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Advance of Interplanetary Physics Study in China: 2008–2010

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Abstract Interplanetary physics study is an important ingredient in space weather research. Considerable progress this aspect has been achieved by the space physics community of China in recent years. This brief report summarizes the latest advances of the interplanetary physics research in China during the period of 2008–2010. This report includes solar corona and solar wind, interplanetary transients, energetic particles, MHD simulation, space plasma, and prediction methods for physical phenomena originating from both solar corona and interplanetary space.

Keywords Solar wind, Coronal mass ejection, Energetic particles, Interplanetary transients

1 Solar Corona and Solar Wind

The origin of the solar wind is a long-standing issue in both observational and theoretical studies. To understand how and where in the solar atmosphere the mass and energy of the solar wind are supplied is very important. Previous observation suggests a scenario in which the fast solar wind originates at heights above 5 Mm in the magnetically open funnel, a process that is accompanied by downward flow below 5 Mm, whereby the mass and energy are supplied through reconnection between the open funnel and adjacent closed loops. Based on this scenario, He, Tu and Marsch[1] developed a fluid model to study the solar wind generation under the assumption that mass and energy are deposited in the open funnel at 5 Mm. The mass supply rate is estimated from the mass loss rate as given by emptying of the side loops as a result of their assumed reconnection with the open funnel. Similarly, the energy input rate is consistent with the energy release rate as estimated from the energy flux associated with the reconnection between the open magnetic funnel and the closed magnetic loops. Following the observations, they not only simulated the plasma flowing upward to form the solar wind but also calculated the downward flow back to the lower atmosphere. This model is a first attempt to study physically the proposed scenario of solar wind origin and gives a new physical illustration of the possible initial deposition and consequent transportation of mass and energy in the coronal funnel.

The radiance and Doppler-shift distributions across the solar network provide observational constraints of two-dimensional modeling of transition-region emission and flows in coronal funnels. These distributions have not, however, been studied in detail. Tian *et al.*[2] attempted an investigation for a quiet Sun region. Two different methods, dispersion plots and average-profile studies, were applied by them to investigate these distributions for three EUV lines. In the dispersion plots, they divided the entire quiet Sun region scanned by SUMER into a

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bright and a dark part according to an image of Fe XII taken by EIT during the scanning; they plotted intensities and Doppler shifts in each bin as determined according to a filtered intensity of Si II. They also studied the difference in height variations of the magnetic field as extrapolated from the MDI magnetogram, in and outside network, in the two parts. For the average-profile study, they selected 74 individual cases and derived the average profiles of intensities and Doppler shifts across the network. Cases with large values of blue shift of Ne VIII were further studied. The dispersion plots reveal that the intensities of Si II and C IV increase from network boundary to network center in both the bright and dark parts. However, the intensity of Ne VIII shows different trends, namely increasing in the bright part and decreasing in the dark part. In both parts, the Doppler shift of C IV increases steadily from internetwork to network center. The height variations in the magnetic field imply a more homogeneous magnetic structure at greater heights and clearly reflect the different magnetic structures in the two regions. The average-profile study reveals that the intensities of the three lines all decline from the network center to internetwork region. The binned intensities of Si II and Ne VIII have a good correlation. They also found that the large blue shift of Ne VIII does not coincide with large red shift of C IV. Their results suggest that the network structure is still prominent at the layer where Ne VIII is formed in the quiet Sun, and that the magnetic structures expand more strongly in the dark part than in the bright part of this quiet Sun region. The results might also hint for a scenario of magnetic reconnection between open funnels and side loops.

Song, Feng and Shen[3] investigated the magnetic evolution of a flare/CME source region to determine the trigger of the flare and the EUV brightening event. Also, they discussed the role of the current helicity (h_c) in solar activity. They used the long duration sequences of SOHO/MDI magnetograms and TRACE 195 Å images for a super Active Region (AR), NOAA AR 8375. Magnetic field changes in the photosphere and the corona are investigated. In AR 8375, the southwestern and northwestern parts of an overlying loop ($h_c < 0$) are influenced by the rising magnetic arcades ($h_c > 0$) and the emerging flux region ($h_c > 0$). Two collisions make the overlying loop inflate in a bounce interaction. However, the related solar events are triggered by a merge interaction which takes place among the fibers of the rising magnetic arcades and among those of the overlying loop.

Tian *et al.*[4] studied the height variations of the sizes of chromospheric and transition-region features in a small coronal hole and the adjacent quiet Sun, considering images of the intensity, Doppler shift, and non-thermal motion of ultraviolet emission lines as measured by SUMER, together with the magnetic field as obtained by extrapolation from photospheric magnetograms. In order to estimate the characteristic sizes of the different features present in the chromosphere and transition region, they calculated the autocorrelation function for the images as well as the corresponding extrapolated magnetic field at different heights. The Half Width at Half Maximum (HWHM) of the autocorrelation function is considered to be the characteristic size of the feature shown in the corresponding image. Their results indicate that, in both the coronal hole and quiet Sun, the HWHM of the intensity image is larger than that of the images of Doppler-shift and non-thermal width at any given altitude. The HWHM of the intensity image is smaller in the chromosphere than in the transition region, where the sizes of intensity features of lines at different temperatures are almost the same. But in the upper part of the transition region, the intensity size increases more strongly with temperature in the coronal hole than in the quiet Sun. They also studied the height variations of the HWHM of the magnetic field magnitude B and its component B_z, and found they are equal to each other at a certain height below 40 Mm in the coronal hole. The height variations of the HWHM of B_z/B seem to be consistent with the temperature variations of the intensity size. Their results suggest that coronal loops are much lower, and magnetic structures expand through the upper transition region and lower corona much more strongly with height in the coronal hole than in the quiet Sun.

Wang and Zhang[5] presented statistical results on the properties of the solar source regions that produced the 57 fastest ($\geqslant 1500\,\mathrm{km/s}$) front-side Coronal Mass Ejections (CMEs) from 1996 June to 2007 January. The properties of these fast-CME-producing regions, 35 in total, were compared with those of all 1143 Active Regions (ARs) in the period studied. An automated method, based on SOHO MDI magnetic synoptic charts, was used to select and characterize the ARs. For each, a set of parameters was derived that includes the areas (positive, negative, and total, denoted with A_p, A_n, and A_t, respectively), the magnetic fluxes (positive, negative, and total, F_p, F_n, and F_t), the average magnetic field strength (B_avg), a quasi elongation (e) characterizing the overall shape of the AR, the number and length of Polarity Inversion Lines (PILs, or neutral lines, N_PIL and L_PIL, respectively), and the average and maximum magnetic gradient on the PILs ($G_\mathrm{op,avg}$ and $G_\mathrm{op,max}$). Their statistical analysis shows a general trend between the scales of an AR and the likelihood of its producing a fast CME; that is, the larger the geometric size (A_t), the larger the magnetic flux (F_t), the stronger the magnetic field (B_avg), and the more complex the magnetic configuration (N_PIL and L_PIL), the greater the possibility of producing a fast CME. When all the ARs were sorted into three evenly sized groups with low, intermediate, and high values of these parameters, they found that for all the parameters, more than 60% of extremely fast CMEs are from the high-value group. The two PIL parameters are the best indicators of fast-CME production, with more than 80% coming from the high-value group.

