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A Brief Review of Interplanetary Investigations in China from 2014 to 2016

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Abstract Great progress has been made in the research of solar corona and interplanetary physics by the Chinese scientists during the past two years (2014—2016). Nearly 100 papers were published in this area. In this report, we will give a brief review to these progresses. The investigations include: solar corona, solar wind and turbulence, superhalo electron and energetic particle in the inner heliosphere, solar flares and radio bursts, Coronal Mass Ejections (CMEs) and their interplanetary counterparts, Magnetohydrodynamic (MHD) numerical modeling, CME/shock arrival time prediction, magnetic reconnection, solar variability and its impact on climate. These achievements help us to better understand the evolution of solar activities, solar eruptions, their propagations in the heliosphere, and potential geoeffectiveness. They were achieved by the Chinese solar and space scientists independently or *via* international collaborations.

Key words Solar wind, Coronal mass ejection, Solar flare, Interplanetary transients, Space weather

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1 Solar Corona

A jet is a considerable amount of plasma being ejected from the chromosphere or lower corona into the higher corona and is a common phenomenon. Usually, a jet is triggered by a brightening or a flare, which provides the first driving force to push plasma upward. In this process, magnetic reconnection is thought to be the mechanism to convert magnetic energy into thermal, nonthermal, and kinetic energies. However, most jets could reach an unusual high altitude and end much later than the end of its associated flare.

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This fact implies that there is another way to continuously transfer magnetic energy into kinetic energy even after the reconnection. The picture described above is well known in the community, but how and how much magnetic energy is released through a way other than reconnection is still unclear. By studying a prominence-like jet observed by the Atmospheric Imaging Assembly (AIA) onboard the Solar Dynamics Observatory (SDO) and the Extreme Ultraviolet Images (EUVI) telescope onboard Solar Terrestrial Relations Observatory Ahead (STEREO-A), Liu *et al.*[1] found that the continuous relaxation of the post-reconnection magnetic field structure is an important process for a jet to climb up higher than it could through only reconnection. The kinetic energy of the jet gained through the relaxation is 1.6 times that gained from the reconnection. The resultant energy flux is hundreds of times larger than the flux required for the local coronal heating, suggesting that such jets are a possible source to keep the corona hot. Furthermore, rotational motions appear all the time during the jet. The analysis suggests that torsional Alfvén waves induced during reconnection could not be the only mechanism to release magnetic energy and drive jets.

As one of the most intriguing phenomena occurring in the solar atmosphere, solar jets have been studied extensively and deeply in the past few decades. The potential relations and interactions between jets and CMEs are intriguing and could enrich their knowledge of the various physical processes in the solar atmosphere. Liu *et al.*[2] presented multi-point, multi-wavelength observations and analysis of a solar coronal jet and Coronal Mass Ejection (CME) event. Employing the GCS model, they obtained the real (three-dimensional) heliocentric distance and direction of the CME and found it to propagate at a high speed of over $1000\,\mathrm{km{\cdot}s^{-1}}$. The jet erupted before the CME and shared the same source region. The temporal and spatial relationship between these two events leads to the possibility that the jet triggered the CME and became its core. This scenario holds the promise of enriching their understanding of the triggering mechanism of CMEs and their relations to coronal large-scale jets. This work was highlighted by the American Astronomical Society NOVA website in its front page.

Zhang *et al.*[3] presented multi-wavelength observations of a prominence eruption originating from a quadrupolar field configuration, in which the prominence was embedded in a side arcade. Within the two-day period prior to its eruption on 22 October 2012 the prominence was perturbed three times by chromospheric fibrils underneath, which rose upward, became brightened, and merged into the prominence, resulting in horizontal flows along the prominence axis, suggesting that the fluxes carried by the fibrils were incorporated into the magnetic field of the prominence. These perturbations caused the prominence to oscillate and to rise faster than before. The absence of intense heating within the first two hours after the onset of the prominence eruption, which followed an exponential increase in height, indicates that ideal instability played a crucial role. The eruption involved interactions with the other side arcade, leading up to a twin coronal mass ejection, which was accompanied by transient surface brightenings in the central arcade, followed by transient dimmings and brightenings in the two side arcades. They suggest that flux feeding from chromospheric fibrils might be an important mechanism to trigger coronal eruptions.

Liu *et al.*[4] combined observations of the Coronal Multi-channel Polarimeter and the SDO/AIA to study the characteristic properties of (propagating) Alfvénic motions and quasi-periodic intensity disturbances in polar plumes. This unique combination of instruments highlights the physical richness of the processes taking place at the base of the (fast) solar wind. The (parallel) intensity perturbations with intensity enhancements around 1% have an apparent speed of $120\,\mathrm{km{\cdot}s^{-1}}$ (in both the 171 and 193 Å passbands) and a periodicity of 15 minutes, while the (perpendicular) Alfvénic wave motions have a velocity amplitude of $0.5\,\text{km}\cdot\text{s}^{-1}$, a phase speed of $830\,\text{km}\cdot\text{s}^{-1}$, and a shorter period of 5 minutes on the same structures. These observations illustrate a scenario where the excited Alfvénic motions are propagating along an inhomogeneously loaded magnetic field structure such that the combination could be a potential progenitor of the magnetohydrodynamic turbulence required to accelerate the fast solar wind.

