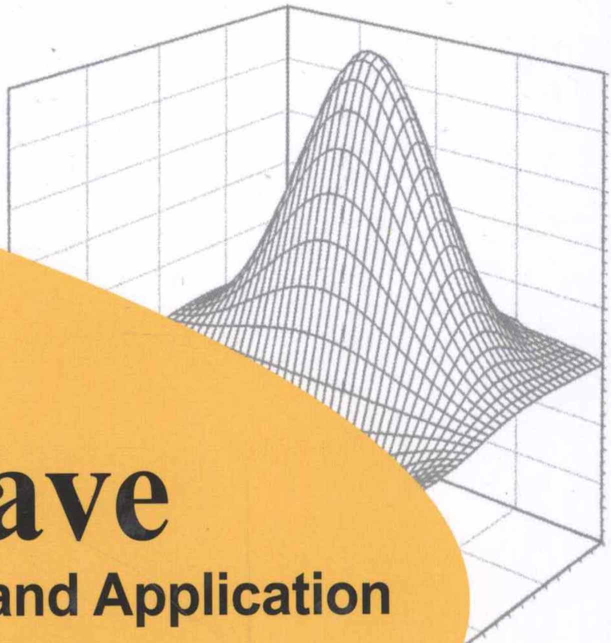
“十二五”国家重点图书出版规划项目



Kinetic Alfvén Wave

Theory, Experiment, and Application

（动力学阿尔文波：理论、实验和应用）

Wu Dejin

SCIENCE PRESS
Beijing

“十二五”国家重点图书出版规划项目

Supported by the National Fund for Academic Publication in Science and Technology

Kinetic Alfvén Wave

Theory, Experiment, and Application

（动力学阿尔文波：理论、实验和应用）

Wu Dejin

SCIENCE PRESS
Beijing

Responsible Editors: Liu Fengjuan Yin Yanfang

Published by Science Press
16 Donghuangchenggen North Street
Beijing 100717, P. R. China

Printed in Beijing

ISBN 978-7-03-036124-0

To my parents

Brief Introduction

Kinetic Alfvén waves (KAWs hereafter) are dispersive Alfvén waves with a short perpendicular wavelength comparable to microscopic kinematic scales of particles, such as the ion (or the ion-acoustic) gyroradius and the electron inertial length, but a parallel wavelength longer than the ion inertial length because of their low frequencies below the ion cyclotron frequency. Due to their strongly anisotropic characteristics in both electromagnetic polarization states and spatial magnetized structures, KAWs can play an important role in the energization of charged particles and the formation of filamentous structures in various magneto-plasma environments from laboratory and space plasmas near the Earth, to the solar wind, the solar atmospheric, and other astrophysical plasmas. Since the 1990s, experimental studies of KAWs from the laboratory as well as the space have dramatically advanced our knowledge of physics of KAWs.

On the basis of recent works related to KAWs by *The Research Group on the Solar and Heliospheric Plasmas* at Purple Mountain Observatory, Chinese Academy of Sciences, this monograph is the first to present a comprehensive understanding of KAWs, including their basic physical characteristics, excitation and generation mechanisms, and one- and two-dimensional nonlinear structures. This timely volume also covers the experimental investigations of KAWs in both laboratory and space plasmas and their applications to the terrestrial auroral electron acceleration, the anomalous energization of minor heavy ions in the extended solar corona, and the inhomogeneous heating of magneto-plasma structures in the solar corona. In addition, some basic concepts and description methods for magneto-plasmas are introduced as an introductory chapter in this text-book, with emphasizing the characteristics of individual particle motion in a magneto-plasma and the relationship between different description methods. We believe that these are very helpful for beginners, especially for the readers who are likely unfamiliar with plasma physics. This book may provide a much-needed introduction and reference for graduate students and researchers from fields of laboratory, space and astrophysical plasmas.

Foreword

Since the publication of the monograph on Alfvén waves by Hasegawa and Uberoi (1982), which was particularly focused on kinetic Alfvén waves (KAWs), a great deal of new theoretical and experimental data on KAWs has been accumulated. These new results point to KAWs' importance for energy release and transport in many laboratory and space plasmas. In particular, KAWs appeared to be a common cornerstone for so distinct phenomena as the turbulence dissipation in the solar wind and the energy release in magnetic reconnection. It is therefore surprising, in view of these discoveries, that no book dedicated to KAWs and related phenomena has appeared in the last twenty years.

