Interplanetary Physics Research in China: 2006—2008*

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Abstract  This brief report summarized the latest advances of the interplanetary physics research in China during the period of 2006—2007, made independently by Chinese space physicists and through international collaboration. The report covers all aspects of the interplanetary physics, including theoretical studies, numerical simulation and data analysis.

Key words  Solar wind plasma, Energetic particles, Coronal mass ejection, Interplanetary shock

1 Solar Wind and Interplanetary CMES/Shocks

Solar flares and metric type II radio bursts are one kind of preliminary manifestations of solar disturbances and they are fundamental for predicting the arrival of associated Interplanetary (IP) shocks at Earth. Zhao, Feng and Wu[1] statistically studied 347 solar flare type II radio burst events during 1997.2—2002.8 and found (1) only 37.5% of them were followed by the IP shocks at L1 (in other words, at Earth), the others without such IP shocks account for 62.5%; (2) the IP shocks associated with intense flares have large probability to arrive at Earth; (3) the IP shocks associated with central flares are more likely to arrive at Earth than those associated with the limb flares, and the most probable location for flares associated with IP shocks at Earth is 20°W; and (4) there exists a east-west asymmetry in the distribution of geoeffectiveness of flare-associated IP shocks along the flare longitude. Most severe geomagnetic storms ($Dst_{\text{min}} \leq 100$ nT) are usually caused by flare-associated shocks originating from western hemisphere or middle regions near central meridian, and the most probable location for strong flares associated with more intense geomagnetic storms is 20°W as well. These results could provide some criteria to estimate whether the associated shock would arrive at Earth and corresponding geomagnetic storm intensity.

Based on the same data set, Zhao et al[2] investigate the relative positions between the flare sources, the Heliospheric Current Sheet (HCS), and the Earth and found the following results. (1) Solar flares are usually distributed within $[30^\circ S, 30^\circ N]$ in heliographic latitude and $[30^\circ S, 30^\circ N] \times [10^\circ E, 30^\circ W]$ is the predominant source region on the solar disk that includes the majority of geoeffective solar flares. (2) The shocks with the associated flares located near the HCS would have a lower probably of reaching the Earth. For the Earth-encountered shocks, their initial speeds are distinctly higher when their associated flares are located near the HCS. (3) The angular distance from the flare source to the Earth (defined as $\Psi$ below) also contributes to the probability of the associated shock being observed at the Earth. The shock arrival probability decreases with the increment of $\Psi$ and the mean initial shock speed increases with $\Psi$ for those Earth-encountered shocks. (4) The so-called “same-opposite side effect” of the HCS is confirmed to exist. That is, the shocks whose associated flares are located on the same side of the HCS as the Earth (called as “same side events”) have a greater chance of reaching the Earth than those shocks with their associated flares on the opposite side (“opposite side events”). Here for the first time, a comprehensive sample of solar transient events of both arriving and nonarriving ones (at Earth) is used to testify to the

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same-opposite side effect. These results would be valuable in understanding the solar-terrestrial relations, and helpful for space weather prediction.

The electromagnetic wave growth or damping depends basically on the number density and anisotropy of energetic particles as the resonant interaction takes place between the particles and waves in the magnetosphere. Xiao and Feng[3] systematically evaluated the variance of both the number density and anisotropy along the magnetic field line by modeling four typically prescribed distribution functions. It is shown that in the case of “the positive anisotropy” (namely, the perpendicular temperature $T_{\perp}$ exceeds the parallel temperature $T_{\parallel}$), the number density of energetic electrons always decreases with the magnetic latitude for a regular increasing magnetic field and the maximum wave growth is therefore generally confined to the equator where the resonant energy is minimum, and the number density is the largest. However, the “loss-cone” anisotropy of the electrons with a “pancake” distribution or kappa distribution keeps invariant or nearly invariant, whereas the “temperature” anisotropy with a pure bi-Maxwellian distribution or Ashour-Abdalla and Kennel’s distributions decreases with the magnetic latitude. The results may provide a useful approach to evaluating the number density and anisotropy of the energetic electrons at latitudes where the observation information is not available.

