Physics of Space Storms

From the Solar Surface to the Earth

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Preface

Space weather can be defined as a subtopic of solar–terrestrial physics, which deals with the spatially and temporally variable conditions in the Sun, solar wind, magnetosphere, and ionosphere that may disturb or damage technological systems in space and on the ground and endanger human health. *Space storms* are the strongest and most harmful appearances of space weather.

During the 1990s space weather grew to a prominent, if not the dominant, sector within solar–terrestrial physics. Also a significant fraction of basic space plasma physics research became motivated by its potential to contribute to useful space weather applications including more accurate forecasts. A key reason for the evolution of space weather activities is the growing understanding that a great number of systems in space, human beings included, and on the ground are vulnerable to severe space weather conditions. In fact, due to miniaturization and increasing complexity many technological systems are becoming more sensitive to the radiation environment than before. At the same time modern society is getting increasingly dependent on space infrastructure. In future the human presence in space, including space tourism, is expected to become more prominent. Some day we most likely will return to the Moon and, perhaps, initiate manned missions to Mars. On the ground the effects of space storms, such as saturation of transformers in electric power transmission networks or perturbations in telecommunication and global positioning systems, may be easier to handle, but this requires that the underlying physics be understood much better than today.

The developers of space weather services have done their best to follow the needs, sometimes real, sometimes imagined, of potential users of space weather applications. There is growing activity to produce tools for modeling and forecasting space weather conditions based on a limited set of observations, for specification of environmental conditions during storms, and for after-the-fact analysis of anomalous behavior of technological systems and hazards caused by severe space weather. Unfortunately, this activity is often based on insufficient knowledge of the underlying physical systems, sometimes even at the cost of basic research aiming at increasing this knowledge. This development is not always healthy in the long-term perspective. Furthermore, it is not enough just to solve the acute problems: the knowledge being gained today also needs to be maintained tomorrow.

While a large number of research articles and review papers on space storms have been published over the last several years, there is no comprehensive systematic textbook approach to the relevant physics of the entire chain of phenomena from the surface of the Sun to the Earth. The goal of the present monograph is to fill this gap. The text is aimed at doctoral students and post-doctoral researchers in space physics who are familiar with elementary plasma physics and possess a good command of classical physics. The topics reach from the storms in the solar atmosphere through the solar wind, magnetosphere, and ionosphere to the production of the storm-related geoelectric field on the ground. In the selection of material, preference has as much as possible been given to analytical and quantitative presentation over handwaving, while keeping the volume of the book reasonable.

Of course, several good plasma physics textbooks are available, which are useful in the education of space physicists, e.g., the rewritten classic of Boyd and Sanderson [2003], the little more challenging Sturrock [1994], or the recent volumes written by Gurnett and Bhattacharjee [2004] and Bellan [2006]. However, these books are written for very wide audiences from laboratory and fusion communities to space plasma physicists. Consequently, many important issues in the physics of tenuous space plasmas have had to be dealt with in a brief and cursory manner. For astrophysicists interested in the most abundant form of conventional matter in the universe the book by Kulsrud [2005] is strongly recommended, although quite demanding reading. There are also several textbooks with a clear focus on fundamental space plasma physics [e.g., Baumjohann and Treumann, 1996; Treumann and Baumjohann, 1996; Parks, 2003], but their approach too is more general than the thematically focused topic of the present volume. The multi-authored textbook edited by Kivelson and Russell [1995] covers large parts of the physical environment of this book. However, it does not go very deeply into the plasma physics and suffers to some extent from the different styles of the individually written chapters.

The rapid growth of space weather activities has led to a large number of compilation works of highly variable quality. An inherent problem of multi-authored collections is that each article is relatively short but at the same time written in a complete article style from introduction to conclusions and often with individual reference lists. Thus the books easily become thick but none of the articles can penetrate the basic physical principles. Some of the most useful collections in the present context are those edited by Crooker et al [1997], Tsurutani et al [1997], Daglis [2001], Song et al [2001], Scherer et al [2005], Baker et al [2007], Bothmer and Daglis [2007], and Lilensten et al [2008]. These books contain many excellent articles and provide students with a large body of study material with up-to-date observational data. However, these volumes rather complement than compete with this self-contained monograph.

This book can be interpreted to consist of three parts. The long Chapter 1 forms the first part. It contains a phenomenological introduction to the scene, from the Sun to the Earth, where space weather plays are performed. A reader familiar with basic physics of the Sun, solar wind, magnetosphere and ionosphere can jump over this chapter and only return to it when there is a need to check definitions or concepts introduced there.

