A Collected Works on the Solar-Terrestrial Space Physics

空间物理中的若干前沿科学问题

Edited by

Lu Quanming
Wang Chi

University of Science and
Technology of China Press

当代科学技术基础理论与前沿问题研究丛书

中国科学技术大学
校友文库

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总　序

侯建国

（中国科学技术大学校长、中国科学院院士、第三世界科学院院士）

大学最重要的功能是向社会输送人才。大学对于一个国家、民族乃至世界的重要性和贡献度，很大程度上是通过毕业生在社会各领域所取得的成就来体现的。

中国科学技术大学建校只有短短的50年，之所以迅速成为享有较高国际声誉的著名大学之一，主要就是因为她培养出了一大批德才兼备的优秀毕业生。他们志向高远、基础扎实、综合素质高、创新能力强，在国内外科技、经济、教育等领域做出了杰出的贡献，为中国科大赢得了“科技英才的摇篮”的美誉。

2008年9月，胡锦涛总书记为中国科大建校五十周年发来贺信，信中称赞说：半个世纪以来，中国科学技术大学依托中国科学院，按照全院办校、所系结合的方针，弘扬红专并进、理实交融的校风，努力推进教学和科研工作的改革创新，为党和国家培养了一大批科技人才，取得了一系列具有世界先进水平的原创性科技成果，为推动我国科教事业发展和社会主义现代化建设做出了重要贡献。

据统计，中国科大迄今已毕业的5万人中，已有42人当选中国科学院和中国工程院院士，是同期（自1963年以来）毕业生中当选院士数最多的高校之一。其中，本科毕业生中平均每1000人就产生1名院士和700多名硕士、博士，比例位居全国高校之首。还有众多的中青年才俊成为我国科技、企业、教育等领域的领军人物和骨干。在历年评选的“中国青年五四奖章”获得者中，作为科技界、科技创新型企业界青年才俊代表，科大毕业生已连续多年榜上有名，获奖总人数位居全国高校前列。鲜为人知的是，有数千名优秀毕业生踏上国防战线，为科技强军做出了重要贡献，涌现出20多名科技将军和一大批国防科技中坚。

为反映中国科大五十年来人才培养成果、展示毕业生在科学研究中的最新进展，学校决定在建校五十周年之际，编辑出版《中国科学技术大学校友文

库》,于2008年9月起陆续出书,校庆年内集中出版50种。该《文库》选题经过多轮严格的评审和论证,入选书稿学术水平高,已列为国家"十一五"重点图书出版规划。

入选作者中,有北京初创时期的毕业生,也有意气风发的少年班毕业生;有"两院"院士,也有 IEEE Fellow;有海内外科研院所、大专院校的教授,也有金融、IT行业的英才;有默默奉献、矢志报国的科技将军,也有在国际前沿奋力拼搏的科研将才;有"文革"后留美学者中第一位担任美国大学系主任的青年教授,也有首批获得新中国博士学位的中年学者……在母校五十周年华诞之际,他们通过著书立说的独特方式,向母校献礼,其深情厚意,令人感佩!

近年来,学校组织了一系列关于中国科大办学成就、经验、理念和优良传统的总结与讨论。通过总结与讨论,我们更清醒地认识到,中国科大这所新中国亲手创办的新型理工科大学所肩负的历史使命和责任。我想,中国科大的创办与发展,首要的目标就是围绕国家战略需求,培养造就世界一流科学家和科技领军人才。五十年来,我们一直遵循这一目标定位,有效地探索了科教紧密结合、培养创新人才的成功之路,取得了令人瞩目的成就,也受到社会各界的广泛赞誉。

成绩属于过去,辉煌须待开创。在未来的发展中,我们依然要牢牢把握"育人是大学第一要务"的宗旨,在坚守优良传统的基础上,不断改革创新,提高教育教学质量,早日实现胡锦涛总书记对中国科大的期待:瞄准世界科技前沿,服务国家发展战略,创造性地做好教学和科研工作,努力办成世界一流的研究型大学,培养造就更多更好的创新人才,为夺取全面建设小康社会新胜利、开创中国特色社会主义事业新局面贡献更大力量。

是为序。

2008年9月

Preface

The Sun is the ultimate source of almost all energy on Earth. Besides sending warmth and light to Earth, it also has different kinds of influences on the Earth and the geospace through its magnetic fields, particles, plasma and electromagnetic emissions. Since the launch of the first artificial satellite in 1957, we have entered the space age. Space-borne and ground based observations contribute greatly to our understanding and predicting the effects of solar activity on the Earth and in space. In addition to theoretically understanding the flow of energy from the Sun through interplanetary space, the Earth's magnetotail, magnetosphere and ionosphere, there are important practical implications for satellites' and astronauts' safety, ground electrical power systems, navigation and communication system. This volume covers the broad scope of phenomena related to space physics, from the solar activities, interplanetary disturbances, magnetospheric effects, ionospheric and thermospheric consequences. The purpose is to promote our current understanding of the chain of processes that occur between the Sun and Earth.