During solar cycle 23, 82 interplanetary Magnetic Clouds (MCs) were identified by Wu et al[4] using Wind (1995—2003) solar wind plasma and magnetic field data from solar minimum through the maximum of cycle 23. The average occurrence rate is 9.5 MCs per year for the overall period. It is found that some of the anomalies in the frequency of occurrence were during the early part of solar cycle 23: (1) only four MCs were observed in 1999, and (2) an unusually large number of MCs (17 events) were observed in 1997, just after solar minimum. The relationship between MCs, Coronal Mass Ejections (CMEs), and geomagnetic storms are also discussed. During the period 1996—2003, almost 8000 CMEs were observed by SOHO-LASCO. The occurrence frequency of MCs appears to be related neither to the occurrence of CMEs as observed by SOHO LASCO nor to the sunspot number. If the “Magnetic Cloud-Like Structures” (MCLs) are included, it is found that the occurrence of the joint set (MCs+MCLs) is correlated with both sunspot number and the occurrence rate of CMEs. The average duration of the MCL structures is about 40% shorter than that of the MCs. The MCs are typically more geoeffective than the MCLs, because the average southward field component is generally stronger and longer lasting in MCs than in MCLs. In addition, most severe storms caused by MCs/MCLs with $Dst_{\text{min}} \leq -100\text{nT}$ occurred in the active solar period. The following characteristics of MCs and MCL structures are also found by Wu and Lepping[5]: (1) The average duration, $\Delta t$, of MCs is 21.1 h, which is 40% longer than that for MCLs ($\Delta t = 15\text{h}$); (2) the average $B_{z,\text{min}}$ (minimum $B_z$ found in MC/MCL measured in geocentric solar ecliptic coordinates) is $-10.2\text{nT}$ for MCs and $-6\text{nT}$ for MCLs; (3) the average $Dst_{\text{min}}$ (minimum $Dst$ caused by MCs/MCLs) is $-82\text{nT}$ for MCs and $-37\text{nT}$ for MCLs; (4) the average solar wind velocity is $453\text{km}\cdot\text{s}^{-1}$ for MCs and $413\text{km}\cdot\text{s}^{-1}$ for MCLs; (5) the average thermal speed is $24.6\text{km}\cdot\text{s}^{-1}$ for MCs and $27.7\text{km}\cdot\text{s}^{-1}$ for MCLs; (6) the average magnetic field intensity is $12.7\text{nT}$ for MCs and $9.8\text{nT}$ for MCLs; (7) the average solar wind density is $3.7\text{cm}^{-3}$ for MCs and $6.3\text{cm}^{-3}$ for MCLs; and (8) a MC is one of the most important interplanetary structures capable of causing severe geomagnetic storms.

The observational data of 70 magnetic cloud Boundary Layers (BLs) from the Three-Dimensional (3D) Plasma and Energetic Particle (3DP) and 50 BLs from the Solar Wind Experiment (SWE) instruments on Wind spacecraft from February 1995 to June 2003 are analyzed by Wei et al[6]. It is 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. The main results are that (1) the BL is often a non-pressure-balanced structure with the magnetic pressure decrease associated with the abrupt variation of field direction angle $(\theta, \phi)$ for about 90% and more than 85% of the BLs investigated from 3DP and SWE data, respectively; (2) the events of heated and accelerated plasma in the BLs are about 90%, 85% and 85%, 82% of the BLs investigated, respectively, from 3DP and SWE data; (3) the reversal flows are observed and their occurrence ratio is as high as 80% and 90% of the BLs investigated from 3DP and SWE data, respectively; and (4)
the plasma and field characteristics for the BLs are also obviously different from those in the Jump Layers (JLs) of shock waves. These results show that there exist important dynamic interactions inside the BLs. As a preliminary interpretation, this could be associated with the magnetic reconnection process possibly occurring inside the BLs. Thus the study of the BLs, as a new non-pressure balanced structure in interplanetary space, could open a “new window” for revealing some important physical processes in interplanetary space.

The observations of the slow shocks associated with the interplanetary coronal mass ejections near 1 AU have seldom been reported in the past several decades. Zuo et al\cite{7} report the identification of an interplanetary slow shock observed by Wind on September 18, 1997. This slow shock is found to be just the front boundary of a magnetic cloud boundary layer. A self-consistent method based on the entire R-H relations is introduced to determine the shock normal. It is found that the observations of the jump conditions across the shock are in good agreement with the R-H solutions. The intermediate Mach number $M_i = u_n/(v_A \cos \theta_B)$ is less than 1 on both sides of the shock. In the upstream region, the slow Mach number $M_{s1} = u_{n1}/v_{s1}$ is 1.44 (above unity), and in the downstream region, the slow Mach number $M_{s2} = u_{n2}/v_{s2}$ is 0.8 (below unity). Here $v_s$ and $v_A$ represent the slow magnetoacoustic speed and Alfven speed respectively. In addition, the typical interior magnetic structure inside the shock layer is also analyzed using the 3 s time resolution magnetic field data since the time for the spacecraft traversing the shock layer is much longer (about 17 s). As a potential explanation to the formation of this kind of slow shock associated with magnetic clouds, this slow shock could be a signature of reconnection that probably occurs inside the magnetic cloud boundary layer.

