

Preface

Motivated by the presentations and discussions carried out at the Magnetic Reconnection Workshop, held at the National Institute for Space Research (INPE) of Brazil in March 2014, some of the scientists who attended it thought that it was timely to prepare a new book on magnetic reconnection since previous books on this topic have been published already eight years before or more. Thus, this book deals with a review of fundamental concepts on magnetic reconnection that are still open for research and with applications of this important cosmic plasma process to regions going from the Sun's atmosphere and the Earth's magnetosphere to domains involving heliospheric magnetospheres, stellar atmospheres, turbulent astrophysical plasmas, radiation dominated astrophysical systems, and even quantum systems in which annihilation of quantum magnetic fluxes seems to take place.

This book updates and extends the scope of previous books on magnetic reconnection, especially of those edited by Priest and Forbes (2000) and by Birn and Priest (2007), to which the readers are referred for reviews on fundamental aspects of MHD reconnection and of collisionless reconnection.

Most of the chapters of this book have been prepared having graduate students and postdocs as the main readers in mind, thus providing illustrations and introductory discussions for the addressed topics. However, we believe that all researchers in the field of magnetic reconnection will also profit from the reviews presented in this book since several of the authors have made an effort to incorporate new research material in their reviews. Concerning the units used in this book, because the chapters were written by different authors with some of them preferring the MKS system and some the CGS system, we have not made the effort to present all chapters with only one of these units, also because we assume that the readers are already familiar to find this same situation when reading papers in which the authors prefer to use one system or the other.

In Chap. 1, several of the book authors present opinions about two fundamental questions on magnetic reconnection that still remain unsettled. They refer to the meaning of the generally used expression “magnetic field lines cut and reconnect” as well as to the location and nature of a “diffusion” region of reconnection and to its role in defining the reconnection rate, as compared to that associated with the

global reconnecting system and the boundary conditions. Although one can read about illuminating considerations in the discussions presented in this chapter on such fundamental issues, one can also see that no consensus about them is presently available, thus indicating that the subject of magnetic reconnection remains open for further theoretical, computational, and observational studies.

Although the topic of collisionless reconnection has been reviewed extensively in recent years (Yamada et al. 2010; Mozer and Pritchett 2012; Karimabadi et al. 2013; Treumann and Baumjohann 2013; Hesse et al. 2014), J. Scudder, H. Karimabadi, and B. Daughton present in Chap. 2 of this book a complementary review dealing mostly with the electron physics of reconnection and more particularly with the role of electron demagnetization in collisionless reconnection. From this study the authors present a set of phenomenological parameters that are intended to be used as proxies to locate the electron diffusion region of reconnection, both in 2D and 3D.

The MHD approach to study reconnection still provides important results especially when one deals with global aspects. Thus, E. Priest presents in Chap. 3 a review about the different 3D-MHD structures of reconnection, where the electric current tends to concentrate leading to reconnection-related null points, separators, and quasi-separators. The review also discusses the role of magnetic helicity and of other topological invariants, together with the conditions for flux and field line conservation and for reconnection itself.

In Chap. 4, M. Yamada, J. Yoo, and S. Zenitani present a review on energy conversion and partitioning for a prototypical magnetic reconnection layer, incorporating recent results from laboratory experiments, space observations, and numerical simulations. They conclude that about half of the incident magnetic energy is converted into particle energy, of which $2/3$ is ultimately transferred to ions and $1/3$ to electrons. They also discuss these results in the context of a systematic variability of the boundary conditions.

The important problem of rapid reconnection and associated changes in field line topology, which has been discussed in several recent publications, is reviewed in Chap. 5 by E.N. Parker and F. Rappazzo. This situation arises where the magnetic stresses drive the plasma and field toward increasing field gradients, so that the current density becomes large without bound, with the plasma dynamics and the kinetics of the thin current sheet controlling the rate of the reconnecting fields. The authors consider where and how the local rapid reconnection phenomenon arises in the overall topology of the surrounding magnetic field and exemplify it with the common bipolar magnetic fields arching above the solar photosphere. Studying the final equilibrium of such a common interlaced field line topology, they conclude that thin current sheets form as intrinsic sites for rapid reconnection.

Magnetopause reconnection has been one of the most studied topics of magnetic reconnection since the initial work by Dungey (1961). In Chap. 6, P.A. Cassak and S.A. Fuselier present an updated review on this topic to give fresh answers to the fundamental questions of where reconnection happens at the magnetopause and how efficient it is as a function of the solar wind driving parameters. The chapter is a pedagogical treatment of magnetopause reconnection, although the authors also try

to incorporate results of recent studies including asymmetries, the diamagnetic drift, and flow shear. For this aim, results from theoretical, observational, and numerical simulations are used.