The physical implication of large blue shift of Ne Ⅷ in the quiet Sun region was investigated by Tian *et al.*[6]. They compared the significant Ne Ⅷ blue shifts, which are visible as large blue patches on the Doppler-shift map of a middle-latitude quiet-Sun region observed by SUMER, with the coronal magnetic-field structures as reconstructed from a simultaneous photospheric magnetogram by means of a force-free-field extrapolation. They showed for the first time that coronal funnels also exist in the quiet Sun. The region studied contains several small funnels that originate from network lanes, expand with height and finally merge into a single wide open-field region. However, the large blue shifts of the Ne Ⅷ line are not generally associated with funnels. A comparison between the projections of coronal loops onto the solar xy-plane and the Ne Ⅷ dopplergram indicates that there are some loops that reveal large Ne Ⅷ blue shifts in both legs, and some loops with upflow in one and downflow in the other leg. Their results suggest that strong plasma outflow, which can be traced by large Ne Ⅷ blue shift, is not necessarily associated with the solar wind originating in coronal funnels but appears to be a signature of mass supply to coronal loops. Under the assumption that the measured Doppler shift of the Ne Ⅷ line represents the real outflow velocity of the neon ions being markers of the proton flow, they estimated the mass supply rate to coronal loops to be about $10^{34}\,\mathrm{s}^{-1}$.

The kink wave, which has often been observed in coronal loops, is considered as a possibly important energy source contributing to coronal heating. However, its generation has not yet been observed. He *et al.*[7] reported the first observation of kink-wave excitation caused by magnetic reconnection as inferred from Solar Optical Telescope measurements made in the Ca Ⅱ line. They observed transverse-displacement oscillations on a spicule which propagated upwardly along the spicule trace and originated from the cusp of an inverted Y-shaped structure, where apparently magnetic reconnection occurred. Such transverse oscillation of an individual spicule was interpreted by them to be the signature of a kink wave that is excited by magnetic reconnection. They presented the height variations of the velocity amplitude, δv, and the phase speed, C_k, of the kink wave, starting from its source region. The kink wave is found to steepen with height and to evolve into a nonlinear state with a large relative disturbance, yielding a ($\delta v/C_k$) of 0.21 at 5.5 Mm. This nonlinear kink wave seems to be damped in velocity amplitude beyond 5.5 Mm, which may result from the conversion of transverse-fluctuation energy to longitudinal-motion energy required to sustain the spicule. They also estimated the energy flux density carried by the kink wave, and in spite of its attenuation in the transition region concluded it to be sufficient for heating the quiet corona. Their findings shed new light on future modeling of coronal heating and solar wind acceleration involving magnetic reconnection in the chromosphere.

Plasma blobs are observed to be weak density enhancements as radially stretched structures emerging from the cusps of quiescent coronal streamers. Chen *et al.*[8] suggested that the formation of blobs is a consequence of an intrinsic instability of coronal streamers occurring at a very localized region around the cusp. The evolutionary process of the instability, as revealed in their calculations, can be described as follows. (1) Through the localized cusp region where the field is too weak to sustain the confinement, plasmas expand and stretch the closed field lines radially outward as a result of the freezing-in effect of plasma-magnetic field coupling; the expansion brings a strong velocity gradient into the slow wind regime providing the free energy necessary for the onset of a subsequent magnetohydrodynamic instability. (2) The instability manifests itself mainly as mixed streaming sausage-kink modes, the former results in pinches of elongated magnetic loops to provoke reconnections at one or many locations to form blobs. Then, the streamer system returns to the configuration with a lower cusp point, subject to another cycle of streamer instability. Although the instability is intrinsic, it does not lead to the loss of the closed magnetic flux, neither does it affect the overall feature of a streamer. The main properties of the modeled blobs, including their size, velocity profiles, density contrasts, and even their daily occurrence rate, are in line with available observations.

Song *et al.*[9] searched for persistent and quasi-periodic release events of streamer blobs during 2007 with the Large Angle Spectrometric Coronagraph on the Solar and Heliospheric Observatory and assessed the velocity of the slow solar wind along the plasma sheet above the corresponding streamer by measuring the dynamic parameters of blobs. They found ten quasi-periodic release events of streamer blobs lasting for three to four days. In each day of these events, they observed 3–5 blobs. The results are in line with previous studies using data observed near the last solar minimum. Using the measured blob velocity as a proxy for that of the mean flow, they suggested that the velocity of the background slow solar wind near the Sun can vary significantly within a few hours. This provides an observational manifestation of the large velocity variability of the slow solar wind near the Sun.

Using NSO/Kitt Peak synoptic charts from 1975 to 2003, Song *et al.*[10] grouped the main solar magnetic fields into two categories: one for Active Regions (ARs) and the other for Extended Bipolar Regions (EBRs). Comparing them, they found that there exist three typical characteristics in the variability of EBRs. First, there exists a correlation between ARs and EBRs. The phase of EBR flux has a delay nearly two CRs. Second, the EBR flux has two prominent periods at 1.79 years and 3.21 years. The 1.79-year period seems to only belong to large-scale magnetic features. Lastly, the North-South asymmetry of EBR flux is not very significant on a time scale of one solar cycle. However, during solar maxima, its dominance is found to shift from one hemisphere to the other.

Magnetic reconnection is commonly believed to be responsible for flare-like events and plasma ejections in the solar atmosphere, but the field-line reconfiguration observed in association with magnetic reconnection has rarely been observed before. He *et al.*[11] attempted to reconstruct the configuration of the magnetic field during a magnetic reconnection event, estimate the reconnection rate, and analyze the resulting X-ray burst and plasma ejection. They used the Local-Correlation-Tracking (LCT) method to track the convergence of magnetic fields with opposite polarities using photospheric observations from SOT/Hinode. The magnetic field lines were then extrapolated from the tracked footpoint positions into the corona, and the changes in field-line connections are marked. They estimated the reconnection rate by calculating the convective electric field in the photosphere, which was normalized to the product of the plasma jet speed and the coronal magnetic field strength inside the inflow region. The observed X-ray burst and plasma ejection were analyzed with data from XRT/Hinode and TRACE, respectively. They found that in this reconnection event the two sets of approaching closed loops were reconfigured to a set of superimposed large-scale closed loops and another set of small-scale closed loops. Enhanced soft X-ray emission was seen to rapidly fill the reconnected loop after the micro-flare occurred at the reconnection site. Plasma was ejected from that site with a speed between 27 and 40 km/s. The reconnection rate was estimated to range between 0.03 and 0.09. Their work presents a study of the magnetic field reconfiguration owing to magnetic reconnection driven by flux convergence in the photosphere. This observation of the magnetic structure change is helpful for future diagnosis of magnetic reconnection. The results obtained for the reconnection rate, the X-ray emission burst, and the plasma ejection provides new observational evidence, and places constraints on future theoretical study of magnetic reconnection in the Sun.