The present volume consists of two parts: the first part is concerned with the solar and heliospheric physics, and the second, the magnetospheric physics. An introduction is presented ahead of each part to give a summary of all papers included, followed by these papers. We acknowledge that this classification may not be appropriate for some papers, since the study of solar terrestrial system involves a variety of aspects. Besides, we have intentionally mixed theoretical and observational studies.

Papers included in this volume are derived from peer-reviewed publications of which the first authors are the USTC (University of Science and Technology of China) graduates. These authors are Jinbin Cao(814), Yao Chen(937), Youqiu Hu(597), Xinlin Li(774), Xing Li(824), Wei Liu(937), Quanming Lu(907B), Yingjuan Ma (937), Chi Wang(857), Yuming Wang(957), Chuanbing Wang(937B), Fengsi Wei (587), Lidong Xia(857), Fuliang Xiao(817), Yan Xu(937), Xianghui Xue(987), Guocheng Zhou(587), and Lie Zhu(777).

We dedicate this volume to the memory of the 50th Anniversary of USTC.

Fengsi Wei
Center for Space Science and Applied Research, Chinese Academy of Sciences

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Part One Solar and Heliospheric Physics

Introduction

[1] The solar corona is the extended outer atmosphere of the Sun. It has a temperature of millions of degrees, but it is 10 billion times less dense than the atmosphere of the Earth at sea level. Due to its high temperature, the solar corona expands away from the Sun, forming the solar wind. Starting with the beginning of the space age around 1950, solar and heliospheric dedicated spacecrafts have been launched that permitted us to conduct quantitative physics modeling of solar and heliospheric phenomena, supported by numerical simulations using the theories of magneto-hydrodynamics (MHD) and plasma particle physics. This introduction focuses on the recent work done by the USTC graduates, which covers the subjects of the modeling of the solar wind, coronal heating processes, solar activities and space weather effects etc.

[2] Using a one-dimensional two-fluid model with anisotropic proton temperature, *Hu et al*. [1997] presented high-speed solar solutions which meet most of the empirical constraints currently available from in situ measurements in interplanetary space and very recent remote sensing observations of the inner corona. Included in the model is the momentum exerted on the flow by Alfvén waves, as well as heating due to their damping. Furthermore, *Hu et al*. [1999] conducted a numerical study which explores the nonlinear cascade effect associated with Alfvén waves in the fast solar wind. The set of one-dimensional, two-fluid equations describing the solar wind and a power spectrum equation for Alfvén waves, as first proposed by *Tu et al*. [1984], are solved simultaneously in a self-consistent manner. The numerical results confirm conclusions reached by earlier studies, namely, that the Kolmogorov process produces a stronger cascade effect than the Kraichnan process and seems more relevant for Alfvén waves in the fast solar wind, at least beyond 0.29 AU. The approach shows that Alfvén waves, with periods of hours or shorter, undergo an appreciable evolution from the solar surface to 1 AU, thus implying that their spectrum; hence their total energy flux at the Sun cannot be readily predicted form that observed in interplanetary space.

[3] There are lots of physical processes presented in the solar corona. As for the coronal heating processes, it became customary to classify coronal heating models into DC (Direct Current) and AC (Alternating Currenting) types. Plasma heating by ion cyclotron waves in rapidly expanding flow tubes in the transition region, referred to as coronal funnels, is investigated in a three-fluid plasma consisting of protons, electrons, and alpha particles [*Li*, 2002]. Ion cyclotron waves are able to heat the plasma from 6×10^4 to 10^6 K over a distance range of 10^4 km by directly heating alpha particles.

