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Basic Space Plasma Physics

Revised Edition

Imperial College Press

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Preface to the Revised Edition

After just over one decade where, to our surprise and also to our delight, this treatise has received widespread interest and use in basic courses in space plasma physics, and after all the positive reactions to its publication and the encouraging comments we received, we feel obliged to modernise its content in order to bring it up to the current state of knowledge in space plasma physics and to meet the needs of students and teachers in this field. We have been approached several times in the meantime by various colleagues to invest some effort into a new edition but have resisted for this long, not only because of the heavy workload we both had but also because we knew that the interested students and colleagues had already detected misprints and had corrected them in their copies. We were also thinking of possibly writing another book which would have consisted solely of problems, so that the interested student could have learned from solving the problems instead of reading a text. However, as things evolved, though we started it, we never found the time to proceed with that project, and so ultimately decided to take the bull by the horns and produce a revised and slightly extended edition of the original text, now including problems at the end of each tutorial chapter, and also adding some more literature. The result is what the reader has in his or her hands.

Most extensions have been seamlessly integrated in an attempt not to distort the flow. We have also taken great care in detecting the misprints. Hopefully their number has become undetectable. In addition to the many changes in paraphrasing here and there, we also added a few new sections, like the one on magnetopause reconstruction in Chapter 8. These are based on new developments in space physics which we felt the reader should be informed about in passing.

In the same spirit, we decided to add a chapter on instability and thermal fluctuations. This chapter is needed in order to complete the discussion of the kinetic dispersion relation, which, in general, has complex solutions. In many cases, one of these solutions runs unstable. The alert reader has probably already wondered what happened to those solutions. The new chapter on instability provides the important answer. We, however, felt that it was then also necessary to raise and answer another question, about how a wave could grow if it is not already initially present. Fortunately, quantum theory offers an answer to this question in terms of thermal fluctuation theory, which in the classical case simplifies considerably. This theory has been noted in this chapter and illustrated with a few examples.

Finally, we also felt that a few application chapters should be provided. As the first we selected the problem of collisionless reconnection, which is at the heart of the physics of the magnetosphere and thus is directly related to near-Earth space plasma physics. By today's belief, it is responsible for the general convective motion of plasma in the magnetosphere, for filling the magnetosphere with plasma in the first place and for the global instability of the magnetosphere, the substorm and ultimately the magnetospheric storm. Reconnection is a difficult problem which unites global and microscopic aspects. Its theory is still in active and rapid evolution. We therefore give only a cursory account of it, adding two brief observational applications: reconnection at the magnetopause and in the magnetotail, respectively, which from the space physics point of view are closest to our interest. However, reconnection has a much wider application to solar physics, the universe, and last but not least in the laboratory and in fusion research.

For the second application we chose the problem of collisionless shocks. This choice was guided by the importance of shocks in the universe and the plasma physical interest in this very complicated and fascinating subject. The theory of shocks is a nice example of lucidity, and in the non-relativistic case it has achieved a state where it makes sense to attempt a concise textbook review. We do not touch the much more complicated question of formation of relativistic shocks in this book, however, as in near-Earth space no examples of such shocks are known, except, possibly, shocks artificially produced in Laser fusion experiments.

This shock chapter and the former chapter on collisionless reconnection are thus less tutorial than all other chapters in this volume, but they provide some meat to the dry theory developed there. We consider this of some value for the reader to also become confronted with some new developments, which, in addition, go beyond what is contained in our companion volume. For reasons of limited time we are not in the position to also revise that book. Including new material on these matters in a way which simply continues the present book makes sense. That this policy led to an extension over its original size might be considered disadvantageous. It is, however, our feeling that the advantages compensate for the disadvantages.

The degree of difficulty of the problems added to the chapters spans a wide range. Most of them can be answered by intelligent guessing, some of them require simple calculations by using the formulae given, some are possibly difficult for the beginner as they require insight and inventive thinking. We have, however, intentionally not given any answers or solutions as is usually done in textbooks. The reason is that, from our own experience, an appendix containing the solutions and answers is not helpful. Rather, it seduces readers to look for the solution instead of investing some effort themselves. Instead, they will find hints in order to put them on the right track.

The revised version we present herewith is hopefully void of the misprints and misconceptions that the first edition contained. We are deeply indebted to the students – in the first place to Kevin Schoeffler from UMD – for detecting and communicating a number of them to us. We have taken care to keep this text free of errors. Any comments are requested to be sent by electronic mail to *wolfgang.baumjohann@oeaw.ac.at*. We hope the readers, students or instructors will enjoy the new edition or, at least, will find it useful.

Wolfgang Baumjohann and Rudolf Treumann

Preface to the First Edition

One more textbook on plasma physics? Indeed, there are a number of excellent textbooks on the market, like the incomparable book *Introduction to Plasma Physics and Controlled Fusion* by Francis F. Chen. It is impossible to compete with a book of this clarity, or some of the other texts which have been around for longer or shorter periods. However, we found most of the books not well-suited for a course on space plasma physics. Some are directed more toward the interests of laboratory plasma physics, like Chen's book; others are highly mathematical, such that it would have required an additional course in applied mathematics to make them accessible to the students. The vast majority of books in the field of space plasma physics, however, are collections of review articles, like the recent *Introduction to Space Physics* edited by Margaret G. Kivelson and Christopher T. Russell. These books require that the reader already has some knowledge of the field.

The only textbook specifically addressed to the needs of space plasma physics is *Physics of Space Plasmas* by George K. Parks. This book covers many aspects of space plasma physics, but is ordered in terms of phenomena rather than with respect to plasma theory. To give the students a feeling for the coherency of our field, we felt the need to find a compromise between classical plasma physics textbooks and the books by Parks and Kivelson and Russell. We tried to achieve this goal during a third-year space plasma physics course, which we have given at the University of Munich since 1988 for undergraduate and graduate students of geophysics, who had an average knowledge of fluid dynamics and electromagnetism.