The second part of the book consists of several chapters on fundamental space plasma physics. While this part is written in a self-consistent way, it is aimed at readers who already have been exposed to basic plasma physics. Chapter 2 briefly introduces the fundamental concepts and tools of plasma physics inherited from both electrodynamics and statistical physics. Chapter 3 reviews the classical guiding center approach to single particle motion and adiabatic invariants, including motion in the dipole field, near a current sheet, and in a time-dependent electric field.

Common problems to all plasma physics texts are in what order the microscopic and macroscopic pictures should be introduced and at what stage the waves and instabilities be discussed. The strategy in the present volume is to start with the wave concepts in the cold plasma approximation in Chapter 4. The chapter includes a discussion of radio wave propagation in the ionosphere as an example of dealing with wave propagation in inhomogeneous media in the WKB approximation, which is a powerful theoretical tool in problems where the wavelength is short as compared to the gradient scale lengths of the background parameters. Chapter 5 is a standard discussion of the Vlasov theory starting from Landau's solution and extending to the wave modes in uniformly magnetized plasma. Only after these is magnetohydrodynamics (MHD) treated in Chapter 6. Here more emphasis is placed on the field-aligned currents (i.e., force-free fields) than in many other plasma physics texts because they are of such great importance in the solar atmosphere, solar wind, and magnetosphere and in magnetosphere–ionosphere coupling. The chapter is concluded with a brief peek beyond the MHD approximation, including a quasi-neutral hybrid approach and the introduction of kinetic Alfvén waves.

Space plasma instabilities are the topic of Chapter 7. In whatever way you approach this complex, you end up being incomplete if you wish to keep the discussion within reasonable limits and focused. Here the approach is to introduce the basic ideas, such as the free-energy sources and stability criteria, behind several of the most important instabilities studied in the context of space storms, but most of the long and tedious derivations of the equations have been omitted. The reader interested in the details is recommended to consult more advanced textbooks in plasma theory and relevant research articles. Another choice motivated by the theme of this book is to discuss the magnetic reconnection and the tearing modes separately from other instabilities in a dedicated Chapter 8. Whatever the microphysical mechanisms associated with reconnection are, the understanding of its basic characteristics is an essential part of literacy in space physics, regardless of whether one is interested in solar flares, coronal mass ejections, solar wind interaction with the magnetosphere, or the substorms therein. Unlike other textbooks, the concept of dynamo is introduced in this chapter because the annihilation and generation of magnetic flux can be seen as two faces of related physical processes.

The primary goal of this book is to bridge the gap between the fundamental plasma physics and modern research on space storms. This is the challenge of the third part of the book. As in modern concertos, transition from the second to the third movement is not necessarily well-defined. In some sense Chapter 8 already opens the third part as here the treatise begins to focus more on the key issues in space storm research. Chapter 9, in turn, discusses the mechanisms giving rise to radiation that we see coming from the solar atmosphere at the time of solar storms as well as the scattering of radio waves from electrons and plasma fluctuations in the ionosphere. In Chapter 10 the adiabatic invariants introduced in Chapter 3 are used in formulating the kinetic equations for studies of plasma transport and acceleration in the inner magnetosphere.

Fluid turbulence remains one of the toughest problems in classical physics and turbulence in collisionless magnetized plasmas is an even harder problem. Particularly interesting environments, where turbulence is critical, are the interplanetary and planetary shocks with the associated sheath regions. Shocks and shock acceleration are discussed in Chapter 11.

Finally the treatise returns to the more phenomenological treatment of space storms in various parts of the solar–terrestrial system. Chapter 12 deals with the storms on the Sun and their propagation into the solar wind. In Chapter 13 magnetospheric storms and substorms and their drivers are investigated. As storm phenomena in the inner magnetosphere are of particular practical interest, they are discussed separately in Chapter 14. At the end of the journey some effects of space storms on the atmosphere and the current induction on the ground during rapid ionospheric disturbances are briefly discussed in Chapter 15.

The great variety of phenomena from the Sun to the Earth and the vast amount of different theoretical and modeling approaches to explain them make some hard choices necessary, in particular, the choice between a Sun–centered and an Earth–centered approach. The solar atmosphere, in particular the corona, is a much more stormy place than the Earth's environment. The Sun is also the driver of practically all space storm phenomena in the solar–terrestrial system. These facts would suggest adoption of the Sun–centered view on space storms. On the other hand, we live on the Earth and here we have to learn to handle the consequences of space storms. Thus the present choice is Earth-centered but more emphasis is put on the entire space storm sequence than in traditional textbooks on magnetospheric physics. There is a recent very comprehensive textbook on the physics of solar corona by Aschwanden [2004]. Actually just browsing through that volume, containing citations of about 2500 scientific articles, illustrates how difficult it is to compile a concise text on that end of the space storm chain. The first decade of the 21st century also forms a "golden age" of solar physics when several multi-wavelength spacecraft are producing an enormous amount of new empirical information on the active Sun. To digest all this will certainly take some time.