Although only alpha particles dissipate the waves, the strong Coulomb coupling between alpha particles and protons and between protons and electrons makes it possible for protons and electrons to be heated also to more than 10^6K. By assuming that magnetic flux tubes are strongly concentrated at the boundaries of supergranule convection cells and a power law spectrum of high frequency Alfvén waves with a spectral index -1 originating from the sun to supply all the energy needed to energize the plasma flowing in such magnetic flux tubes, *Li* [2003] found that at the high frequency end, the waves are eroded by ions due to ion cyclotron resonance. The magnetic flux concentration is essential since it allows a sufficiently strong energy flux to be carried by high frequency ion cyclotron waves and these waves can be readily released at the coronal base by cyclotron resonance. Two scenarios of possible ion heating due to finite amplitude parallel propagating Alfvén waves in the solar atmosphere are investigated using a 1D test particle approach [*Li et al.*, 2007]. It is generally believed that linear wave-particle resonant interaction between thermal protons and Alfvén waves is ineffective when the proton beta is low. However, *Wang et al*. [2006] demonstrated that the ions can be heated by Alfvén waves via nonresonant nonlinear interaction. Contrary to the customary expectation, it is found that the lower the plasma beta value, the more effective is the heating process, and the ion temperature increase is more prominent along perpendicular direction.

[4] To investigate the possibility of differential flow speeds between ions of the same element and their roles in the determination of ionic fractions, *Chen et al*. [2003] extended the latest minor-ion model to a five-fluid model, describing the behavior of five species of minor ions of one given element in the fast solar wind. The five species of minor ions are taken as test particles flowing in a background plasma consisting of electrons, protons, and alpha particles. It is found that the majority of C and O ions are frozen-in below 1.2 solar radii, while most Si, Mg, and Fe ions are frozen-in beyond 1.3 - 1.5 solar radii. Comparing the cases with and without differential flows shows that even though differential flow speeds between ions of the same element do develop beyond a certain heliocentric distance (e.g., 1.2 solar radii for Si ions), they cannot account for the high ion charge states observed in situ. Using recent coordinated UVCS and LASCO measurements by Strachan and coworkers to constrain the heating parameters of a one-dimensional single-fluid minor ion model, *Chen et al*. [2004] showed that in this slow-wind source region the O^{+5} outflow speed varies nonmonotonically with increasing heliocentric distance. There is a local minimum of the outflow speed near the streamer cusp point (about 3 Solar Radii), which is below the current observational sensitivity, and that the observed effective temperature in the perpendicular direction (to the magnetic field) and the outflow speed of the O^{+5} ions can be used to put limits on their parallel thermal temperature.

[5] By directly comparing Doppler shift maps of Ne^{7+} with charts of the photospheric magnetic field in an equatorial coronal hole, *Xia et al*. [2003] reported new observations concerning the source of the fast solar wind. There are both dark and bright regions in this coronal hole as seen in the Ne VIII line. The larger blue shifts of the Ne VIII line are associated mainly with the darker region, where the strong magnetic flux with a single polarity is concentrated. These observational results are in agreement with the model prediction that the fast solar wind is initially accelerated in the coronal funnels, which are regions with globally open coronal fields rooted in the magnetic network. *Xia et al*. [2005] also studied the dynamic properties of EUV spicules seen at the solar limb. They found that spicules occur repeatedly at the same location with a birth rate of around 0.16/min as estimated at 10″ above the limb and a lifetime ranging from 15 down to ≈3 min, and be able to see some spicules showing a process of "falling after rising" indicated by the sudden change of the Doppler velocity sign.

[6] The Sun is the prime source of energy in our system and it is the prime source of space weather. *Liu et al*. [2006] presented analyses of the spatial and spectral evolution of hard X-ray emission observed by RHESSI during the impulsive phase of an M1.7 flare on 2003 November 13. In general, as expected, the loop top (LT) source dominates at low energies, while the footpoint (FP) sources dominate the high-energy emission. At intermediate energies, both the LT and FPs may be seen. *Xu et al*. [2008] presented the results of a new approach to studying the acceleration and propagation of bremsstrahlung-producing electrons in solar flares, and found that hard X-ray images from 10 M-class limb events have the general form of a single extended source. The propagation and evolution of interstellar disturbance including ICMEs and shocks has also important impact on the space weather. Using a 2.5-dimensional, time-dependent ideal magnetohydrodynamic model in spherical coordinates, *Hu et al*. [2003] presented a numerical study of the property of magnetostatic equilibria associated with a coronal magnetic flux rope embedded in an axisymmetrical background magnetic field. It is shown that the flux rope either sticks to the solar surface so that the whole magnetic configuration stays in equilibrium or escapes from the top of the computational domain, leading to the opening of the background field. The rope sticks to the solar surface when the magnetic energy of the system is less than a certain threshold, and it escapes otherwise. It implies that a catastrophe occurs when the magnetic energy of the system exceeds the threshold.