In Chap. 7, A. Petrukovich, A. Artemyev, and R. Nakamura review the topic of magnetotail reconnection, which also has a long history of theoretical, observational, and modeling efforts. The authors discuss the initiation mechanisms for near-Earth tail reconnection concluding that it still represents one of the major unsolved problems in space physics. They review progress in this research topic during the last decade, especially highlighting variants of overcoming the famous tearing stability problem and discussing with recent multipoint spacecraft observations detailed structures of pre-onset and reconnection zones down to the ion Larmor scale. The latter is argued to support the importance of a self-consistent formation of an unstable state through internal magnetotail reconfiguration.

G. Lapenta, R. Wang, and E. Cazzola give in Chap. 8 a review on reconnection separatrices as studied in recent years for both classical regions of magnetospheric reconnection, dayside and tail. The review primarily focuses on numerical simulations but is supplemented with spacecraft observations. The natural importance of the separatrices lies in the fact that they connect the central region of reconnection with the larger-scale external region that also incorporates the boundary conditions. The authors summarize the average properties of particles and fields in the separatrix regions, also dealing with the various types of instabilities and acceleration processes that tend to occur there. They argue that a significant part of energy conversion takes place in the separatrix regions during reconnection.

Since reconnection is expected to take place also at other planetary magnetospheres, Chap. 9 is devoted to reviewing some reconnection properties for the magnetospheres of Jupiter and Saturn and comparing them with those for the Earth's magnetosphere. Thus, in this chapter, R. Walker and X. Jia present a review especially dealing with plasma transport associated with reconnection in the magnetospheres of these planets. Since observations at the outer planets are sparse, the authors use numerical simulations to give an overall view of plasma transport. The authors claim that solar wind dynamic pressure controls reconnection at Saturn, while both dynamic pressure and the IMF are important at Jupiter. They also present evidence about the importance of Kelvin-Helmholtz waves during transport for the magnetosphere of Saturn.

When studying reconnection at the Sun and at other stellar environments, recent results show an important fractal reconnection scenario that seems to explain several apparently unrelated observations. Thus in Chap. 10, K. Shibata and S. Takasao present a review on this topic using theory and observations. The authors associate a fractal current sheet structure as a source for both small-scale reconnection at the Sun, leading to nano-flares, and to large-scale ones, leading to long-duration flares or giant arcades. They mention that often such reconnection events are closely related with multiple plasmoid ejections from a fractal current sheet. They claim that bursty radio and hard X-ray emissions from flares also suggest fractal reconnection and associated particle acceleration. The authors also discuss about recent findings of many superflares on solar-type stars, which seem to extend the applicability of the

fractal reconnection model of solar flares to a much wider parameter space involving stellar flares.

The topic of turbulent reconnection has received especial attention during recent years with applications mainly in astrophysical systems. In Chap. 11, A. Lazarian, G. Kowal, M. Tamamoto, E.M. De Gouvea Dal Pino, and J. Cho, present a review on this topic using theoretical studies and numerical simulations. The authors claim that magnetic reconnection occurs frequently due to the common and ubiquitous presence of turbulence in cosmic plasmas. They even associate the efficiency and rate of reconnection to the level of turbulence present in the plasma during reconnection. The theory presented in this review is also extended to the relativistic domain.

Since reconnection in astrophysical systems frequently involves radiations there has been increasing efforts trying to incorporate radiation in the reconnection dynamics and energetics in such scenarios. Thus, in Chap. 12, D. Uzdensky reviews this subject, presenting an overview of recent theoretical progress and key high-energy astrophysical applications of radiative reconnection to pulsar wind nebulae, pulsar magnetospheres, black hole accretion-disk coronae, and hot accretion flows in X-ray binaries and active galactic nuclei, with important consequences for the study of relativistic jets, magnetospheres of magnetars, and gamma-ray bursts.

Finally, in Chap. 13, W.D. Gonzalez reviews the very recent topic of annihilation of quantum magnetic fluxes (QMFs) which, although observed to occur until now only in laboratory superconducting systems, is argued to also occur at the superconducting outer core of neutron stars with a probable role in the observed variable dynamics of some neutron stars. The author presents a synthesis of some fundamental aspects associated with QMFs, including the Aharonov-Bohm effect for the phase change of electrons passing in the neighborhood of localized magnetic flux tubes, the Ginzburg-Landau phenomenological theory explaining the origin of QMFs, some laboratory observations of QMFs in superconducting systems, the Treumann et al. (2012) quantum mechanical study of the interaction of oppositely directed QMFs, a quantum field theory approach for the study of the energetics of the annihilation of QMFs and of the emitted radiation, and a discussion about the possible scenario of QMF-annihilation at the superconducting cores of some neutron stars.

The editors would like to thank the efforts done by the contributing authors to this book and expect that its content be useful especially to new researchers in the field of magnetic reconnection.

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