The magnetic cloud Boundary Layer (BL) is a disturbance structure that is located between the magnetic cloud and the ambient solar wind. Zuo et al\cite{8} statistically analyze the characteristics of the magnetic field $B_z$ component (in GSM coordinates) inside the magnetic cloud boundary layers as well as the relationship between the magnetic cloud boundary layers and the magnetospheric substorms based on 35 typical BLs observed by Wind from 1995 to 2006. It is found that the magnetic field $B_z$ components are more turbulent inside the BLs than those inside the adjacent sheath regions and the magnetic clouds. The substorm onsets are identified by the auroral breakups that are the most reliable substorm indicators by using the Polar UVI image data. The UVI data are available only for 17 BLs. The statistical analysis indicated that 9 of the 17 events triggered the substorms when BLs crossed the magnetosphere and that the southward field in the adjacent sheath region is a necessary condition for these triggering events. In addition, the SF-type BLs, named by their features of the $B_z$ components inside the BLs and adjacent sheath regions, can easily trigger the substorms during their passage of the magnetosphere. SF-type BLs are characterized by sustained strong southward magnetic fields persisting for at least 30 minutes in the adjacent sheath regions and at least one change in the polarity of the $B_z$ component inside the BL. 7 out of 8 such SF-type BL events triggered the substorm expansion phase, suggesting that the SF-type BLs are another important interplanetary disturbance source of substorms.

A double discontinuity is a rarely observed compound structure composed of a slow shock layer and an adjoining rotational discontinuity layer in the downstream region. Zuo and Feng\cite{9} report the observations of a double discontinuity detected by Wind on May 15, 1997. This double discontinuity is found to be the front boundary of a magnetic cloud boundary layer. The shock layer and the rotational discontinuity layer are strictly identified by using the high-resolution plasma and magnetic field data from Wind. The observed jump conditions of the upstream and downstream region of the slow shock layer are in good agreement with the Rankine Hugoniot relations. The flow speeds in the shock frame $u_n < v_A \cos \theta_B$ on both sides of the slow shock layer. In the upstream region, the slow Mach number $M_{s1} = u_{n1}/v_{s1}$ is 1.95 (above unity), and in the downstream region, the slow Mach number $M_{s2} = u_{n2}/v_{s2}$ is 0.31 (below unity). Here $v_A$ and $v_s$ represent the Alfven speed and the local slow magnetoacoustic speed, respectively, and $\theta_B$ is the angle between the direction of the magnetic field and the shock normal. The magnetic cloud boundary layer observed by Wind was also detected by Geotail 48 min later when the spacecraft was located outside the bow shock of the magnetosphere. However, Geo-
A magnetic cloud event observed by ACE at Earth on 4—6 March 1998 is tracked from the location of ACE to Ulysses by Du et al\cite{10}. They propagate the ACE data to the location of Ulysses and confirm that the two magnetic clouds observed by both spacecraft have the same solar origin. The Grad-Shafranov (GS) reconstruction technique is then employed to recover the 2.5D cross sections of the magnetic clouds at locations of ACE and Ulysses, respectively. The magnetic clouds observed at ACE and Ulysses both show magnetic flux rope configurations of the same chirality and unidirectional axial magnetic field along approximately the same direction. It is found that the magnetic cloud is expanding while propagating outward. Their relevant toroidal (axial) and poloidal magnetic flux contained within each flux rope are different but approximately of the same order of magnitude. However, the relative magnetic helicity contained in each flux rope differs significantly.

2 MHD Simulations

The solar wind plays an important role in the study of space weather prediction. It can be used for measuring the arrival time of solar disturbances at 1AU. Wu et al\cite{11,12} track a group of specific solar events’ plasma and magnetic field output as they propagate into interplanetary space. A one-dimensional, time-dependent adaptive grid MHD code is used to study the evolution and interaction of shocks from Sun through the heliosphere. The MHD simulation results demonstrate that the solar wind speed might increase about 25\% after two shocks collide with each other. This kind of interaction can affect the accuracy of the identification of the solar source that causes the interplanetary event. In this study they further simulate part of the famous Halloween 2003 events that contain at least four major solar events (flares) during 28 October to 1 November 2003. These major events, simulated by pressure pulses, generated shocks that matched well with ACE observations as reported in previous study.