[7] Magnetic clouds (MCs), as important interplanetary structures, have been widely investigated. The basic characteristics of the coronal mass output near the Sun are analyzed with the statistic and numerical methods by using observational data from K corona brightness, interplanetary scintillation, and photospheric magnetic field during the

descending phases (1983) and the minimum (1984) of solar activity [*Wei et al.*, 2003]. Based on a statistical analysis of the boundary physical states of 80 magnetic clouds reported in the literature from the years 1969 to 2001, *Wei et al.* [2003] suggested a new identification of the magnetic cloud boundary by describing it as front and tail boundary layers (BLs) formed through the interaction between the magnetic cloud and the ambient medium. By analyzing the observational data of 70 magnetic cloud boundary layers (BLs) from the three-dimensional (3-D) plasma and energetic particle (3DP) and 50 BLs from the Solar Wind Experiment (SWE) instruments on Wind spacecraft from February 1995 to June 2003, *Wei et al.* [2006] discovered that the boundary layer of a magnetic cloud is a new non-pressure-balanced structure different from the jump layer (i.e., shocked front) of an interplanetary shock wave. By analyzing 23 magnetic cloud boundary layers (BLs) in Feb. 1995 - Oct. 1998, *Wei et al.* [2003] found that the distribution function of fluctuations in the southward field component inside the boundary layer, is very different from in the background solar wind and inside the cloud, with the enhancement in the fluctuation amplitude and the variation of the magnitude and direction of the average field, and in the maximum variance plane (MVP) composed of the maximum and medium variance directions, the walk of the tips of the magnetic field vectors in the BL could be classified into two types based on: (a) field vectors vibrate along a circle arc, which is possibly related with Alfvén fluctuations inside the BL; (b) field vectors walk randomly in the MVP, which could be correlated with the turbulence inside the BL. These results suggest that the cloud's BL owns the magnetic structure different from that in the solar wind and cloud body, which is a manifestation for the interaction of the magnetic cloud (MC) with the solar wind (SW). *Wang et al.* [2002] used a simple flux rope model to get the primary magnetic field features of multi-MCs. Their results indicate that the magnetic field configuration of multi-MCs mainly depends on the magnetic field characteristics of each member of multi-MCs. It may be entirely different in another situation. Using the data from the ACE spacecraft, *Wang et al.* [2003] identified three cases of Multi-MC in the period from March to April 2001.

[8] In order to recover the magnetic structures of small-scale flux ropes in the solar wind, *Hu and Sonnerup* [2001] applied the Grad-Shafranov technique in the Wind spacecraft data. The cross-sections of two recovered flux ropes show nested non-circular loops of transverse field lines rather than concentric circles. The expected helical structure is recovered, albeit with significant distortions from axial symmetry.

[9] Solar wind structures which are the interplanetary counterparts of CMEs at the Sun are now generally referred to as interplanetary coronal mass ejections (ICMEs). These ICMEs often trigger geomagnetic storms, affecting the whole solar system. By using multiple spacecraft data throughout the heliosphere, *Wang et al.* [2005] identified and characterized ICMEs from 0.3 to 5.4 AU. The occurrence rate of ICME

approximately follows the solar activity cycle. ICMEs expand as they move outward since the internal pressure is generally larger than the external pressure. The average radial width of ICMEs increases with distance. ICMEs expand by a factor of 2.7 in radial width between 1 and 5 AU. The radial expansion speed of ICMEs decreases with distance and is of the order of the Alfvén speed. The density and magnetic field magnitude decrease faster in ICMEs, which fall off with distance R, than in the ambient solar wind; however, the temperature decreases slightly less rapid than in the ambient solar wind. Using Voyager observations and a multi-fluid solar wind MHD model, *Wang and Richardson* [2002] showed that the solar wind stream structures associated with the April, 2001 solar events observed at Earth have merged in the distant heliosphere into the single strong interplanetary shock that was subsequently detected by Voyager 2 in October 2001. Their demonstration that large shocks can and do form from this merging mechanism may have significances for the formation of merged interaction regions and the triggering of the heliospheric radio emission.