Zhao *et al.*[12] performed a detailed analysis of a Coronal Mass Ejection (CME) on January 2, 2008. The combination of SOHO and the twin STEREO spacecraft provides three-point observations of this CME. They tracked the CME in imaging observations and compared its morphology and kinematics viewed from different vantage points. The shape, angular width, distance, velocity and acceleration of the CME front were different in the observations of these spacecraft. They also compared the efficiency of several methods, which convert the elongation angles of the CME front in images to radial distances. The results of their kinematic analysis demonstrate that this CME experienced a rapid acceleration at the early stage, which corresponded to the flash phase of the associated solar flare in time. Then at a height of about 3.7 R_s the CME reached a velocity of 790 km/s and propagates outward without an obvious deceleration. Because of its propagation direction away from the observers, the CME was not detected in situ by either ACE or STEREO.

Between July 5th and July 7th 2004, two intriguing fast Coronal Mass Ejection (CME)-streamer interaction events were recorded by the Large Angle and Spectrometric Coronagraph (LASCO). At the beginning of the events, the streamer was pushed aside from their equilibrium position upon the impact of the rapidly outgoing and expanding ejecta; then, the streamer structure, mainly the bright streamer belt, exhibited elegant large scale sinusoidal wavelike motions. The motions were apparently driven by the restoring magnetic forces resulting from the CME impingement, suggestive of magnetohydrodynamic kink mode propagating outwards along the plasma sheet of the streamer. The mode was supported collectively by the streamer-plasma sheet structure and was therefore named "streamer wave" in Chen *et al.*'s study. With the white light coronagraph data, Chen *et al.*[13] showed that the streamer wave has a period of about 1 hour, a wavelength varying from 2 to 4 solar radii, an amplitude of about a few tens of solar radii, and a propagating phase speed in the range 300 to 500 km/s. They also found that there is a tendency for the phase speed to decline with increasing heliocentric distance. These observations provide good examples of large scale wave phenomena carried by coronal structures, and have significance in developing seismological techniques for diagnosing plasma and magnetic parameters in the outer corona.

2 Interplanetary Transients

In August 2007, Voyager 2 reached the termination shock and entered the heliosheath at a distance of about 83.6 AU. Due to the variations of the solar wind dynamic pressure or waves on the shock front, the termination shock moved back and forth, and Voyager 2 crossed the termination shock multiple times. Li, Wang and Richardson[14] used the best fit solution of the Monte-Carlo method to define the upstream and downstream conditions and determine the properties of termination shock, such as the shock normal, speed, and strength. For the crossings on Day of Year (DOY) 243.819–243.875 (shock 1) and DOY 243.99–244.012 (shock 2), the termination shock moved almost in the radial direction. The shock is nearly perpendicular, and the angle between the shock normal and the solar wind magnetic field is about 70°. In the case of the first crossing, the termination shock moved away from the Sun with a speed of about 100 km/s, whereas the termination shock moved toward Sun with a speed of about 30 km/s for the second crossing. The density ratios of the termination shock are 2.2 and 1.6, respectively. For both crossing events, the flow is found to be still supersonic with respect to the thermal ions downstream of the termination shock, probably due to the fact that most of the solar wind energy is transferred to the pickup ions.

Zhang *et al.*[15] gave an investigation of the effects of Corotating Interaction Regions (CIRs) in the heliosphere (<1 AU) on geomagnetic disturbances during solar cycle 23 (1996–2005). Three kinds of interplanetary structures, “pure” CIR, interaction of CIR with ICME, and “pure” ICME by transient events, were identified by using the Hakamada-Akasofu-Fry (HAF) solar wind model. Yearly occurrence of 157 “pure” CIRs has a minimum value in 2001 and a peak value in 2003 at the declining phase during the 23rd solar cycle. The maximum correlation coefficient of the daily sum of Kp indices between consecutive Carrington Rotations indicates that recurrent geomagnetic disturbances are dominant during the declining phase near solar minimum. Eighty percent of storms that are related to “pure” CIRs belong to weak and moderate storms. The statistical analysis shows that about 50% of CIRs produce classical interplanetary shocks during the descending phase and 89% of the CIR-related shocks are followed by geomagnetic storms. These results demonstrate that CIR-related shock is not a necessary condition for generating a magnetic storm, but most CIR-related shocks are related to a storm. The Dst index that corresponds to CIR-related storms has a better linear relationship with IMF B_z, E_y, and the coupling function (ε) when the Dst indices are higher than -100 nT. Finally, the geoeffectiveness of CIRs appears clearly to have a seasonal variation.

Liu *et al.*[16] examined the upstream meridional deflection flows of Interplanetary Coronal Mass Ejections (ICMEs) in an effort to investigate their cross-sectional shape and the magnetic field orientation in their sheath regions. Eight out of 11 Magnetic Clouds (MCs) near solar minimum identified for the curvature study are concave outward as indicated by the elevation angle of the MC normal with respect to the solar equatorial plane; an inverse correlation is observed between the meridional deflection flow and the spacecraft latitude for these concave-outward MCs, which suggests that the upstream plasma is deflected toward the equatorial plane. MHD simulations, however, show that the meridional deflection flow moves poleward for a concave-outward CME. The poleward flow deflection is observed only ahead of convex-outward MCs. Possibilities leading to this discrepancy are discussed. The deflection flow speed in sheath regions of ICMEs increases with the ICME speed relative to the ambient solar wind, which together with the coupling between the meridional magnetic field and deflection flow yields a positive linear correlation between the sheath meridional field and the ICME relative speed. This empirical relationship could predict the sheath meridional field based on the observed CME speed, which may be useful for space weather forecasting as ICME sheaths are often geoeffective. Implications of the deflection flows and ICME curvature were also discussed in terms of magnetic reconnection and particle acceleration in ICME sheaths.

Coronal Mass Ejections (CMEs) are often assumed to be magnetic flux ropes, but direct proof has been lacking. A key feature, resulting from the translational symmetry of a flux rope, is that the total transverse pressure as well as the axial magnetic field has the same functional form over the vector potential along any crossing of the flux rope. Liu *et al.*[17] tested this feature (and hence the flux-rope structure) by reconstructing the 2007 May 22 Magnetic Cloud (MC) observed at STEREO B, Wind/ACE, and possibly STEREO A with the Grad-Shafranov (GS) method. The model output from reconstruction at STEREO B agrees fairly well with the magnetic field and thermal pressure observed at ACE/Wind; the separation between STEREO B and ACE/Wind is about 0.06 AU, almost half of the MC radial width. For the first time, they reproduced observations at one spacecraft with data from another well separated spacecraft, which provides compelling evidence for the flux-rope geometry and is of importance for understanding CME initiation and propagation. They also discussed the global configuration of the MC at different spacecraft on the basis of the reconstruction results.

Wang *et al.*[18] performed a statistical survey of geospace magnetic field responses, including the geosynchronous magnetic field and the sudden impulses on the ground, to interplanetary shocks (IP shocks) between 1998 and 2005. The magnitude of the geosynchronous magnetic field $\mathrm{d}B_z$ responses to IP shocks depends strongly on local time, which peaks near the noon meridian; however, the relative magnitude of the responses depends only weakly on local time. These results are similar to those obtained from the statistical study of the responses to solar wind dynamic pressure pulses. However, negative responses (where $\mathrm{d}B_z$ is negative) are sometimes observed in the nightside of the magnetosphere even though the IP shocks always cause increases in the solar wind dynamic pressure, a new phenomenon not widely reported in the literature. Their analysis shows that about 75% of negative responses in the midnight sector are associated with southward interplanetary magnetic field. For a moderately compressed magnetosphere, the amplitude of the geosynchronous response $\mathrm{d}B_z$ could be determined by the average value of the background local magnetic field. As the magnitude of the upstream solar wind dynamic pressure increases, the rate of response increases correspondingly. The $\mathrm{d}B_z$ at the geosynchronous orbit near local noon and the amplitude of sudden impulses d,/SYM($-H$) on the ground are highly correlated.