A newly developed hybrid code, HAFv.2+3D MHD, that combines two simulation codes, Hakamada-Akasofu-Fry code version 2 (HAFv.2) and a fully three-dimensional, time-dependent MHD simulation code, is used by Wu et al\cite{13,14} to study the global Interplanetary Coronal Mass Ejection (ICME) from the 12 May 1997 solar event. The derived ICME velocity and number density are compared with the Wind spacecraft observations near Earth. The integrated line-of-sight density in the plane of sky is compared with the white light brightness data observed by the Large-Angle Spectrometric Coronagraph (LASCO) instrument on SOHO. This simulation will provide a tool to link the general cases of ICME at 1AU to their solar sources, as well as to identify the possible origins of shock formation due to CMEs and CME/corotating interaction region interactions. The results show that both CMEs and heliosphere current sheet/plasma sheet were deformed by interacting with each other.

Shen et al\cite{15} used a 3D time-dependent, numerical Magnetohydrodynamic (MHD) model to investigate the propagation of Coronal Mass Ejections (CMEs) in the nonhomogenous background solar wind flow. On the basis of the observations of the solar magnetic field and K-coronal brightness, the self-consistent structure on the source surface of 2.5 $R_{\odot}$ is established with the help of MHD equations. Using the self-consistent source surface structures as initial-boundary conditions, they develop a 3D MHD regional combination numerical model code to obtain the background solar wind from the source surface of 2.5 $R_{\odot}$ to the Earth’s orbit (215 $R_{\odot}$) and beyond. This model considers solar rotation and volumetric heating. Time-dependent variations of the pressure and velocity configured from a CME model at the inner boundary are applied to generate transient structures. The dynamical interaction of a CME with the background solar wind flow between 2.5 and 215 $R_{\odot}$ (1AU) is then investigated. The well-defined halo-CME event of 6—12 January 1997 is chosen as a test case. Because detailed observations of this disturbance at 1AU (by WIND spacecraft) are available, this event provides an excellent opportunity to verify their MHD methodology and to learn about the physical processes of the Sun-Earth connection. It is found that this 3D MHD model, with the self-consistent structures on the source surface as input, provides a relatively satisfactory comparison with the
WIND spacecraft observations.

A three-dimensional MHD simulation is conducted by Xiang et al\textsuperscript{[16]} to study the steady solar wind in Carrington Rotation (CR) 1935 by using the three-dimensional numerical Magnetohydrodynamic (MHD) model introduced by Feng et al. The numerical results demonstrate that the neutral current sheet has two peaks and two valleys, which is consistent with the result of PFSS model at Wilcox Solar Observatory (WSO). The obtained proton number density at 2.5 $R_s$ is of the same order of magnitude as the result estimated from K-coronal brightness during the CRs 1733\textendash 1742 in 1983 made. The radial velocity profile along heliocentric distance is consistent with that of low solar wind speed deduced by Wang-Sheeley model. However, it is not able to reproduce the fast-speed flow in coronal holes and slow solar wind in streamers because of oversimplified energy equation adopted in our model. Future efforts must be made to remedy this deficiency.

Xiang et al\textsuperscript{[17]} used photospheric magnetic field measurements and coronal polarized brightness observations as constrains to develop a single-fluid solar wind background mode 1, which includes proton density, bulk velocity and magnetic field. Proton temperature will be dealt with in further studies. The synoptic maps of K-corona polarized Brightness (pB) at 1\textendash 36 solar radii observed by MKIII in High Altitude Observatory (HAO) are applied to derive corona density according to the solar wind density model constructed by Guhathakurta in 1996. In order to determine the global magnetic field, the synoptic maps of photospheric magnetic field in Wilcox Solar Observatory (WSO) are adopted to be the bottom boundary condition of the model of Horizontal Current and Current Sheet (HCCS) established by Zhao in 1994. Researches on observations during Ulysses' first and second polar fly-byes made by Phillips in 1995 and McComas in 2003 demonstrate that the solar wind momentum flux density scaled to 1 AU is almost invariant except that it is slightly small in the latitude of $\pm 10^\circ \sim 30^\circ$, thus the solar wind speed can be derived from this conclusion and the obtained density data. The model is applied to study the solar wind background in Carrington Rotation (CR) 1918 and the results are roughly consistent with the observations in solar minimum. However, the area of high density and slow speed is slightly larger than that observed and thus the density model needs to be further improved.