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A fast solar wind model with anisotropic proton temperature

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[1] We explore the energy requirements for the fast solar wind when the anisotropy in the proton temperature is taken into account. Using a one-dimensional, two-fluid model with anisotropic proton temperature, we present high-speed solar wind solutions which meet most of the empirical constraints currently available from in situ measurements in interplanetary space and very recent remote sensing observations of the inner corona. Included in the model is the momentum exerted on the flow by Alfvén waves, as well as heating due to their damping. However, to produce solutions consistent with these empirical constraints, additional heat input to both electrons and protons, as well as momentum addition to the protons, are found to be needed. These are described by ad hoc functions with adjustable parameters. While classical thermal conduction is adopted for both electrons and protons in the inner corona in the model computations, the corresponding heat fluxes in the outer corona are limited to values comparable to current observations. The fast solar wind solutions thus obtained differ from each other mainly in their thermal properties within 0.3 AU from the Sun, a region that is still poorly probed by in situ and remote sensing measurements. To satisfy observational constraints, we find that the inclusion of a proton temperature anisotropy in the modeling of the solar wind requires that either the protons be highly anisotropic in the inner corona or that there exist a mechanism, in addition to adiabatic expansion, to cool them in the direction parallel to the magnetic field. Given these observational constraints and in the absence of knowledge of an efficient cooling mechanism, our model computations imply that the maximum temperature of the protons in the parallel direction has to be limited to 10^6 K in the corona. Furthermore, because of the strong coupling between electrons and protons, and between the parallel and perpendicular motions, at the coronal base, the electron temperature as well as the perpendicular proton temperature cannot be much higher than 10^6 K there. Although thermal anisotropy of the protons is found to have little influence on the dynamics of the fast solar wind, its inclusion imposes new requirements on the unknown coronal heating mechanisms.

1. Introduction

[2] Recent observations of the Lyman α spectral line profiles and intensities in the

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inner corona [*Kohl et al.*, 1996; *Strachan et al.*, 1997] strongly suggest that the anisotropy in the proton temperature in the fast solar wind, reported much earlier by interplanetary measurements (see, e.g., review by *Marsch* [1991]), originates in the inner corona. These recent observations thus place new constraints on solar wind models in addition to existing limits on the species temperature, flow speed, and density, established from in situ measurements beyond 0.3 AU [e.g., *Feldman et al.*, 1976; *Phillips et al.*, 1995], and from remote sensing observations in the inner corona [*Fisher and Guhathakurta*, 1995; *Grall et al.*, 1996; *Kohl et al.*, 1996; *Strachan et al.*, 1997].

[3] Model computations involving the treatment of the solar wind as a single fluid or multifluid have been instrumental in providing an understanding of the mechanisms of energy storage and transfer in the solar wind plasma, as described so elegantly in *Parker*'s [1963] original work. In the absence of knowledge of these mechanisms, Alfvén waves have been commonly invoked [e.g., *Hollweg and Johnson*, 1988]. Ad hoc parameterizations of heating and momentum addition functions [e.g., *Hartle and Sturrock*, 1968; *Metzler et al.*, 1979; *Withbroe*, 1988; *Habbal et al.*, 1995; *Hansteen and Leer*, 1995; *McKenzie et al.*, 1995, *Esser et al.*, 1997] have been instrumental in yielding a thorough understanding of the behavior of the solar wind [e.g., *Holzer and Leer*, 1980; *Leer and Holzer*, 1980]. Despite the extent of the parameter space explored and the increased sophistication, in time, of these approaches, solar wind models still fall short in providing self-consistent solutions that can match empirical constraints established from both in situ and remote sensing measurements.

[4] The aim of this study is to take into account the additional constraint of proton temperature anisotropy in the modeling of the fast solar wind, in light of the more recent observations in the inner corona. Attempts to consider this anisotropy were first made by *Leer and Axford* [1972], followed more recently by *Sandbaek and Leer* [1994]. These studies concentrated primarily on the proton temperature anisotropy observed at 1 AU, without necessarily fitting other observational constraints. In their model, *Leer and Axford* [1972] established the electron temperature a priori, using the conduction dominated assumption, introduced an ad hoc heating function for the protons, but neglected their thermal conductivity. Their results were typical of the slow solar wind. *Sandbaek and Leer* [1994], on the other hand, focused on the role of Alfvén waves in producing the observed proton temperature anisotropy. These authors included the effects of proton thermal conduction parallel and perpendicular to the magnetic field. Additional momentum resulted from the presence of Alfvén waves, while heating was provided by the damping of these waves beyond $7R_S$. Their parameter study yielded a range of measurables at 1 AU that was also typical of slow solar wind conditions.