The plasma and magnetic-field instruments on the Helios 2 spacecraft, which was on 3 April 1979 located at 0.68 AU, detected an Interplanetary Coronal Mass Ejection (ICME) that revealed itself by the typical signature of magnetic field rotation. The solar wind flow speed ranged between 400 and 500 km/s. Marsch, Yao and Tu[19] presented some detailed proton velocity distributions measured within the ICME. These cold distributions are characterized by an isotropic core part with a low temperature, $T \leqslant 10^5$ K, but sometimes reveal a broad and extended hot proton tail or beam propagating along the local magnetic field direction. These beams last only for about an hour and are unusual as compared with the normal ICME protons distributions that are comparatively isotropic. Furthermore, they looked into the velocity and field fluctuations in this ICME and found signatures of Alfvén waves, which might be related to the occurrence of the hot proton beams. However, it cannot be excluded that the beam originates from the Sun.

A generic self-similar flux rope model was proposed by Wang, Zhang and Shen[20] to probe the internal state of CMEs in order to understand the thermodynamic process and expansion of CMEs in interplanetary space. Using this model, three physical parameters and their variations with heliocentric distance can be inferred based on coronagraph observations of CMEs' propagation and expansion. One is the polytropic index Γ of the CME plasma, and the other two are the average Lorentz force and the thermal pressure force inside CMEs. By applying the model to the 8 October 2007 CME observed by STEREO/SECCHI, they found that (1) the polytropic index of the CME plasma increased from initially 1.24 to more than 1.35 quickly and then slowly decreased to about 1.34; it suggests that there be continuously heat injected/converted into the CME plasma and the value of Γ tends to be 4/3, a critical value inferred from the model for a force-free flux rope; (2) the Lorentz force directed inward while the thermal pressure force outward, and both of them decreased rapidly as the CME moved out; the direction of the two forces reveals that the thermal pressure force is the internal driver of the CME expansion, whereas the Lorentz force prevents the CME from expanding. Some limitations of the model and approximations were discussed meanwhile.

Li *et al.*[21] introduced a new definition of the quantity, residue, based on all field line invariants of a specified flux rope model to measure the deflection between the assumed axis and the true flux rope axis. Then, a new Minimum Residue (MR) method was proposed to infer the axial orientation of IFR with the observational data from a single spacecraft. For an arbitrarily assumed flux rope axis, the natural coordinate system can be constructed, then a magnetic flux function, A, and each invariant of the specified flux rope model can also be concurrently calculated under this coordinate system. The direction corresponding to the minimum residue is expected to be the real axial orientation. In previous study, the residue was first defined with A and a single invariant P_{t} of a static equilibrium flux rope model. Here, the new MR method is tested with simulated magnetic cloud data sets constructed from the analytical model outputs of two different flux rope models with "trend noise" added. It shows that the new MR method is applicable in real case analysis and the inferring results are acceptable for cases with small closest approach distance and proper noise level. Compared with results from traditional methods, accuracy of the inferred axial orientation is improved by the new method. The new MR method is also applied to a typical in situ event observed by Wind spacecraft. The comparison of the inferring results from different models indicates that application of a more accurate flux rope model is useful for inferring techniques.

Li *et al.*[22] reported two MC events observed by WIND spacecraft with good examples of field-aligned residual flow inside the MC structure. For both events, the co-moving frames are determined through the deHoffman-Teller (HT) analysis and the axial orientations are inferred by the newly developed Minimal Residue (MR) method. The nature coordinate system for both events are constructed with velocity of the HT frame and the inferred MC axis, the field and flow remaining in the HT frame are analyzed at this coordinate system. As a result, they found that the residual flows in the co-moving HT frame of the two MC events are almost anti-parallel to the helical magnetic field. They speculated that the field-aligned residual flows are large scale coherent hydrodynamic vortices co-moving with the MCs at the supersonic speed near 1 AU. Data analyses show that the event in slow ambient solar wind is expanding at 1 AU and another one in fast solar wind does not show apparent expansion. Proton behaviors for both events are quasi-isothermal. Accelerated HT analysis shows that both events have no suitable HT frame with constant accelerations, which suggests that both events may be moving at the constant speed near 1 AU under the assumptions of the HT analysis. For both events, the ratio of the dynamic pressure to the magnetic pressure is larger than that of the thermal pressure to magnetic pressure, which suggests that the dynamic effects due to the plasma flows remaining in the co-moving HT frame are more important than the thermal effects in the study of MC evolution and propagation.

3 Energetic Particles

Current sheets are common structures in the solar wind and possibly the boundaries of individual flux tubes. Observations show that magnetic field directions often change abruptly upon crossing these structures. The presence of these structures introduces a new source of solar wind turbulence intermittency and can affect the transport of energetic particles. Previous studies of energetic-particle transport in the solar wind often assume a uniform large-scale background magnetic field, with a turbulent field superposed. With the existence of flux tubes in the solar wind, this picture needs to be changed. Qin and Li[23] studied the effects of flux tubes on the transport of energetic particles in the solar wind. They constructed a model turbulence of the solar wind by including explicitly flux-tube-like structures. In their model, the solar wind is composed of many individual cells with a local uniform mean magnetic field chosen randomly. The turbulence in each cell is modeled by either a slab and/or 2D type. They then calculated numerically the particle diffusion coefficients by following single particle trajectories. Their results show that flux tubes in the solar wind can lead to stronger scatterings of particles in directions both parallel and perpendicular to the large-scale background magnetic field. In particular, a true diffusion in the large-scale perpendicular direction (with respect to B_0) is obtained even when the local intrinsic turbulence in individual cells is of pure slab type.

The behavior of Solar Energetic Particles (SEPs) in a shock–Magnetic Cloud interacting complex structure observed by the Advanced Composition Explorer (ACE) spacecraft on 5 November 2001 was analyzed by Shen *et al.*[24]. A strong shock causing magnetic field strength and solar wind speed increases of about 41 nT and 300 km/s, respectively, propagated within a preceding Magnetic Cloud (MC). It is found that an extraordinary SEP enhancement appeared at the high-energy ($\geqslant$ 10 MeV) proton intensities and extended over and only over the entire period of the shock–MC structure passing through the spacecraft. Such SEP behavior is much different from the usual picture that the SEPs are depressed in MCs. The comparison of this event with other top SEP events of solar cycle 23 (2000 Bastille Day and 2003 Halloween events) shows that such an enhancement resulted from the effcts of the shock–MC complex structure leading to the highest $\geqslant 10\,\mathrm{MeV}$ proton intensity of solar cycle 23. Their analysis suggests that the relatively isolated magnetic field configuration of MCs combined with an embedded strong shock could significantly enhance the SEP intensity; SEPs are accelerated by the shock and confined into the MC. Further, they find that the SEP enhancement at lower energies happened not only within the shock MC structure but also after it, probably owing to the presence of a following MC-like structure. This is consistent with the picture that SEP fluxes could be enhanced in the magnetic topology between two MCs, which was proposed based on numerical simulations by Kallenrode and Cliver.