One of the main goals of the present book by Dr. Wu is to fill this gap; another objective is to provide an in-depth introduction to the KAW physics.

The book is written in a stand-along manner and contains all necessary preliminary steps starting from first principles. It begins with a general introduction to plasma physics, including kinetic and magnetohydrodynamic (MHD) plasma models. Then, after a short but rigorous description of MHD plasma waves, it is demonstrated how KAWs emerge from the traditional MHD Alfvén waves when their perpendicular wavelengths become sufficiently short. "Perpendicular" here means normal to the background magnetic field, and "sufficiently short" means comparable to kinetic plasma scales, such as the ion gyroradius. The book continues with detailed derivations of conventional KAW properties, and comprehensive descriptions of related applications follow. Many processes and phenomena driven by KAWs as, for example, auroral electron acceleration, are well founded and elaborated in detail. This part will be particularly useful for graduate students and young scientists joining the field of plasmas and plasma waves in space and in laboratory.

But the author does not stop at that point and proceeds further across the less studied or even controversial KAW properties and applications. These constitute the forefront research area where the author himself is one of the most active actors. There is still no consensus on several major issues like, for example, the coronal heating problem where the Parker's nanoflare model and several other mechanisms are strong competitors for the KAW heating mechanisms. Whereas most of the reported results have already been published in scientific journals, these publications are scattered and are not always easily accessible. This material will be interesting for the most advanced researchers working actively in the field. Many of them will find it useful to have all KAW-related topics and models collected in one place.

In the beautiful city of Nanjing, the old southern capital of China, in the famous Purple Mountain Observatory, there is a fast developing and productive research group called "Theory of solar and heliospheric plasmas". I had the opportunity to visit this team in the summer of 2012, when I was invited by the group leader Dr. Wu Dejin. At that time he was finalizing his book on KAWs. These waves are of special interest for the group and became the main subject of our discussions during my visit. It is my greatest pleasure to express my sincere gratitude to Dr. Wu and his team for their warmest hospitality ever, and fruitful exchange of ideas while we were enjoying many cups of Chinese tea. Moreover, I am glad that I am one of the first readers of this book and the author of the foreword.

I am now leaving it for the reader to make their journey through the immense and interesting world of kinetic Alfvén waves.

Good luck!

Yuriy M. Voitenko
Scientist of Space Physics
Belgian Institute for Space Aeronomy
Brussels, September 2012

Preface

Kinetic effects in plasmas are essential properties, in which the individual motion of particles plays an important role. Kinetic Alfvén wave (KAW) is a dispersive Alfvén wave (AW) with a short perpendicular wavelength comparable to microscopic kinematic scales of particles, such as the ion (or ion-acoustic) gyroradius or the electron inertial length, but a parallel wavelength longer than the ion inertial length because of their low frequencies below the ion gyrofrequency. AWs, including shear and compressible AWs (also called magnetosonic waves), are the basic low-frequency wave modes in magneto-plasmas and ubiquitous in various space and astrophysical plasma environments. The most striking property of AWs is that their group velocity propagates exactly along the unperturbed magnetic field lines, regardless of the orientation of the wave front. This implies that AWs can efficiently transport energy among different dynamical regions of plasmas, which are remote apart each other and are electrodynamically coupled by the steady magnetic fields. Therefore, AW can play an important role in the dynamical coupling of magneto-plasmas and has been a subject of intense study since it was found by Hannes Alfvén, a Swedish plasma physicist and the winner of the 1970 Nobel Prize in Physics, in 1942.

About three decades later, KAWs, as a kind of dispersive AWs with a short perpendicular wavelength, were proposed by Chen and Hasegawa in studies on the heating of laboratory and space plasmas in the 1970's. Although KAWs retain some basic properties of AWs, such as the quasi-parallel propagation of the wave group velocity, they have a lot of the novel important characteristics AWs do not possess. These new characteristics can usually be attributed to the so-called kinetic effects due to the short-wavelength modification, in which the individual motion of particles plays an important role. One of them is that a nonzero electric field parallel to the steady magnetic field can rise in KAWs because of their coupling with small-scale electrostatic modes. This makes KAWs capable of field-aligned accelerating or heating electrons. Other one is the smallness of their perpendicular scales, which leads to the motion of ions in the plane perpendicular to the steady magnetic field considerably deviates from the Larmor gyrocircle motion. In consequence, an effective exchange of the cross-field energy also can occur between the waves and ions. In particular, the exchanging efficiency of the cross-field energy sensitively depends on the mass and charge of the ion species.

