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Plasma Turbulence in the Solar System

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Preface

Turbulence represents random motions of flow, and is one of the common experiences in our daily life as can be seen in air and water flow. Whether or not turbulence exists in the extraterrestrial world turns out to be one of the fundamental questions in understanding astrophysical systems. Stellar dynamics, interplanetary and interstellar space, cosmic ray, and accretion disks - these systems are largely maintained by the existence of turbulence, but their dynamical behaviors are substantially different from that of ordinary gas or fluid, since the medium is an ionized gas, called the plasma, and is electrically conducting.

Plasma turbulence is a challenge in physics both in theories and observations, and the aim of this book is to review plasma turbulence on the introductory level and also to review recent developments and knowledge obtained by Cluster, the multi-spacecraft mission. Cluster is a four-spacecraft mission in near-Earth space and has enabled us for the first time to determine spatial structures of space plasma dynamics. Different branches of physics are involved in plasma turbulence: fluid dynamics, electromagnetism and electrodynamics, plasma physics, geophysics, space, and astrophysics. Studying plasma turbulence requires these backgrounds, while progress in plasma turbulence research has mutual impacts on these subjects in return, bringing the different research fields together.

This book is organized in the following fashion. Chapter 1 introduces the concept of plasma turbulence with its historical developments. Chapter 2 is a review of theoretical building blocks for understanding plasma turbulence. Chapter 3 presents the analysis methods for Cluster data. Chapter 4 is a review of plasma turbulence studies using Cluster data in near-Earth space. Chapter 5 presents the impacts of plasma turbulence on the related subjects: plasma turbulence as general physics problem, as astrophysics problem, and as Earth science problem.

Space plasma research has entered a new era with multi-spacecraft missions. It is a pleasure to the author if students and researchers in other fields become interested in physics in the extraterrestrial world, and use this book as a guide to this subject.

The writing of this book was performed under the auspices of Institut für Geophysik und extraterrestrische Physik, Technische Universität Braunschweig as well as Kavli Institute for Theoretical Physics. The author thanks all colleagues in theory and experiment who, through their unselfish collaborations with the author, have substantially contributed to the insights and interpretations found in this book. Among these many individuals I would like to thank Karl-Heinz Glassmeier and David Gross who have been particularly generous, cooperative, and persistent in supporting the author's efforts to understand the subject of the book. The research described here has been supported by Budesministerium fürWirtschaft und Technologie and Deutsches Zentrum für Luft- und Raumfahrt under contract 50 OC 0901, and in part by the National Science Foundation under Grant No. NSF PHY05-51164.

Braunschweig Yasuhito Narita

Contents

Chapter 1
Introduction

Abstract Plasma turbulence in the solar system is an interdisciplinary field of study and also a challenge in physics in theory and observation. This chapter reviews historical developments of the two distinct subjects: turbulence research and space plasma research, and introduces fundamental concepts and notions such as energy cascade in turbulence as well as the plasma physical picture of the solar system.

1.1 What is Plasma Turbulence?

Solar system science is one of interdisciplinary research fields, and has developed together with space technology: rockets, spacecraft, space telescopes, and so on. It is the world where plasma physics plays a major role. The reason for this is the fact that the gas is so hot and dilute that it remains in the plasma state as ionized gas. Plasmas exhibit various kinds of dynamics, and in particular it behaves as a turbulent fluid under some conditions. Plasma turbulence plays an important role not only in many places in the solar system such as at the Sun, in the interplanetary space, and in planetary magnetospheres, but also in many astrophysical systems such as star and planet formation, accretion disks, interstellar medium, and cosmic ray.

Plasma turbulence is the phenomenon that plasma and electromagnetic field fluctuate randomly in appearance. It is one of major challenges in physics both in the theoretical and observational senses. The solar system serves as the only accessible, natural laboratory of astrophysical plasmas as it is a collisionless gas (Sect. 2.1.1.2) and the scale of dynamics cannot be achieved in laboratory experiments on the ground. Studying plasma turbulence in the solar system necessarily involves fundamental physics (plasma physics, fluid dynamics, electromagnetism and electrodynamics), solar system science (the Sun and its interaction with the Earth and planets), and signal processing of spacecraft data. The study has in return impacts on these subjects. Knowledge of plasma turbulence is valuable in understanding the problems of space weather and possibly Earth climate, too.