Xiao *et al.*[25] utilized a recently introduced relativistic Kappa-Type (KT) distribution function to model the omnidirectional differential flux of energetic electrons observed by the SOPA instrument on board the 1989–046 and LANL-01A satellites at geosynchronous orbit. They derived a useful correlation between the differential flux and the distribution of particles, which can directly offer those best fitting parameters (*e.g.*, the number density N, the thermal characteristic speed q and the spectral index k) strongly associated with evaluation of the electromagnetic wave instability. They adopted the assumption of a nearly isotropic Pitch Angle Distribution (PAD) and the typical LMFIT function in the program IDL to perform a non-linear least squared fitting, and found that the new KT distribution fits well with the observed data during different universal times both in the lower and higher energies. They also carried out the direct comparisons with the generalized Lorentzian (Kappa) distribution and found that kappa distribution fits well with observational data at the relatively lower energies but display deviations at higher energies, typically above hundreds of keV. Furthermore, the fitting spectral index k basically takes 4, 5 or 6 while the fitting parameters N and q are quite different due to different differential fluxes of electrons at different universal times. These results, which are applied to the case of a nearly isotropic PAD, demonstrate that the particle flux satisfies the power law not only at the lower energies but also at the relativistic energies, and the new KT distribution may present valuable insights into the dynamical features in those space plasmas (*e.g.*, the Earth's outer radiation belts and the inner Jovian magnetosphere) where highly energetic particles exist.

Pitch-angle diffusion is a key process in the theory of charged particle scattering by turbulent magnetic plasmas. This process is usually assumed to be diffusive and can, therefore, be described by a pitch-angle diffusion or Fokker-Planck coefficient. This parameter controls the parallel spatial diffusion coefficient as well as the parallel mean free path of charged particles. Qin and Shalchi[26] determined pitch-angle diffusion coefficients from numerical computer simulations. These results were then compared with results from analytical theories. Especially, they compared the simulations with quasilinear, second-order, and weakly nonlinear diffusion coefficients. Such a comparison allows the test of previous theories and will lead to an improved understanding of the mechanism of particle scattering.

Zhang, Qin and Rassoul[27] presented a model calculation of solar energetic particle propagation in a three-dimensional interplanetary magnetic field. The model includes essentially all the particle transport mechanisms: streaming along magnetic field lines, convection with the solar wind, pitch-angle diffusion, focusing by the inhomogeneous interplanetary magnetic field, perpendicular diffusion, and pitch-angle dependent adiabatic cooling by the expanding solar wind. They solved the Fokker-Planck transport equation with simulation of backward stochastic processes in a fixed reference frame in which any spacecraft is roughly stationary. As an example they modeled the propagation of those high-energy ($E \geqslant 10\,\mathrm{MeV}$) solar energetic particles in gradual events that are accelerated by large coronal mass ejection shocks in the corona and released near the Sun into interplanetary space of a Parker spiral magnetic field. Modeled in different scenarios, the source of solar energetic particles can have a full or various limited coverages of latitude and longitude on the solar surface.

They computed the long-term time profiles of particle flux and anisotropy at various locations in the heliosphere up to 3 AU, from the ecliptic to high latitudes. Features from particle perpendicular diffusion are revealed. Their simulation reproduced the observed reservoir phenomenon of solar energetic particles with constraints on either solar particle source or the magnitude of perpendicular diffusion.

4 MHD Simulations

Zhou, Feng and Wu[28] used a newly developed SIP-CESE MHD model to simulate Sun-Earth connection event with the well-studied 12 May 1997 CME event as an example. The main features and approximations of their numerical model are as follows: (1) The modified Conservation Element and Solution Element (CESE) numerical scheme in spherical geometry is implemented in their code. (2) The background solar wind is derived from a 3D time-dependent numerical MHD model by input measured photospheric magnetic fields. (3) Transient disturbances are derived from solar surface by introducing a mass flow of hot plasma. The numerical simulation has enabled us to predict the arrival of the interplanetary shock and provided us with a relatively satisfactory comparison with the WIND spacecraft observations.

Based on the SIP-CESE MHD model, Hu *et al.*[29] have investigated 3D large-scale solar corona study. Their aim is to describe the application of this new MHD model to study the global coronal magnetic structures by using the observed line-of-sight photospheric magnetic field from the Wilcox Solar Observatory (WSO) as boundary conditions. With this model, the magnetic structures of the global corona are obtained for fifteen Carrington Rotations (CRs) spanning solar cycle 23. The results illustrate how the shape and location of the Heliospheric Current Sheet (HCS) and the coronal magnetic field configuration evolve during the course of the solar cycle. Comparison between their numerical results for the coronal magnetic structures and those from the standard Potential Field Source Surface (PFSS) model, with, in addition, white light observations further validates this new MHD model. The source surface neutral lines calculated from the MHD and PFSS models generally match each other closely; however, differences occur at different phases in the solar cycle. The location of the HCS shows good overall agreement with the bright structures in the observed white-light intensity pattern, especially around solar minimum or well after solar maximum, and this result confirms that the observed white-light streamer structures originate from a single, large scale plasma sheet located near the HCS.

Using SIP-CESE MHD model, Zhou and Feng[30] presented the solar-terrestrial transit process of three successive Coronal Mass Ejections (CMEs) of November 4–5, 1998 originating from active region 8375 by using a time-dependent three-dimensional Magnetohydrodynamics (MHD) simulation. These CMEs interacted with each other while they were propagating in inter-planetary space and finally formed a “complex ejecta”. A newly developed SIP-CESE MHD model was applied to solve MHD equations numerically. The quiet solar wind was started from Parker-like 1D solar wind solution and the magnetic field map was calculated from the solar photospheric magnetic field data. In their simulation, the ejections were initiated using pulse in the real active region 8375. The interplanetary disturbance parameters, such as speed, direction and angular size of the expanding CME, were determined from the SOHO/LASCO data with the cone-model. They discussed the three-dimensional aspects of the propagation, interaction and merging of the three ejections. The simulated interplanetary shocks were compared with the nearby-Earth measurement. The results showed that their simulation could reproduce and explain some of the general features observed by satellite for the “complex ejecta”.

An asynchronous and parallel time-marching method for three-dimensional (3D) time-dependent Magnetohydrodynamic (MHD) simulation was used by Shen, Feng and Song[31] for large-scale solar wind simulation. It uses different local time steps in the corona and the heliosphere according to the local Courant-Friedrichs-Levy (CFL) conditions. The solar wind background with observed solar photospheric magnetic field as input was first presented. The simulation time for the background solar wind by using the asynchronous method is $< 1/6$ of that by using the normal synchronous time-marching method with the same computation pre-cision. Then, they chose the Coronal Mass Ejection (CME) event of 13 November, 2003 as a test case. The time-dependent variations of the pressure and the velocity configured from a CME model at the inner boundary were applied to generate transient structures in order to study the dynamical interaction of a CME with the background solar wind flow between 1 and 230 $R_{\rm s}$. This time-marching method is very effective in terms of computation time for large-scale 3D time-dependent numerical MHD problem. In this validation study, they found that this 3D MHD model, with the asynchronous and parallel time-marching method, provides a relatively satisfactory comparison with the ACE spacecraft observations at L1 point.

