t}\,N(t)\Big|_U + \int\limits_S (\dot{X} f)\,dS = \frac{\partial}{\partial t}\,N(t)\Big|_U + \int\limits_S \mathbf{J}\cdot d\mathbf{S} = 0\,. \tag{1.6}$$

Here a surface element $d\mathbf{S}$, normal to the boundary S, is oriented towards its outside, so that imports are counted as negative (e.g., Smirnov, 1965, Section 126). $\mathbf{J} = \dot{X} f$ is the *particle flux density* in phase space. Thus