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Fig. 1.1 Water falling into a pool, sketched by Leonardo da Vinci in ca. 1508–1513

1.2 Historical Development

Turbulence can be found in many kinds of fluids such as air or water flow. Its existence and importance in the extrasolar world such as in the solar system or astrophysical systems have been revealed together with the progress in space plasma research. Plasma turbulence in the solar system exhibits both plasma physical and fluid turbulence characters. Some processes are similar between fluid turbulence and plasma turbulence, while others are different. These two research fields have different backgrounds and their historical developments are reviewed.

1.2.1 View from Turbulence Research

Recognition of turbulence as a physics problem dates back to Leonardo Da Vinci. His sketch in the early sixteenth century (Fig. 1.1) is the first scientific recognition and description of fluid turbulence. It was noticed that turbulence exhibits eddies at different sizes and in different directions. He also noted in the sketch: "Observe the motion of the surface of the water, which resembles that of hair, which has two motions, of which one is caused by the weight of the hair, the other by the direction of the curls; thus the water has eddying motions, one part of which is due to the principal current, the other to random and reverse motion" [4].

Fluid dynamics was then established through contributions by celebrated mathematicians and physicists such as Euler, Navier, Stokes, Taylor, and so on, from seventeenth to twentieth century. Even to date turbulence is recognized as one of the unsolved problems in physics and mathematics. For example, it is not known if the Navier–Stokes equation has a unique solution. Only few special solutions are known in fluid dynamics.

Current understanding of fluid turbulence owes a lot to the picture of energy cascade proposed by Richardson and Kolmogorov. Figure 1.2 is an illustration of this concept. Large-scale eddies are created by an external force (referred to as the energy injection), and energy is put into the flow system. A certain instability process is operating which deforms the large-scale eddies and makes the eddies split into those on a smaller scale. The instability then acts on that small-scale eddies,

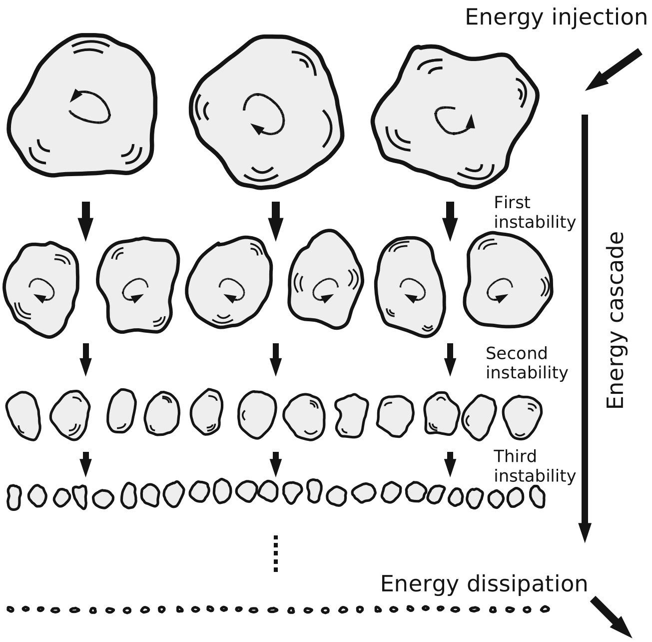

Fig. 1.2 Energy cascade picture according to Richardson and Kolmogorov. Illustration after Frisch, Turbulence (1995), Cambridge University Press [3]

creating eddies at an even smaller size. The instability operates successively and eddies split into ever smaller sizes (energy cascade), until finally the smallest scale is reached and eddies disappear due to the viscosity of the fluid (energy dissipation). Fluid turbulence thus consists of eddies at various sizes.

The concept of chaos needs to be addressed here. The governing equation, the Navier–Stokes equation, is in fact known and it is deterministic. In other words, we know what kind of forces are acting on the fluid elements and it should be possible to calculate the future behavior of the flow using the equation. Nevertheless, predicting the future behavior of the flow is very difficult, and this is due to the presence of nonlinearity. It is the effect that makes the fluid motion so random and irregular that even smallest difference or uncertainty at the initial condition ends up with completely different states. This problem, called the chaos, was recognized even earlier before the development of quantum mechanics which states that particle position and momentum cannot be measured and determined with arbitrary accuracy due to Heisenberg's uncertainty principle, and instead, one can only study the probability of particle position and momentum. It should be noted, however, that in quantum mechanics this probability itself is predictable. In turbulence, in a similar fashion, predicting the state of individual fluid elements is virtually impossible because of nonlinearity. Therefore the emphasis of turbulence studies is on its statistical properties, i.e. we are not studying the exact future state of the flow. This