On the other hand, in a low-β plasma, where β is the ratio of the plasma kinetic pressure to the magnetic pressure, the strong ambient magnetic field inhibits the averaged motion of charged particles across the field lines due to the bound gyrocircle motion, while along the field lines the particles are free to move. Thus, this gyrocircle motion can maintain the plasma with large density and/or temperature gradients across the field lines, while the fast parallel motion quickly smoothes out the gradients along the field lines. In consequence, this strong anisotropy in the motion directly leads to the formation of field-aligned filamentous structures, which are characterized by the field-aligned scale of the inhomogeneity much larger than the cross-field scale. In principle, the smallest cross-field scale of these filamentous structures should be in the order of the ion gyroradius, which is also a typical scale of the perpendicular wavelength of KAWs. This implies that KAWs play an essential and key role in the formation of these filamentous structures.

Because of their anisotropic characteristics in the electromagnetic polarization as well as in the spatial scale and propagation direction, KAWs can play an important role in the particle energization and the formation of fine, filamentous structures, which frequently are encountered in various magneto-plasmas from magnetically controlled plasmas in laboratory to space and astrophysical plasmas. Since the pioneer work of Chen and Hasegawa, KAWs have been attracting the attention of researchers in fields of space and laboratory plasmas. In particular, since the 1990's, the advances in both space- and ground-based plasma experimental techniques have resulted in a series of great progresses in experimental studies of KAWs. This leads to the reevaluation of the importance of KAWs in the dynamics of magneto-plasmas and remotivates the interest of studying KAWs, in particular, studying their roles in various phenomena of particle energization and structure formation in laboratory, space, and astrophysical plasmas. In recent decade, KAWs have been applied extensively in the acceleration of terrestrial auroral electrons, the heating of solar coronal plasmas, the dissipation of solar wind turbulence, the formation of magneto-plasma fine structures, the microscopic physics of magnetic reconnection processes, the zonal flow phenomena in laboratory plasmas, and nonlinear structures in dusty plasmas and other complex plasmas. Without doubt, the KAW is an increasingly and greatly interesting subject.

This book was written with the aim of attempting to provide a unified treatment of the characteristics and applications of KAWs, which is suitable for beginning researchers from different fields of laboratory, space, and astrophysical plasmas. In the literature, the term "KAW" is frequently used with a narrower meaning, that is, the short-wavelength dispersive AW in the kinetic regime with the plasma β parameter $m_e/m_i \ll \beta \ll 1$, where m_e/m_i is the mass ratio of electrons to ions. While in the inertial regime with the parameter $\beta \ll m_e/m_i \ll 1$, other term, the so-called *Iner-*

tial Alfvén Wave (IAW), is used to name the short-wavelength dispersive AW. In this book, the term "KAWs" will be understood to include "IAWs" in the inertial regime as well as KAWs in the kinetic regime.

There is, of course, an enormous volume of work on KAWs in the literature. I, however, have primarily selected topics for this book, in which I have research experience. The plan of the book is as follows. In the first chapter I introduce some basic concepts and description methods of magneto-plasmas, with emphasizing the characteristics of individual particle motion in a magneto-plasma and the relationship between different description methods. This introductory chapter is very helpful for beginners, especially for the readers who are likely unfamiliar with plasma physics. Then, theories of KAWs are presented in Chapters 2 through 5, including the linear theory and basic properties of KAWs (Chapter 2), instabilities and generation mechanisms of KAWs (Chapter 3), one- and two-dimensional solitary structures of KAWs (Chapter 4), and KAWs in complex plasmas (Chapter 5). Chapter 6 reviews the experimental studies of KAWs, including their experimental measurements in the laboratory, satellite *in situ* observational identifications in space plasmas, and remotely sensing evidence from the solar atmosphere. Chapters 7, 8, and 9 focus on the application of KAWs in space and solar plasmas. Based on myself research experience, I have selected three topics related with the application of KAWs, they are the acceleration of the terrestrial auroral energetic electrons (Chapter 7), the anomalous energization of minor heavy ions in the solar extended corona (Chapter 8), and the nonuniform heating of magneto-plasmas in the solar atmosphere, especially in the solar corona (Chapter 9). They are typical kinds of particle energization phenomena in space and solar plasmas. Finally, Chapter 10 looks at some perspectives for further developments, which are growing or gestating new topics relevant to KAWs.