Another choice taken here is not to deal with space weather effects or practical modeling approaches. Concerning these we point the interested reader to the recent volumes by Bothmer and Daglis [2007] and Lilensten et al [2008] and references therein. In fact, the present book and those by Aschwanden [2004] and Bothmer and Daglis [2007] are strongly complementary to each other. They have quite different approaches but are dealing with closely related issues.

As one of the goals of this book is to provide material for advanced students, exercise problems of varying difficulty have been embedded within the text. They are grouped into three categories: Problems labeled *Train your brain* are mostly straightforward, often boring, derivations of expressions that are useful for students learning to master the basic material of the book. The label *Feed your brain* refers to problems or tasks that add to the reader's knowledge beyond the actual text and can also be useful for testing the reader's understanding of the material. Problems identified as *Challenge your brain* are a little harder (at least to the author), dealing also with unsolved or controversial issues. Creative solutions to some of these may be worth publishing in peer-reviewed journals.

A textbook discussing basic physics necessarily borrows material from earlier sources. The author was introduced to plasma physics through the classic texts by Boyd and Sanderson [1969], Krall and Trivelpiece [1973], and Schmidt [1979], which certainly can be recognized in the presentation of the fundamental plasma issues. When discussing "generally known" (or believed to be known) topics, in particular in Chapter 1, references to the scientific literature have been used sparsely. However, a number of references to some of the truly classic reports have been included. New generations of scientists every now and then tend to forget the original works with the risk of independent reinvention of the wheel. For students it is sometimes useful to recall that there was intelligent life even before they were born. In this respect the internet has actually made life much easier. We do no more need to have physical access to the best equipped libraries to read many of the classic reports in the scientific literature. Unfortunately, books like this are harder, or more expensive, to access electronically.

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Helsinki, September 2010 *Hannu E. J. Koskinen*

Units and Notation

SI units are used throughout the book. As a common exception energy and temperature are often expressed in electronvolts (eV), but in equations involving the temperature the Boltzmann constant k_B is written explicitly, in which case the temperature is given in kelvins (K). Furthermore, physical distance measures, such as the radius of the Sun ($R_\odot$), the radius of the Earth (R_E), or the astronomical unit (AU), are in frequent use. Also, when dealing with densities of a few particles per cm^3, or magnetic fields of a few nT, it is preferable to use these as units in order to avoid unnecessary use of powers of ten.

A person working within theoretical plasma physics or solar physics must also master the Gaussian cgs unit system, as much of the literature in these fields is still written in these units. Transformation from grams to kilograms, from centimeters to meters, or ergs to joules is trivial, but in formulas involving electrodynamic quantities the different unit systems are a nuisance. This sometimes leads to erroneous calculations, not only by factors of 10, but examples of errors by a factor of 3 or 4π are not too difficult to find in the literature, peer-reviewed articles included.

Macroscopic quantities in the three-dimensional configuration space are denoted by capital letters, e.g., electric current $\mathbf{J}$, fluid velocity $\mathbf{V}$, pressure P, etc., vectors in boldface and scalars in italics. The lowercase $\mathbf{v}$ is reserved to denote particle velocity as a function of time and the velocity coordinates in the phase space, e.g., in expressions as $f(\mathbf{r},\mathbf{v},t)$, whereas the lowercase $\mathbf{p}$ denotes the particle momentum $\mathbf{p}(t)$. In order to avoid conflict electric potential is denoted by φ, whereas ϕ is an angular variable. Similarly volume is denoted by $\mathscr{V}$ in order not to mix up it in some expressions with speed V. The volume differential in integral expressions is denoted by either d^3r or $d\mathscr{V}$.

In an ideal world a textbook should have a unique system of symbols. However, this is not a practical goal for a book that combines material from several different disciplines of physics, all with their own and by no means common or unique notations. Thus the most usual conventions are followed in the book, accepting that some symbols become heavily overloaded. One of them is μ, that in this book may denote the magnetic permeability of a medium, the magnetic moment of a charged particle, or the cosine of the pitch angle. J can denote the second adiabatic invariant, the absolute value of electric current $|\mathbf{J}|$, and omni-directional particle flux. γ in turn appears as the polytropic index, as the Lorentz factor and in some instances as the wave growth rate, n as the particle density, the index of refraction and in vector form the unit normal vector, σ as electrical conductivity and the collision cross-section, etc. However, none of these ambiguities should lead to misunderstanding. After all, physicists are expected see the forest for the trees.