Numerical studies of the interplanetary "Multiple Magnetic Clouds (Multi-MC)" are performed by a 2.5-dimensional ideal Magnetohydrodynamic (MHD) model in the heliospheric meridional plane\textsuperscript{[18]}. Both slow MC1 and fast MC2 are initially emerged along the heliospheric equator, one after another with different time intervals. The coupling of two MCs could be considered as the comprehensive interaction between two systems, each comprising of an MC body and its driven shock. The MC2-driven shock and MC2 body are successively involved into interaction with MC1 body. The momentum is transferred from MC2 to MC1. After the passage of MC2-driven shock front, magnetic field lines in MC1 medium previously compressed by MC2-driven shock are prevented from being restored by the MC2 body pushing. MC1 body undergoes the most violent compression from the ambient solar wind ahead, continuous penetration of MC2-driven shock through MC1 body, and persistent pushing of MC2 body at MC1 tail boundary. As the evolution proceeds, the MC1 body suffers from larger and larger compression, and its original vulnerable magnetic elasticity becomes stiffer and stiffer. So there exists a maximum compressibility of Multi-MC when the accumulated elasticity can balance the external compression. This cutoff limit of compressibility mainly decides the maximally available geoeffectiveness of Multi-MC because the geoeffectiveness enhancement of MCs interacting is ascribed to the compression. Particularly, the greatest geoeffectiveness is excited among all combinations of each MC helicity, if magnetic field lines in the interacting region of Multi-MC are all southward. Multi-MC completes its final evolutionary stage when the MC2-driven shock is merged with MC1-driven shock into a stronger compound shock. With respect to Multi-MC geoeffectiveness, the evolution stage is a dominant factor, whereas the collision intensity is a subordinate one. The magnetic elasticity, magnetic helicity of each MC, and compression between each other are the key physical factors for the formation, propagation, evolution, and resulting geoeffectiveness of interplanetary Multi-MC.

3 Space Weather Prediction Method

Solar transient activities such as solar flares, dis-
appearing filaments, and Coronal Mass Ejections (CMEs) are solar manifestations of Interplanetary (IP) disturbances. Forecasting the arrival time at the near Earth space of the associated interplanetary shocks following these solar disturbances is an important aspect in space weather forecasting because the shock arrival usually marks the geomagnetic Storm Sudden Commencement (SSC) when the IMF \( B_z \) component is appropriately southward and/or the solar wind dynamic pressure behind the shock is sufficiently large. Combining the analytical study for the propagation of the blastwave from a point source in a moving, steady-state, medium with variable density with the energy estimation method in the ISP model, Feng and Zhao\(^\text{[19]}\) present a new Shock Propagation Model (called SPM below) for predicting the arrival time of interplanetary shocks at Earth. The duration of the X-ray flare, the initial shock speed and the total energy of the transient event are used for predicting the arrival of the associated shocks in the model. Especially, the background speed, i.e., the convection effect of the solar wind is considered in this model. Applying this model to 165 solar events during the periods of January 1979 to October 1989 and February 1997 to August 2002, it is found that their model could be practically equivalent to the prevalent models of STOA, ISPM and HAFv.2 in forecasting the shock arrival time. The absolute error in the transit time in our model is not larger than those of the other three models for the same sample events. Also, the prediction test shows that the relative error of our model is \( \leq 10\% \) for 27.88\% of all events, \( \leq 30\% \) for 71.52\%, and \( \leq 50\% \) for 85.46\%, which is comparable to the relative errors of the other models. These results might demonstrate a potential capability of their model in terms of real-time forecasting.

Wang \textit{et al}\(^\text{[20]}\) do a statistical survey of solar wind dynamic pressure \( (P_d) \) pulses and geosynchronous magnetic field observations between 1998 and 2005. In geomagnetic quiet times with \( Dst > -50 \text{nT} \), we find 111 solar wind dynamic pressure pulses which produce geosynchronous magnetic field responses. These responses are often observed by two or three GOES spacecraft at different local times in geosynchronous orbit. The magnitudes of the geosynchronous magnetic field changes \( (dB_z) \) have a peak near the noon meridian, similar to the results obtained in the study of the response of the geosynchronous field to the large and sharp solar wind dynamic pressure variations. However, the relative change of the geosynchronous magnetic field \( dB_z / B_z \) (where \( B_z \) is the average of the geosynchronous magnetic field \( B_z \) observed during the response to the pressure pulse) depends weakly on the local time; thus the change of \( B_z \) \( (dB_z) \) is proportional to the average field \( (B_z) \). As the magnitude of the relative change of solar wind dynamic pressure \( (dP_d / P_d) \) increases, the rate of geosynchronous magnetic field variation increases correspondingly. These results imply that the magnitude of the geosynchronous magnetic field response could be determined by \( B_z \). In addition, the interplanetary field orientation does not affect the response significantly. Using an MHD code which models the global behavior of the solar wind-magnetosphere-ionosphere system, they reproduce the main characteristics of the observations.