I would like to particularly thank Professor Wang Deyu at Purple Mountain Observatory, Chinese Academy of Sciences, Professor Carl-Gunne Fälthammar at Alfvén Laboratory, Royal Institute of Technology, Sweden, and Professor Huang Guangli at Purple Mountain Observatory, Chinese Academy of Sciences, who are my initial research collaborators on the nonlinear theory of KAWs at the beginning of my career. I would also like to thank my recent collaborators on the application of KAWs in space and solar plasmas, Professor Fang Cheng at Department of Astronomy, Nanjing University, Professor Jih-Kwin Chao at Institute of Space Science, National Central University, and Doctors Yang Lei, Chen Ling, and Zhao Jinsong at Purple Mountain Observatory, Chinese Academy of Sciences. The major of my works encompassed in this book should be owed to their contributions in the collaboration. I am grateful to Professor Wang Shui at School of Earth and Space Sciences, University of Science and Technology of China and Professor Wei Fengsi at Center for Space Science and Applied Research, Chinese Academy of Sciences for their encouragement to my writing this book. A special thank is attributed to Doctor Chen Ling, one of my collaborators. She carefully and patiently checked the first draft of this book, including the spelling and grammar in English language, the reevaluation of mathematic equations, and the reproduction of figures, and the rearrangement of references. Also special thank is due to Miss Liu Fengjuan, the editor at Science Press, for her endeavor to publish this book. Finally, I thank Chinese Academy of Sciences, National Natural Science Foundation of China, and Ministry of Science and Technology of China, because our works encompassed in this book had been supported by grants from these organizations.

Wu Dejin
Purple Mountain Observatory, Chinese Academy of Sciences
Nanjing, China, 2012

Contents

Chapter 1

Descriptions of Magneto-Plasmas

1.1 Introduction

A plasma is an ionized gas that consists of a large number of charged particles, positively charged ions and negatively charged electrons. The complexity of plasma descriptions lies in the fact that the dynamics of phenomena or processes occurring in a plasma strongly, sensitively depends on their temporal and spatial scales. Therefore, in plasma physics many different methods have been developed to describe plasma phenomena occurring in different scales. They usually can be classed as three kinds: kinetic, two-fluid, and MHD (*MagnetoHydroDynamics*) descriptions. In the kinetic description, the plasma is treated plumply as a collective of a large number of charged particles, and hence to be the most accurate but the most complicated mathematically. In the two-fluid description, the plasma is dealt with as electromagnetically coupling two fluids, that is, the electron-fluid and the ion-fluid. In the MHD description, the plasma is treated simply as a single conducting fluid, which is the least accurate, but with the simplest mathematics.

More than 99% of all observable matter in the universe is in the plasma state. *Alfvén Wave* (AW) is one of the three basic low-frequency and long-wavelength wave modes in the plasma MHD description, which is ubiquitous in cosmic plasmas and can be encountered in a wide variety of space physics and astrophysics, including the magnetosphere-ionosphere coupling, the solar coronal heating and the solar wind acceleration, accretion disk physics of dense objects, and the interstellar and intercluster medium physics (Hasegawa & Uberoi, 1982; Cross, 1988; Jatenco-Pereira, 1995; Cramer, 2001). Now it has been extensively recognized that the AW can play important roles in electrodynamical coupling phenomena of various magneto-plasmas. In fact, in the history of plasma physics, it is the discovery of AWs by H. Alfvén in 1942 (Alfvén, 1942) that leads to the establishment of the MHD theory.

Kinetic Alfvén Wave (KAW) is one kind of dispersive AWs. The term "KAW" originates from kinetic properties of the dispersive AWs with a short perpendicular wavelength. When the perpendicular wavelength of AWs becomes comparable to the ion gyroradius, ions can no longer follow the magnetic field lines, whereas electrons