The numerical studies of the interplanetary coupling between multiple magnetic clouds (MCs) were continued by Xiong, Zheng and Wang[32] by a 2.5-Dimensional ideal magnetohydrodynamic (MHD) model in the heliospheric meridional plane. The interplanetary Direct Collision (DC)/Oblique Collision (OC) between both MCs results from their same/different initial propagation orientations. Here the OC is explored in contrast to the results of the DC. Both the slow MC1 and fast MC2 are consequently injected from the different heliospheric latitudes to form a compound stream during the interplanetary propagation. The MC1 and MC2 undergo contrary deflections during the process of oblique collision. Their deflection angles of $|\delta\theta_1|$ and $|\delta\theta_2|$ continuously increase until both MC-driven shock fronts are merged into a stronger compound one. The $|\delta\theta_1|$, $|\delta\theta_2|$, and total deflection angle $\Delta\theta$ ($\Delta\theta = |\delta\theta_1| + |\delta\theta_2|$) reach their corresponding maxima when the initial eruptions of both MCs are at an appropriate angular difference. Moreover, with the increase of MC2's initial speed, the OC becomes more intense, and the enhancement of $\delta\theta_1$ is much more sensitive to $\delta\theta_2$. The $|\delta\theta_1|$ is generally far less than the $|\delta\theta_2|$, and the unusual case of $|\delta\theta_1| \approx |\delta\theta_1|$ only occurs for an extremely violent OC. But because of the elasticity of the MC body to buffer the collision, this deflection would gradually approach an asymptotic degree. As a result, the opposite deflection between the two MCs, together with the inherent magnetic elasticity of each MC, could efficiently relieve the external compression for the OC in the interplanetary space. Such a deflection effect for the OC case is essentially absent for the DC case. Therefore, besides the magnetic elasticity, magnetic helicity, and reciprocal compression, the deflection due to the OC should be considered for the evolution and ensuing geoeffectiveness of interplanetary interaction among successive coronal mass ejections.

5 Space Plasma

Wavelength dependence of laser ablation of silicon was investigated by Lu *et al.*[33] with nanosecond ultraviolet, visible, and infrared laser pulses in the irradiance range from 3×10^{10} to 1×10^{12} W/cm^2. For 266 and 532 nm laser pulses, the depth of laser-produced crater shows a dramatic increase at a laser irradiance threshold of approximately 2×10^{10} and 4×10^{11} W/cm^2 respectively, above which, large micron-sized particulates were observed to eject from the target about 300–400 ns after the laser pulse. In contrast, for 1064 nm pulse, this dramatic increase was not observed. The underlying mechanism for the observed threshold phenomenon was presented in this study, which can be attributed to the thermal diffusion and subsequent explosive boiling after the completion of the interaction between the nanosecond laser pulse and silicon. Based on their delayed phase explosive model, the ablation depths were calculated for different wavelengths and compared to experimental results. Plasma shielding during laser irradiation was included in the model, which plays a key role to the coupling of laser energy to the irradiated material.

Electron acceleration by the inductive electric field near the X point in magnetic reconnection is an important generation mechanism for energetic electrons. Particle simulations have revealed that most of energetic electrons reside in the magnetic field line pileup region, and a depletion of energetic electrons can be found near the centre of the diffusion region. Wang *et al.*[34] reported direct measurement of energetic electron in and around the ion diffusion region in near-Earth tail by the cluster, and their observations confirm the above predictions: a depletion of the high-energy electron fluxes is detected near the centre of the diffusion region. At the same time, the plasma temperature has a similar profile in the diffusion region.

Previous multi-dimensional particle simulations have shown that electron phase-holes can be formed during the nonlinear evolution of bi-stream instability. In these holes, the parallel cut of the parallel electric field ($E_{\parallel}$) has bipolar structures while the parallel cut of the perpendicular electric field ($E_{\perp}$) has unipolar structures. Two-dimensional (2D) electrostatic particle-in-cell simulations were performed by Lu *et al.*[35] to investigate the evolution of $E_{\perp}$ in such electron holes for different plasma conditions, and the generation mechanism of the unipolar structures of $E_{\perp}$ was also discussed. The electrons trapped in electron holes bounce in the parallel direction, which leads to transverse instability. At the same time, they gyrate in the background magnetic field, which tends to stabilize electron holes. In this way, the trapped electrons are forced to accumulate locally, and the charge density has variations along the perpendicular direction inside the electron holes. The balance between these two effects leads to the following results: in weakly magnetized plasma ($\Omega_{\rm e} < \omega_{\rm pe}$, but $\Omega_{\rm e}$ is comparable to $\omega_{\rm pe}$. Where $\Omega_{\rm e}$ and $\omega_{\rm pe}$ are the electron cyclotron frequency and electron plasma frequency, respectively), electron holes have two-dimensional structures (isolated along both the parallel and perpendicular directions). Within such holes the parallel cut of $E_{\perp}$ has unipolar structures. In strongly magnetized plasma ($\Omega_{\rm e} > \omega_{\rm pe}$), electron holes have one-dimensional structures along the direction perpendicular to the background magnetic field within which a series of islands (with alternate positive and negative $E_{\perp}$) develop because of the variations of the charge density along the perpendicular direction. Therefore one recovers that a parallel cut of $E_{\perp}$ has unipolar structures at the location of the holes. Present results show that the unipolar structure of $E_{\perp}$ in electron holes is attributed to the balance between the electron transverse instability and the stabilization of the background magnetic field. The unipolar structures of $E_{\perp}$ in electron holes last for hundreds to thousands of electron plasma periods. They are destroyed and the streaked structures are formed in the whole simulation domain after the electrostatic whistler waves are excited and have sufficiently large amplitude. The influences of the initial perpendicular thermal velocity of electrons (via temperature anisotropy) and the drift speed of electron beam on the structures of $E_{\perp}$ were also analyzed in detail. At last, the relevance between their simulation results and the unipolar structures of the parallel cut of $E_{\perp}$ observed in the auroral region was discussed.

Zheng, Su and Xiong[36] developed a two-dimensional momentum and pitch angle code to solve the typical Fokker-Planck equation which governs wave-particle interaction in space plasmas. They carried out detailed calculations of momentum and pitch angle diffusion coefficients, and temporal evolution of pitch angle distribution for a band of chorus frequency distributed over a standard Gaussian spectrum particularly in the heart of the Earth's radiation belt $L = 4.5$, where peaks of the electron phase space density are observed. They found that the Whistler-mode chorus can produce significant acceleration of electrons at large pitch angles, and can enhance the phase space density for energies of 0.5–1 MeV by a factor of 10 or above after about 24 h. This result can account for observation of significant enhancement in flux of energetic electrons during the recovery phase of a geomagnetic storm.