Using 100 CME-ICME events during 1997.01—2002.11, based on the eruptive source locations of CMEs and solar magnetic field observations at the photosphere, a Current sheet Magnetic Coordinate (CMC) system is established by Feng and Zhao\(^\text{[21]}\) in order to statistically study the characteristics of the CME-CICME events and the corresponding geomagnetic storm intensity. The transit times of CMEs from the Sun to the Earth are also investigated, by taking into account of the angle between the CME eruption normal (defined as the vector from the Sun center to the CME eruption source) and the Sun-Earth line. Their preliminary conclusions are: (1) The distribution of the CME sources in the CMC system is obviously different from that in the ordinary heliographic coordinate system. The sources of CMEs are mainly centralized near the Heliospheric Current Sheet (HCS), and the number of events decreases with the increment of the angular distance from the CME source to the HCS on the solar surface. (2) A large portion of the total events belong to the same-side events (referring to the CME source located on the same side of the HCS as the Earth), while only a small portion belong to the opposite-side events (the CME source located on the opposite side of the HCS as the Earth). (3) The intense geomagnetic storms are usually induced by the same-side events, while the opposite side events are commonly associated with relatively weak geomagnetic storms. (4) The angle between the CME normal and the Sun-Earth line is
used to estimate the transit time of the CME in order to reflect the influence of propagation characteristic of the CME along the Sun-Earth direction. With their new prediction method in context of the CMC coordinate, the averaged absolute error for these 100 events is 10.33 hours and the resulting relative error is not larger than 30% for 91% of all the events.

In late October and early November 2003, a series of space weather hazard events erupted in solar-terrestrial space. Aiming at two intense storm (shock) events on 28 and 29 October, Xie et al.\cite{22,23} presents a Two-Step method, which combines synoptic analysis of space weather—“observing” and quantitative prediction—“palpating”, and uses it to test predictions. In the first step, “observing”, on the basis of observations of the source surface magnetic field, Interplanetary Scintillation (IPS) and ACE spacecraft, it is found that the propagation of the shock waves is asymmetric and northward relative to the normal direction of their solar sources due to the large-scale configuration of the coronal magnetic fields, and the Earth is located near the direction of the fastest speed and greatest energy of the shocks. Being two fast ejection shock events, the fast explosion of extremely high temperature and strong magnetic field, and background solar wind velocity as high as 600 and 1000 km s$^{-1}$, are also helpful to their rapid propagation. According to the synoptic analysis, the shock travel times can be estimated as 21 h and 20 h, which are close to the observational results of 19.97 h and 19.63 h, respectively. In the second step, “palpating”, they adopt a new membership function of the fast shock events for the ISF method. The predicted results here show that for the onset time of the geomagnetic disturbance, the relative errors between the observational and the predicted results are 1.8% and 6.7%, which are consistent with the estimated results of the first step; and for the magnetic disturbance magnitude, the relative errors between the observational and the predicted results are 4.1% and 3.1%, respectively. Furthermore, the comparison among the predicted results of the Two-Step method with those of five other prevailing methods shows that the Two-Step method is advantageous in predicting such strong shock event. It can predict not only shock arrival time, but also the magnitude of magnetic disturbance. The results of the present paper reveal that understanding the physical features of shock propagation thoroughly is of great importance in improving the prediction efficiency.