This textbook collects and expands lecture notes from these two-semester courses. However, the first part can also be used for a one-semester undergraduate course and research scientists may find the later chapters of the second part helpful. The book is written in a self-contained way and most of the material is presented, including the basic steps of derivation, so that the reader can follow without needing to consult original sources. Some of the more involved mathematical derivations are given in the Appendix. Special emphasis has been placed on providing instructive figures. Even figures containing original measurements are mostly redrawn in a more schematic way.

The first five chapters provide an introduction into space physics, based on a mixture of simple theory and a description of the wealth of space plasma phenomena. A concise description of the Earth's plasma environment is followed by a derivation of single particle motion in electromagnetic fields, adiabatic invariants, and applications to the Earth's magnetosphere and ring current. Then the origin and effects of collisions and conductivities and the formation of the ionosphere are discussed. Ohm's law and the frozen-in concept are introduced on a somewhat heuristic basis. The first part ends with an introduction into magnetospheric dynamics, including current systems, convection electric fields, substorms and other macroscopic aspects of solar wind-magnetosphere and magnetosphere-ionosphere coupling.

The second part of the book presents a more rigorous theoretical foundation of space plasma physics, yet still contains many applications to the subject. It starts from kinetic theory, which is built on the Klimontovich approach. Introducing moments of the distribution function allows the derivation of the single and multi-fluid equations, followed by a discussion of fluid boundaries and shocks, with the Earth's bow shock and magnetopause as examples. Both fluid and kinetic theory are then applied to derive the relevant wave modes in a plasma, again with applications from space physics.

The material presented in this book is extended in *Advanced Space Plasma Physics*, written by the same authors. This companion textbook gives a representative selection of the many macro- and microinstabilities in a plasma, from the Rayleigh–Taylor and Kelvin–Helmholtz to the electrostatic and electromagnetic instabilities, and a comprehensive overview on the nonlinear aspects relevant for space plasma physics, e.g., wave-particle interaction, solitons and anomalous transport.

We are grateful to Rosmarie Mayr-Ihbe for turning our often rough sketches into the figures contained in this book. It is also a pleasure to thank Jim LaBelle for valuable contributions, Anja Czaykowska and Thomas Bauer for careful reading of the manuscript and many suggestions, and Karl-Heinz Mühlhäuser and Patrick Daly for helping with LaTeX. We gratefully acknowledge the support of Heinrich Soffel (Munich University) and Gerhard Haerendel and Gregor Morfill (MPE). We also acknowledge the patience of our colleagues at MPE when we worked on this book instead of finishing other projects in time. Both of us owe deep respect to our teachers who introduced us to geophysics, the late Gerhard Fanselau and Jürgen Untiedt.

Last but not least, we would like to mention that we have profited from many books and reviews on plasma and space physics. References to most of them have been included in the suggestions for further reading at the ends of the chapters. These, however, do not include the very large number of original papers that we made use of and are indebted to.

Needless to say, we tried to make the text error-free. However, this is an insurmountable task. We hope that the readers will kindly inform us about misprints and errors they may find in here, preferably by electronic mail, to *bj@mpe-garching.mpg.de*. We will be grateful for any hints and post them with other errors on *http://www.mpe-garching.mpg.de/bj/bspp.html*.

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Introduction

The context of the term 'geophysics' has changed considerably during the second half of the past century. Well into the fifties the key interest of non-exploratory non-applied geophysics focussed on the interior of our planet, i.e., solely on the geophysics of the solid Earth, covering seismology, rock physics, magnetic and electric properties of crust and mantle, the structure of the outer and inner cores of Earth etc. Clearly, interest in these fields has not diminished; on the contrary, some of them have become mature and have even attracted public interest. This is due to the development of methods of data analysis and interpretation in seismology, new methods in high pressure physics and a better understanding of the processes of wave propagation in matter under high pressure and in fluids, with the latter providing the key to the understanding of the origin of the geomagnetic field. It is also due to the growing public interest in the resources, in the environment and in the history and the future of our planet.

On the other hand, with the advent of the space-flight era, the interests of geophysicists broadened and extended into the external neighbourhood of our planet. It was realised that the extraterrestrial matter is in an ionised state, very different from the state of known matter near the ground of the Earth. Gradually, it was also realised that this environment of Earth plays its own and not completely unimportant role. It is a strongly dynamical environment on time scales much shorter than those of the dynamical processes in the Earth's interior. And it even affects, to sometimes non-negligible extent, the processes close to the Earth's surface which are the direct life-space of mankind. This happened in the history of Earth when the geomagnetic field arose in the interior of the planet and provided a screen, preventing Earth's surface from being hit by medium energy Cosmic Rays, and thus enabled the evolution of sophisticated biological molecules and higher forms of life on Earth. It happened at later times, when the geomagnetic field changed polarity or switched from dipolar to quadrupolar geometry and back again in the unstable phases of the geomagnetic dynamo. It also happens from time to time today when violent events in the immediate vicinity of the Earth, so-called magnetic storms, occur and affect the propagation of electromagnetic waves and other technical installations, having led to the invention of the new research field of Space Weather, a term coined in order to awake a feeling of conscience for a relation between the weather and climate in space and on Earth.

Matter in the state of high ionisation behaves unexpectedly because of its high sensitivity to electric and magnetic fields and because of its ability to carry electric currents, which sometimes can be very strong, and to provide a medium in that electric field may occasionally exist, drive motion of the matter and cause violent electric discharges. Within this context, the *concept of a plasma* was introduced and space