Previous particle-in-cell simulations have evidenced that quasi-perpendicular shocks are nonstationary and suffer a self-reformation on gyro scale of the incoming ions due to the accumulation of reflected ions. Yang *et al.*[37] investigated the detailed mechanisms of ion acceleration in a nonstationary perpendicular shock by separating the incoming ions into reflected and directly transmitted parts. Test particle simulations were performed where the shock profiles were issued from self-consistent one-dimensional full particle-in-cell simulations. Both shell and Maxwellian incoming ion distributions were used. In both cases, most energetic particles correspond to reflected ions, and the associated acceleration mechanisms include both Shock Drift Acceleration (SDA) and Shock Surfing Acceleration (SSA). Two types of results were obtained. First, if they fix the shock profiles at different times within a self-reformation cycle, the mechanisms of particle acceleration are different at different profiles. SDA process appears as the dominant acceleration mechanism when the width of the ramp is broad (and overshoot amplitude is low) whereas both SDA and SSA contribute as the width of the ramp is narrow (and overshoot amplitude is high). For the different shock profiles concerned herein, SDA process is more efficient (higher resulting ion energy gain) than the SSA process. Second, in order to investigate ion acceleration in self-reforming shocks, not only the ramp but also the variations of the whole shock front need to be included. In the continuously time-evolving shock, SDA remains a dominant acceleration mechanism whereas SSA mechanism becomes more and more important with the increase of the initial particle energy. The percentage of reflected ions cyclically varies in time with a period equal to the self reformation cycle, which is in agreement with previous full particle simulations. The reflected ions not only come from the distribution wings of the incoming ions but also from the core part, in contrast with previous results based on stationary shocks.

In the solar wind, alpha particles are observed to flow faster than the core protons. Lu, Du and Li[38] performed two dimensional hybrid simulations to investigate the nonlinear evolution of oblique Alfvén waves excited by an alpha/proton beam instability in a low beta plasma. The propagation angles of the excited waves are within a finite range suggesting the generation of oblique Alfvén waves. During the nonlinear evolution, both the wave numbers and frequencies of the waves drift to smaller values, and the propagation angles decrease. At the same time, the propagation angle of the dominant mode also changes. Eventually the plasma system reaches a marginally stable state according to linear theory.

Ion pickup by a monochromatic low-frequency Alfvén wave, which propagates along the background magnetic field, has recently been investigated in low beta plasma. In the study of Lu, Li and Dong[39], the monochromatic Alfvén wave is generalized to a spectrum of Alfvén waves with random phase. It finds that the process of ion pickup can be divided into two stages. First, ions are picked up in the transverse direction, and then phase difference (randomization) between ions due to their different parallel thermal motions leads to heating of the ions. The heating is dominant in the direction perpendicular to the background magnetic field. The temperatures of the ions at the asymptotic stage do not depend on individual waves in the spectrum, but are determined by the total amplitude of the waves. The effect of the initial ion bulk flow in the parallel direction on the heating is also considered in this paper.

With one-dimensional (1D) hybrid simulations, Guo *et al.*[40] investigated the nonlinear evolution of the ion cyclotron waves excited by the H^+ and He^{2+} temperature anisotropies, and analyzed the evolution by using the wavelet analysis method. The results show that the proton cyclotron waves with the dominant frequency higher than the helium gyro-frequency ($\Omega_{\rm He} = 0.5\Omega_{\rm p}$, with $\Omega_{\rm p}$ and $\Omega_{\rm He}$ the proton and helium gyro-frequencies respectively) are firstly excited, and then the helium cyclotron waves with the dominant frequency lower than the helium gyro-frequency are excited. The relation of their simulation results to the BIF (bifurcated) (there are two peaks in the wave spectrum: one above and one below $\Omega_{\rm He}$) and CON (continuous) (continuous spectrum from 0.1 $\Omega_{\rm p}$ to 1.0 $\Omega_{\rm p}$) wave spectra observed in the magnetosheath were discussed.

The possibility of heating of protons via Alfvén waves is a topic that stimulates much discussion in both plasma physics and astrophysics. Conventional thinking is that dissipation is essential for heating. In two recent discussions it is shown that turbulent Alfvén waves can enhance stochastic particle motion via scattering. This process can lead to a higher proton temperature. In the study of Wang and Wu[41] two essential points are stressed: First, there is no dissipation; second, physically the temperature increment is “apparent” rather than genuine, and consequently the heating is spurious. If the turbulent wave field should diminish, the proton temperature returns to its original value. The purpose of this communication is to elucidate and explain the above points.

Ion heating due to turbulent Alfvén waves via nonresonant wave-particle interaction is discussed to complement a preceding work. Wang and Wang[42] claimed that newborn ions can get extra energy from turbulent Alfvén waves. Since in plasmas newborn ions are created continuously and intrinsically via ionization and recombination, heating associated with these newborn ions may be significant. The heating rate is proportional to the creation rate of newborn ions and the total wave field energy density without dependence on the profile of the wave spectrum. Based on observed nonthermal velocities, they estimate the energy density of the wave field and the corresponding heating rate in the solar atmosphere. The results show that such a heating process could be significant in the upper chromosphere and transition region of the sun.

Ion stochastic heating by a monochromatic Alfvén wave, which propagates obliquely to the background magnetic field, has been studied by Chen *et al.* It is shown that ions can be resonantly heated at frequencies a fraction of the ion cyclotron frequency when the wave amplitude is sufficiently large. In the study of Lu and Chen[43], the monochromatic wave is extended to a spectrum of left-hand polarized Alfvén waves. When the amplitude of the waves is small, the components of the ion velocity have several distinct frequencies, and their motions are quasi-periodic. However, when the amplitude of the waves is sufficiently large, the components of the ion velocity have a spectrum of continuous frequencies near the ion cyclotron frequency due to the nonlinear coupling between the Alfvén waves and the ion gyromotion, and the ion motions are stochastic. Compared with the case of a monochromatic Alfvén wave, the threshold of the ion stochastic heating by a spectrum of Alfvén waves is much lower. Even when their frequencies are only several percent of the ion cyclotron frequency, the ions can also be stochastically heated. The relevance of this heating mechanism to solar corona is also discussed.

In collisionless reconnection, the magnetic field near the separatrix is stronger than that around the X-line, so an electron-beam can be formed and flows toward the X-line, which leads to a decrease of the electron density near the separatrix. Having been accelerated around the X-line, the electrons flow out along the magnetic field lines in the inner side of the separatrix. A quadruple structure of the Hall magnetic field B_y is formed by such a current system. A 2D particle-in-cell (PIC) simulation code was used by Huang *et al.*[44] to study the collisionless magnetic reconnection without an initial guide field. The current system described above is proved by the simulations. Furthermore, the position of the peak of the Hall magnetic field B_y is found to be between the separatrix and the center of the current sheet, which is verified by Cluster observations.

Lu, Hu and Zank[45] performed two-dimensional hybrid simulations to investigate the interaction of Alfvén waves with a perpendicular shock self-consistently. The perpendicular shock is formed by reflecting the particles in the right boundary, and it propagates to the left. The Alfvén waves are injected from the left boundary, and they are convected toward the right. The results show that the injected Alfvén waves have no obvious effects on the propagation speed of the shock. However, after the upstream Alfvén waves are transmitted into the downstream, their amplitude is enhanced about 10–30 times. The transmitted waves can be separated into two parts, and both of them are left-hand polarized Alfvén waves: one propagates along the $+y$ direction and the other along the $-y$ direction. Obvious ripples in the shock front are also found due to the interaction of the Alfvén waves with the shock. The great enhancement of the amplitude of the Alfvén waves by the shock is verified by the satellite observations. The implications of the simulation results to the influences on the diffusive shock acceleration were also discussed in their study.