Using 180 Interplanetary (IP) shock events associated with Coronal Mass Ejections (CMEs) during 1997—2005, Xie et al.\cite{24} investigate the influence of the Heliospheric Current Sheet (HCS) upon the propagation and geoeffectiveness of IP shocks. The preliminary results are: (1) The majority of CME-driving IP shocks occurred near the HCS. (2) The numbers of shock events and related geomagnetic storms observed when the Earth and the solar source are located on the same side of the HCS, represented by $f_{ss}$ and $f_{sg}$, respectively, are obviously higher than those when the Earth and the solar source are located on the opposite sides of the HCS, denoted by $f_{os}$ and $f_{og}$, with $f_{ss}/f_{os} = 126/54$, $f_{sg}/f_{og} = 91/36$. (3) Parameter jumps across the shock fronts for the same-side events are also higher than those for the opposite-side events, and the stronger shocks ($\Delta v \geq 200$ km $s^{-1}$) are mainly attributed to be same-side events, with $f_{osh}/f_{osh} = 28/15$, where $f_{SSH}$ and $f_{osh}$ are numbers of stronger shocks which belong to same-side events and opposite-side events, respectively. (4) The level of the geomagnetic disturbances is higher for the same-side events than for the opposite-side events. The ratio of the number of intense magnetic storms ($Dst < -100$) triggered by same-side events to those triggered by opposite-side events is 25/10. (5) An empirical model is proposed to predict the arrival time of the shock at the Earth, whose accuracy is comparable to that of other prevailing models. These results show that the HCS is an important physical structure, which probably plays an important role in the propagation of interplanetary shocks and their geoeffectiveness.

Using the close degree and membership function and comprehensive evaluation in fuzzy mathematics, in conjunction with the solar observation of CME and IPS observation for the interplanetary solar storms caused by CME, Wang and Feng\cite{25} present a close degree prediction method for geomagnetic disturbance events caused by Coronal Mass Ejection (CME)-shock waves identified by IPS observation. Based on the analysis of 74 geomagnetic disturbance events caused by CME-shock waves identified by IPS observation during 1997—2003, five clustering indices and their weighted fuzzy sets are constructed. Typical fuzzy sets of small, moderate, intense geomag-
netic disturbance events are built based on comprehensive evaluation. By constructing the respective fuzzy set of each event, based on the close degree between the fuzzy set and typical fuzzy sets, the prediction for geomagnetic disturbance magnitudes caused by the events can be obtained. Main results are as follows: For the 74 geomagnetic disturbance events, the prediction accuracy is 53.3% for small geomagnetic disturbance, 100% for moderate geomagnetic disturbances, and 90.20% for intense geomagnetic disturbances. The average precision of this method is 84%. This method is an effective application of fuzzy mathematics to studying the geomagnetic disturbance.

Wang and Feng\cite{26} analyzed the characteristics of accelerating Coronal Mass Ejection (CME) and decelerating CME happening during 1997—2003. Prediction tests are made for geomagnetic disturbance events caused by the gradually accelerating CME-associated interplanetary shock waves and the decelerating CME-associated interplanetary shock waves, which can be identified by Interplanetary Scintillation (IPS) observation during 1997—2003. New membership functions and new correctional item of onset time of geomagnetic disturbances are respectively constituted for two kinds of CME. The main results are: for the onset time of the geomagnetic disturbance in the accelerating CME, the relative error between the observation, \(T_{\text{obs}}\), and the prediction, \(T_{\text{pre}}\), \(\Delta T_{\text{pre}}/T_{\text{obs}} \leq 10\%\) for 21.86% of all events, \(< 30\%\) for 78.13% and \(> 50\%\) for only 9.36%; for the decelerating CME, \(\Delta T_{\text{pre}}/T_{\text{obs}} \leq 10\%\) for 25.00% of all events, \(\leq 30\%\) for 84.37% and \(\geq 50\%\) for only 3.13%. These results show that their method has good feasibility for the geomagnetic disturbance predictions.

Based on the 73 geomagnetic disturbance events caused by Coronal Mass Ejection (CME) associated with interplanetary shock waves and using fuzzy mathematics, Wang and Feng\cite{27} presented a prediction method for geomagnetic disturbances. According to the solar location of CME, the transit time of the interplanetary disturbance, the geomagnetic disturbance magnitude and the velocity jump observed by IPS at the disturbed front, five membership functions \(\mu_\rho, \mu_\varphi, \mu_T, \mu_M, \mu_\Delta\), are constituted. Based on the five membership functions and fuzzy mathematics, prediction tests for the 73 CME associated geomagnetic disturbance events during 1996—2004 are made by considering the influence of CME velocity on the onset time of geomagnetic disturbances. Main results are: (1) For the prediction of the magnetic disturbance onset time, 91.78% is within the range of relative error \(\Delta T_{\text{pre}}/T_{\text{obs}} \leq 30\%\) and 12.33% within \(\Delta T_{\text{pre}}/T_{\text{obs}} > 30\%\); (2) For the prediction of the geomagnetic disturbance amplitudes, 60.27% is within the range of relative error \(\Delta K_p/\Sigma K_{\text{obs}} \leq 30\%\) and 12.33% within \(\Delta K_p/\Sigma K_{\text{obs}} > 50\%\). These results show that the prediction method has good feasibility for geomagnetic disturbance prediction.

