# Space Physics

This textbook, derived from courses given by three leading researchers, provides advanced undergraduates and graduates with up-to-date coverage of space physics, from the Sun to the interstellar medium. Clear explanations of the underlying physical processes are presented alongside major new discoveries and knowledge gained from space missions, ground-based observations, theory, and modeling to inspire students. Building from the basics to more complex ideas, the book contains enough material for a two-semester course, but the authors also provide suggestions for how the material can be tailored to fit a single semester. End-of-chapter problems reinforce concepts and include computer-based exercises especially developed for this textbook package. Free access to the software is available via the book's website and enables students to model the behavior of magnetospheric and solar plasma. An extensive glossary recaps new terms, and carefully selected further reading sections encourage students to explore advanced topics of interest.

Christopher T. Russell has written over 1600 articles in books and journals on planetary and space physics and has been cited over 45 000 times. He has been awarded the AGU's Macelwane medal, its Fleming medal, and COSPAR's Science Award. He has been a principal investigator on numerous missions including ISEE 1 and 2, Pioneer Venus, the ISTP/Polar mission, and the Magnetospheric Multiscale mission. He is also the Principal Investigator of the ion-propelled Dawn Discovery mission to the asteroid belt.

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Robert J. Strangeway is an author or co-author on over 200 publications covering a variety of space physics topics. He regularly teaches the Introduction to Space Physics course at UCLA, which is the basis for this book. He is currently the Senior Editor for the *Journal of Atmospheric and Solar-Terrestrial Physics*. In addition to serving as an Investigator with the missions AMPTE/CCE, Pioneer Venus, and FAST, he was the Principal Investigator for the magnetometers developed for Space Technology 5.

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# Preface

We live on a planet in which three states of matter are very familiar. Our feet are firmly planted on the solid ground; not long ago, we poured ourselves a drink of liquid; and right now we are breathing air. Even if we do not understand the mathematical physics behind the behavior of the solids, liquids, and gases that are all around us, we still have an empirical working knowledge that allows us to stand, drink, and breathe. If we but venture a short way off this planet, our intuition begins to fail us. Soon the particles surrounding us have electric charges. Instead of atomic forces holding the molecules together in solids and liquids, and collisions dominating the forces in gases, we find that electric and magnetic forces are dominant. Gravity is still present, but, unlike in the environment in which you read this book, in the plasma universe gravity can be a minor factor in determining motion.

For the first two millennia of the common epoch, we could largely ignore the fourth state of matter, the plasma state, but now that we are living in the third millennium, we have to address how the more distant space around us behaves. In this millennium, "outer space" becomes important, beginning less than 100 km above our heads, a distance that is no longer far out of reach. It is a region in which many of us work every day, tending to our robotic machines. Some of us even live in space, not just for hours or days, but for significant fractions of a year with the hope of extending human presence for even longer periods.

It is important for us to master this fourth state of matter, as it has become important to all of humanity. Technology has advanced rapidly since the beginning of the industrial revolution, so now we depend on technology for communication, weather prediction, and energy transmission. Our planes travel at high altitudes close to the edge of space. With that advance has come new sensitivities that at first caught us by surprise. We did not know how variable was the plasma environment that surrounds the Earth, or how variable was the connectivity of the Sun and the Earth via that plasma. But when electrical systems across the planet began to fail, when spacecraft stopped obeying our commands, and when the radiation hazards in space and within our upper atmosphere were understood, the study of this region became very necessary.

This book is our attempt to codify the basic principles of the plasma state from the Sun to the edge of the solar system. We do not stop at the outermost planets but extend to where the solar system plasma meets the galactic plasma or, as astronomers call it, to the local interstellar medium. Because our daily lives do not prepare us for this journey, it is difficult to know when and how to begin.

There are several possible approaches. We could start with the simplest systems and add complexity. We could order our journey by spatial location beginning at the center of the solar system and moving outward. We could follow the energy flow outward past all the planets. We could move into another dimension, time, and travel in chronological order, following the history of discovery leading to understanding. There is much to justify the spatial/energy flow approach because the Sun is at the center of our solar system and provides much of the energy for the space around it. The solar wind couples to the planets' magnetospheres and ionospheres, and the Sun's photons couple to their atmospheres through heating and photoionization. On the other hand, the chronological approach follows the way that scientists originally came to understand the solar-terrestrial environment. The chronological approach has the advantage of allowing us to start with simple concepts and then build complexity on top of them. The disadvantages of this approach are that some of the early ideas were wrong, and that science does not necessarily progress along the shortest path. So the purely historical path can be inefficient.