Satellite observations clearly reveal that superthermal electrons in space plasma generally possess a pronounced non-Maxwellian distribution that can be well modeled by a κ distribution. Lu, Zhou and Wang[46] performed one dimensional (1D) particle in-cell simulations to investigate the evolution of whistler waves driven by superthermal electrons with a typical κ distribution in the presence of a cold plasma population. The results obtained from the linear theory are first confirmed: with the increase of the spectral index κ for the κ distribution, the linear growth rate of the excited waves increases and instability threshold for the temperature anisotropy ($A = T_\perp/T_\parallel - 1$) decreases. Then they further found that with the increase of κ, the fluctuating magnetic field energy density at the saturation stage also increases. Therefore, from both the linear growth rate and the fluctuating magnetic field energy density at the saturation stage, they can find that a bi-Maxwellian distribution ($\kappa \to \infty$) overestimates the importance of whistler waves, since the observed value of κ lies in the range $2 \leqslant \kappa \leqslant 6$. They also found that the κ values of the electron distributions become smaller with the excitation of the whistler waves.

6 Prediction Methods

Turner and Li[47] discussed a strong correlation between the behavior of low-energy (tens to hundreds of keV) and high-energy (> 1 MeV) electron fluxes measured at geosynchronous orbit, and this correlation is further enhanced when a time offset is taken into account. A model has been developed incorporating this delay time between similar features in low- and high-energy electron fluxes to forecast the logarithm of daily averaged, 1.1–1.5 MeV electron flux at geosynchronous orbit several days in advance. The model uses only the current and previous days' daily averaged fluxes of low- and high-energy electrons as input. Parameters in the model are set by optimizing Prediction Efficiency (PE) for the years 1995–1996, and the optimized PE for these 2 years is 0.81. The model is run for more than one full solar cycle (1995–2006), and it consistently performs significantly better than a simple persistence model, where tomorrow's forecasted flux is simply today's value. Model results were also compared with an inward radial diffusion forecast model, in which the diffusion coefficient is a function of solar wind parameters. When the two models are combined, the resulting model performs better overall than each does individually.

Li *et al.*[48] investigated methods to improve the predictions of Shock Arrival Time (SAT) of the original Shock Propagation Model (SPM). According to the classical blast wave theory adopted in the SPM, the shock propagating speed is determined by the total energy of the original explosion together with the background solar wind speed. Noting that there exists an intrinsic limit to the transit times computed by the SPM predictions for a specified ambient solar wind, they presented a statistical analysis on the forecasting capability of the SPM using this intrinsic property. Two facts about SPM were found: (1) the error in shock energy estimation is not the only cause of the prediction errors and they should not expect that the accuracy of SPM to be improved drastically by an exact shock energy input; and (2) there are systematic differences in prediction results both for the strong shocks propagating into a slow ambient solar wind and for the weak shocks into a fast medium. Statistical analyses indicate the physical details of shock propagation and thus clearly point out directions of the future improvement of the SPM. A simple modification was presented, which shows that there is room for improvement of SPM and thus that the original SPM is worthy of further development.

In recent years remarkable advances have been made in the development of physics based models of various parts of the solar-terrestrial system. Wu *et al.*[49] focused their discussions in a specific region of the Sun to the Earth's environment (*i.e.*, 1 AU). It is well-known that geomagnetic storms are caused by solar eruptions. The consequences of these storms include particle acceleration, solar wind impact on the Earth's magnetosphere and ionosphere, UV-EUV radiation effects on the lower atmosphere, etc. One of the main challenges is to predict the arrival time at 1 AU of the solar disturbance. The prospects look good for an accurate, real-time forecast scheme built on the acquisition of solar, heliosphere and the near-Earth data and large-scale models. However, the accuracy of these models still needs improvement. They discussed the present status of the models and challenges to improve the simulation models.

A practical database method for predicting the interplanetary shock arrival time at L1 point was given by Feng *et al.*[50]. First, a shock transit time database (hereinafter called Database-I) based on HAFv.1 (version 1 of the Hakamada-Akasofu-Fry model) is preliminarily established with hypothetical solar events. Then, on the basis of the prediction test results of 130 observed solar events during the period from February 1997 to August 2002, Database-I is modified to create a practical database method, named Database-II, organized on a multidimensional grid of source location, initial coronal shock speed, and the year of occurrence of the hypothetical solar event. The arrival time at L1 for any given solar event occurring in the 23rd solar cycle can be predicted by looking up in the grid of Database-II according to source location, the initial coronal shock speed, and the year of occurrence in cycle 23. Within the hit window of $\pm 12\,\mathrm{h}$, the success rate of the Database-II method for 130 solar events is 44%. This could be practically equivalent to the Shock Time of Arrival (STOA) model, the Interplanetary Shock Propagation Model (ISPM), and the HAFv.2 model. To explore the capability of this method, it is tested on new data sets. These tests give reasonable results. In particular, this method's performance for a set of events in other cycles is as good as that of the STOA and ISPM models. This gives us confidence in its application to other cycles. From the viewpoint of long-term periodicity for solar activity, it is expected that the Database-II method can be applicable to the next solar cycle 24.

With the purpose of operational real-time forecasting for arrival times of flare/coronal mass ejection associated shocks in the vicinity of the Earth, Feng *et al.*[51] established a one-dimensional hydrodynamic (HD) shock propagation model by a novel numerical scheme, the space-time conservation element and solution element (CESE) method. The required observational data inputs to this new one-dimensional CESE-HD model are the low coronal radio Type II drift speed, the duration estimation, and the background solar wind speed for a solar eruptive event. Applying this model to 137 solar events during the period of February 1997 to August 2002, it is found that their model could be practically equivalent to the STOA, ISPM, HAFv.2, and SPM models in forecasting the shock arrival time. The absolute error in the transit time from their model is not larger than those of the other four models for the same set of events. These results may demonstrate the potential capability of their model in terms of improving real-time forecasting because the CESE method can be extended to three-dimensional magnetohydrodynamics (3D-MHD) from the solar photosphere to any heliospheric position.

Real-time prediction of the arrival times at Earth of shocks is very important for space weather research. Recently, various models for shock propagation are used to forecast the shock arriving times (SATs) with information of initial coronal shock and flare from near real-time radio and X-ray data. Qin, Zhang and Rassoul[52] added the use of solar energetic particles (SEP) observation to improve the shock arrival time (SAT) prediction. High-energy SEPs originating from flares move to the Earth much faster than the shocks related to the same flares. They developed an SAT prediction model by combining a well-known shock propagation model, STOA, and the analysis of SEPs detected at Earth. They demonstrated that the SAT predictions are improved by the new model with the help of 3853 keV electron SEP observations. In particular, the correct prediction to false alarm ratio is improved significantly.

Song[53] presented an analytical model to predict the arrival time of coronal mass ejections (CMEs). All related calculations are based on the expression for the deceleration of fast CMEs in the interplanetary medium (ICMEs), $v = -(v - V_{\mathrm{SW}})^2/15700$, where V_{SW} is the solar wind speed. The results can reproduce well the observations of three typical parameters: the initial speed of the CME, the speed of the ICME at 1 AU and the transit time. This simple model reveals that the drag acceleration should be really the essential feature of the interplanetary motion of CMEs.

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