4 Energetic Particles

Coronal shocks are important structures, but there are no direct observations of them in solar and space physics. The strength of shocks plays a key role in shock-related phenomena, such as radio bursts and Solar Energetic Particle (SEP) generation. Shen et al\cite{28} proposes an improved method of calculating Alfvén speed and shock strength near the Sun. This method is based on using as many observations as possible, rather than one-dimensional global models. Two events, a relatively slow CME on 2001 September 15 and a very fast CME on 2000 June 15, are selected to illustrate the calculation process. The calculation results suggest that the slow CME drove a strong shock, with Mach number of 3.43–4.18, while the fast CME drove a relatively weak shock, with Mach number of 1.90–3.21. This is consistent with the radio observations, which find a stronger and longer Decameter-Hectometric (DH) type II radio burst during the first event, and a short DH type II radio burst during the second event. In particular, their calculation results explain the observational fact that the slow CME produced a major Solar Energetic Particle (SEP) event, while the fast CME did not. Through a comparison of the two events, the importance of shock strength in predicting SEP events is addressed.

Computation of charged-particle orbits shows that large-amplitude two-dimensional magnetic turbulence supports diffusive transport of charged test particles parallel to the mean magnetic field. This stands in sharp contrast to scattering in the quasi-linear approximation, for which Qin et al\cite{29} show quite generally that the two-dimensional scattering rate vanishes. They also demonstrate that at large amplitude, two-dimensional turbulence makes impor-
tant contributions to the parallel mean free path of particles in mixtures of two-dimensional and slab turbulence. This raises important questions regarding cosmic-ray mean free paths that had been thought to be settled based on quasi-linear theory.

The focused transport equation without adiabatic energy loss is widely used to model Solar Energetic Particles’ (SEP) interplanetary propagation by fitting spacecraft data. Qin et al.\cite{30} incorporate the adiabatic energy loss effect, provided by the divergence of the solar wind flows, into the focused transport equation. The equation is then solved numerically using a time-backward stochastic integration method. They show the comparison between solutions of focused transport equations with and without energy loss. They found the effect of adiabatic cooling is significant on the time profile of the intensity of SEPs. It is also shown that without energy loss, for gradual events, we can only fit the initial phase of SEP events. However, with energy loss, we can fit the entire (initial and decaying) phases. In addition, the values of the mean free path obtained by fitting the SEP events with energy loss is always smaller than that without. The results suggest that including adiabatic cooling effect is another way to partially fix the solar energetic particle mean free paths’ “too small” problem discussed by researcher, i.e., the mean free paths obtained by fitting transport equation to observation data are much larger than the quasi-linear theory results.

Qin\cite{31} obtained a nonlinear theory of the parallel diffusion of charged particles with perpendicular scattering and dynamical turbulence. The combination of the new parallel diffusion theory and the nonlinear guiding center theory shows good agreement with numerical simulations using typical parameters for a solar wind. Furthermore, the combination of the theories has a simpler mathematical form and is more computationally tractable than the weakly nonlinear theory.

Zhang et al.\cite{32} found intensities of about 1–10 MeV relativistic electrons in several energy channels of the High-Energy Telescope (HET) on Ulysses increase dramatically during its flybys of Jupiter in 1992 and 2004. They derived perpendicular diffusion coefficients of these particles by fitting the spatial profile of Jovian electron intensity to a diffusion-convection model of particle transport. It is found that the latitudinal diffusion coefficient during the 2004 Jupiter flyby has to be enhanced from its value during the 1992 Jupiter flyby and it is also enhanced relative to the radial perpendicular diffusion. Such an enhancement of latitudinal particle transport was implied previously through the observations of Jovian electrons, cosmic rays and solar energetic particles at high heliographic latitudes, and now this requirement extends further to low latitude region of the heliosphere. Energy dependence of the perpendicular diffusion coefficient is obtained quite precisely through the variation in the slope of energy spectrum of Jovian electrons. The perpendicular diffusion coefficient increases with energy, which can put a tight constraint on models of the particle transport coefficient. The newest Nonlinear Guiding Center (NLGC) theory of perpendicular diffusion is consistent with this observation, but only when it is combined with a parallel diffusion coefficient from the quasilinear theory in a slab magnetic turbulence without dynamic damping.

References

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