In this book, we attempt to combine these approaches, trying to reduce topics to their basics before introducing complications. We start the book with an historical introduction that attempts both to show how the scientific method proceeds in its most general sense and to provide a description of the plasma environment in which the Earth resides. Chapter 1 begins with the ancient observations of the "northern lights" which we now refer to as the aurora borealis (and its sibling, the aurora australis, in the south). We introduce the magnetic state of the Earth, the plasma in the upper atmosphere, and then the advent of the space age and the space exploration program, around our planet and the other planets.

In Chapter 2, we start from the known, the atmosphere of the Earth, and move outwards. The neutral atmosphere has winds and pressure. It varies with altitude. It supports wave phenomena. We encounter these topics later in the book in their plasma forms. Completing this chapter, we examine how the atmosphere becomes ionized, forming the first of the natural plasmas to be discovered.

In Chapter 3, we introduce the physics of plasmas and the mathematical formalism to treat plasmas quantitatively. Since the advent of the space age, the field of space physics has become increasingly more quantitative, and processes are described much more precisely with theory that has rigorous mathematical underpinnings. Some of this is kinetic theory that treats the behavior of the full plasma. Some of this is magnetohydrodynamic theory that averages over the gyro and thermal motions to describe processes in terms of densities, bulk velocities, momenta, and temperatures. Later in the book we describe the numerical simulations that use this mathematical theory to describe the behavior of these complex systems.

In Chapter 4, we head for the center of the solar system where the energy for the plasma processes is produced (and the gravity that binds the planetary system together originates). We have learned much about the Sun over the past few decades, but our ability to determine how and why processes and phenomena occur is limited when we have only remote-sensing data with which to work. Thus, Chapter 4 stresses what happens on the Sun, even when we do not completely understand it.

Missions now in development will soon provide more information about the hows and whys.

In Chapter 5, we move off the Sun and into the heliosphere. In this chapter, we examine how the solar wind is accelerated, how its variability leads to dynamic phenomena, and how it terminates. The solar wind is very important as it couples the Sun's plasma environment to our own, providing a conduit for solar activity to affect terrestrial activity.

Chapter 6 covers the physics of a very non-linear plasma process, the collisionless shock. This irreversible process increases the entropy of the plasma and converts energy from the bulk motion of the plasma into heat. It is this heated and compressed plasma that interacts with the planets and controls the energization of the planetary atmospheres and magnetospheres. These shocks are also responsible for energizing a small fraction of the plasma particles to sometimes very, very high energies, energies that can be damaging to our space electronics and to living organisms, even those just on the edge of space.

Chapter 7 examines how the solar wind interacts with bodies that are strongly magnetized. It also introduces the reader to numerical simulations of four types: gas dynamic, magnetohydrodynamic, hybrid, and fully kinetic. Each of these types of simulations has its advantages, and each has some limitations.

Chapter 8 describes how the solar wind interacts with bodies that are not strongly magnetized. These bodies may, like the Moon, have almost no atmosphere or may, like Venus, have an atmosphere and an ionosphere. This chapter shows how the planetary ionosphere forms a barrier to the solar wind and deflects it around the planet and how comets and asteroids can interact with the solar wind.

In Chapter 9, we examine how energy is extracted from the solar-wind flow and transferred to the Earth's magnetosphere and ultimately to its atmosphere. This chapter treats reconnection at the magnetopause and in the magnetotail. It discusses magnetospheric substorms and storms. These topics have been of interest since the beginning of the space age, and, in the absence of sufficient observations from the sparsely sampled magnetosphere, these topics were initially quite controversial. In writing this chapter, we have not attempted to replay the entire history of these studies, but we simply explain the energy flow and its temporal behavior in terms of physical processes that we now understand well, on a theoretical and operational basis.

In Chapter 10, we examine the inner magnetosphere, the region in which the ionosphere extends upward to form the plasmasphere. This is the most stable of the regions of the magnetosphere, but it is far from being boring. This region is home to the radiation belts and some very interesting and important wave–particle interactions.

In Chapter 11, we step outside the "stable" zone into the auroral and polar ionospheres and the magnetosphere above these regions in which the temporal variation of the magnetosphere is the greatest and where the main coupling of the energy transfer process occurs.

Chapter 12 takes us to the magnetospheres of the magnetized planets other than the Earth: Mercury, Jupiter, Saturn, Uranus, and Neptune, and their moons. We benefit from our knowledge of these systems by understanding more fully the same processes as on Earth, but under very different conditions.

Chapter 13 brings us back to wave processes and gives us a more mathematical treatment of these phenomena that are so important to the evolution, scattering, and thermalization of the plasma in the solar wind and planetary magnetospheres.

Our intention in this book is to provide an understanding of the basic physical principles in space physics for the beginning graduate student. Much of the material is suitable for upper division undergraduates and has been tested on both undergraduate and graduate students in the Department of Earth, Planetary, and Space Sciences at the University of California, Los Angeles.

## HOW TO USE THIS BOOK

It is our intention in preparing this text to provide the material necessary to enable a graduate student to embark profitably on a career in space physics. The material has a range of difficulty and has both descriptive and some very mathematical sections. It would be difficult to cover in depth all this material in a single semester or quarter. We would recommend a two-semester approach with the following material in the first semester to give the student a basic working knowledge of the physics of space plasmas. The course would begin with Chapter 1, which covers first the history of the field. All of Chapter 2 would follow, giving an introduction to the physics of neutral gases as a prelude to the analogous physics of plasmas, closing with a discussion of the nearest geophysical plasma, the ionosphere. Following this, we recommend Sections 3.1 to 3.2 together with 3.5, which would cover single-particle theory and fluid theory.

In Chapter 4, Sections 4.1 to 4.3 cover the Sun and solar cycle. Chapter 5's Sections 5.1 and 5.2 bring in the solar wind and coronal sources. Chapter 6's Sections 6.1, 6.2, and 6.4 add a discussion of shock types and shock observations. Chapter 7's Sections 7.1 to 7.6 cover planetary magnetic fields and the formation of a magnetosphere, as well as fluid treatments of the solar-wind flow past planetary obstacles. In Chapter 8, Sections 8.1 to 8.3 treat the basic unmagnetized planet interaction. All of Chapter 9 is recommended in this first course because understanding the energization of the Earth's magnetosphere is perhaps the most important part of space plasma studies. In Chapter 10, Sections 10.1 to 10.2.4 and 10.3 would add cold plasmas in the magnetosphere and the radiation belts. In Chapter 11, we recommend covering Sections 11.1 to 11.3 in the first course, which will allow understanding of auroral emissions. In Chapter 12, Sections 12.1 to 12.4 provide an overview of the size and circulation of planetary magnetospheres. Chapter 13 and the remaining materials in the earlier chapters provide a more intensive look at the physical processes that underlie the phenomenology.

Several features of this book are worthy of note. The book does not simply end with Chapter 13, but continues with four appendices, a glossary, a list of references, and an index. Appendix 1 discusses notation, vector identities, and differential operators of use in treatments of space plasmas. Appendix 2 lists fundamental constants and formulas for the plasma parameters of space physics. Appendix 3 describes many of the coordinate systems used in space plasma physics, and how to transform from one coordinate system to another. Finally, Appendix 4 gives an introduction to power spectral analysis, especially dynamic power spectral analysis including how to determine the direction of propagation of electromagnetic waves in a plasma and their handedness as compared to the motion of charged particles in a plasma, which is the plasma physicist's definition of right-handed and left-handed.

The glossary includes all terms included in bold in the pages of the textbook, usually when the term is first used. The glossary provides a simple definition of the term in bold. The list of references gives those references to classic papers that we felt needed referencing in the text when certain concepts or observations were introduced. Also included are the references in which figures that we did not originate can be found. The index includes those important topics covered in the book that one might like to find without having to read entire sections of the book.

Additional suggested reading and problems are listed at the ends of chapters. We include the reason one might like to consult the additional reading. The problems consist of two types: those that reinforce a concept in the chapter and can be completed by students after having mastered the material in the chapter; and those that are more like laboratory exercises which require use of web-based software developed as an adjunct to the course. Science courses are often accompanied by "labs" in which students do experiments, but in a space plasma the scales are so vast one cannot conceive of building a student laboratory. One must resort to the use of computers. The exercises were developed over a decade of teaching space plasma physics at UCLA to demonstrate the behavior of magnetospheric and solar plasma. They have been recoded and upgraded in conjunction with the publishing of this book and made available over the web. Instructors will soon appreciate that the same software can be used for a variety of different problems and may stray away from the specific problems listed toward problems tailored to the needs of a specific course.

## ACKNOWLEDGMENTS

An earlier book, *Introduction to Space Physics*, edited by M. G. Kivelson and C. T. Russell, was published in 1995. This book was a compilation of chapters written by leading researchers in the field. While this was an efficient means of assembling the first comprehensive textbook in the

field, it did not result in a uniform treatment of the topics. When it became time to publish a successor volume, three of the original authors volunteered to work together to prepare a new volume with a more even treatment of the topical areas involved.

Chapter 1 contains much of the material in the earlier book, but with additional discussion and tables that summarize the progress made in the two decades since the earlier book. Chapter 2 contains material on the neutral atmosphere and the physics of gases leading to a discussion of the ionosphere which was largely discussed in Chapter 7 of the original edition. Chapter 3 covers the physics of magnetized plasmas, replacing and expanding on the chapter by M. G. Kivelson. Chapter 4 discusses what we know about the Sun and its atmosphere, replacing the earlier chapter by E. R. Priest that emphasized the role of the magnetic field in solar phenomena. Chapter 5 on the heliosphere includes the traditional material found in A. J. Hundhausen's treatment of the solar wind, but expands the discussion to include the increased knowledge we now have on the radial evolution of the solar wind and its interactions with neutrals, dust, cosmic rays, and the interstellar mechanism. Chapter 6 is a complete rewrite of the chapter originally written by D. Burgess with a mathematical derivation of the Rankine–Hugoniot relations that are the key to understanding the behavior of collisionless shocks. Chapter 7 is an update of the material in the chapter by R. J. Walker and C. T. Russell in the earlier book. This chapter has a more complete treatment of the types of numerical simulations used in the study of solar-wind interactions. Chapter 8 is an update of the material on the solar-wind interaction with unmagnetized objects by the original author. Today, we know about interactions that were not even dreamed about two decades ago. Chapter 9 replaces the chapter originally written by W. J. Hughes on solar-wind coupling with the Earth's magnetosphere. This chapter focuses on the dynamics associated with magnetic reconnection between the solar wind and the terrestrial magnetic field. Chapter 10 replaces the chapter originally written by R. A. Wolf. This new chapter preserves the classic treatment of the radiation belts but covers the low-energy plasma and magnetospheric waves in detail not found in the earlier work. Chapter 11 replaces the auroral chapter of H. C. Carlson and A. Egeland. This chapter emphasizes the physics of the auroral processes more than in the earlier chapter. Chapter 12 replaces the chapter originally authored by C. T. Russell and R. J. Walker. This largely preserves the original material but updates it with the results from recent planetary missions. The final chapter in the book covers waves in plasmas and is a complete rewrite of the earlier chapter by C. K. Goertz and R. J. Strangeway, here stressing electromagnetic wave phenomena over electrostatic waves. The book ends with four appendices. Appendices 1, 2, and 3 are updates of the earlier appendices, but Appendix 4 is a completely new appendix that explains fundamental elements in the analysis of time series of magnetic fluctuations in plasmas.

The authors of this book thank the earlier authors for permission to use excerpts from their earlier works where appropriate. We are particularly

grateful to the students of the UCLA Department of Earth, Planetary, and Space Sciences who have provided feedback on this project, and to the California Space Grant Consortium for supporting the preparation of some of the graphics for this book and the conversion of the software to a web-based version. We are also grateful to Sharon Uy, Margie Sowmendran, and Richard Sadakane for their help in preparing the volume.