Liu *et al.*[5] reported the observation of an X-class long-duration flare which is clearly confined. It appears as a compact-loop flare in the traditional EUV passbands (171 and 195 Å), but in the passbands sensitive to flare plasmas (94 and 131 Å), it exhibits a cusp-shaped structure above an arcade of loops like other long-duration events. Inspecting images in a running difference approach, they find that the seemingly diffuse, quasi-static cusp-shaped structure consists of multiple nested loops that repeatedly rise upward and disappear approaching the cusp edge. Over the gradual phase, they detect numerous episodes of loop rising, each lasting minutes. A differential emission measure analysis reveals that the temperature is highest at the top of the arcade and becomes cooler at higher altitudes within the cusp-shaped structure, contrary to typical long-duration flares. With a nonlinear force-free model, the analysis shows that the event mainly involves two adjacent sheared arcades separated by a T-type Hyperbolic Flux Tube (HFT). One of the arcades harbors a magnetic flux rope, which is identified with a filament that survives the flare owing to the strong confining field. They conclude that a new emergence of magnetic flux in the other arcade triggers the flare, while the preexisting HFT and flux rope dictate the structure and dynamics of the flare loops and ribbons during the long-lasting decay phase, and that a quasi-separatrix layer high above the HFT could account for the cusp-shaped structure.

Gou *et al.*[6] performed a Differential Emission Measure (DEM) analysis of candle-flame-shaped flares observed with the Atmospheric Imaging Assembly onboard the SDO. The DEM profile of flaring plasmas generally exhibits a double peak distribution in temperature, with a cold component around $\lg T \approx 6.2$ and a hot component around $\lg T \approx 7.0$. Attributing the cold component mainly to the coronal background, they propose a mean temperature weighted by the hot DEM component as a better representation of flaring plasma than the conventionally defined mean temperature, which is weighted by the whole DEM profile. Based on the corrected mean temperature, the majority of the flares studied, including a confined flare with a double candle-flame shape sharing the same cusp-shaped structure, resemble the famous Tsuneta flare in temperature distribution, *i.e.*, the cusp-shaped structure has systematically higher temperatures than the rounded flare arcade underneath. However, the M 7.7 flare on 19 July 2012 poses a very intriguing violation of this paradigm: the temperature decreases with altitude from the tip of the cusp toward the top of the arcade; the hottest region is slightly above the X-ray loop-top source that is co-spatial with the emission-measure-enhanced region at the top of the arcade. This signifies that a different heating mechanism from the slow-mode shocks attached to the reconnection site operates in the cusp region during the flare decay phase.

The second peak in the Fe XVI 33.5 nm line irradiance observed during solar flares by the Extreme-Ultraviolet Variability Experiment (EVE) is known as the EUV late phase. Liu *et al.*[7] defined the extremely large late phase because it not only has a bigger peak in the warm 33.5 irradiance profile, but also releases more EUV radiative energy than the main phase. Through detailed inspection of the EUV images from three points of view, it was discovered that aside from the later-phase loop arcades, the main contributor of the extremely large late phase is a hot structure that fails to erupt. This hot structure is identified as a flux rope, which is quickly energized by the flare reconnection and later on continuously produces the thermal energy during the gradual phase. Together with the late-phase loop arcades, the flux rope failing to erupt with the additional heating create the extremely large EUV late phase.

Liu *et al.*[8] studied a Coronal Mass Ejection (CME) associated with an X-class flare whose initiation is clearly observed in the low corona with high-cadence, high-resolution EUV images, providing a rare opportunity to witness the early evolution of an energetic CME in detail. The eruption starts with a slow expansion of cool overlying loops ($\sim$1 MK) following a jet-like event in the periphery of the active region. Underneath the expanding loop system, a reverse S-shaped dimming is seen immediately above the brightening active region in hot EUV passbands. The dimming is associated with a rising diffuse arch ($\sim$6 MK), which they interpret as a preexistent, high-lying flux rope. This is followed by the arising of a double hot channel ($\sim$10 MK) from the core of the active region. The higher structures rise earlier and faster than lower ones, with the leading front undergoing extremely rapid acceleration up to $35\,\mathrm{km\cdot s^{-2}}$. This suggests that the torus instability is the major eruption mechanism and that it is the high-lying flux rope rather than the hot channels that drives the eruption. The compression of coronal plasmas skirting and overlying the expanding loop system, whose aspect ratio h/r increases with time as a result of the rapid upward acceleration, plays a significant role in driving an outward-propagating global EUV wave and a sunward-propagating local EUV wave, respectively.

2 Solar Wind and Turbulence

The edge of the Active Region (AR) is possibly associated with the source of the slow/intermediate solar wind. How the plasma is supplied to the solar wind is not yet investigated. Zhang *et al.*[9] conducted detail study of the edge of the AR 10977. They selected three small regions with positive correlations between the temporal profiles of the radiation intensity and Doppler shift for all the five emission lines as labelled by white boxes in Figure 1. One of the regions show weak dimming, while the other two show weak brightening, indicating a slow draining (replenishing) of plasma in the solar wind flux tubes. They suggest that the plasma supply of the slow/intermediate solar wind at the source region is intermittent and with alternation of draining and replenishing.

Traditionally the out layer of the solar atmosphere is composed of photosphere, chromosphere, transition region, corona. The energy and mass flow to the corona and the solar wind must pass through the transition region. The transition region is important for understanding the heating of the corona and the heating and acceleration of the solar wind. Recently, transit transition region embedded below the traditional transition region was reported by Yan *et al.*[10]. The appearance of the chromospheric absorption lines like Ni II and Fe II, and the self-absorption of Si IV lines formed in the transition region temperature, with additional estimated density information, suggest that the magnetic reconnection occurs in the middle choromsphere and the plasma is heated to the transition region temperature. The self-absorption of Si IV lines is first reported here.

The interchange reconnection scenario, with footpoint shearing flow being used to energize the system and drive the reconnection, is probably an effective way to supply the mass and energy to solar wind. Fast-propagating Magnetosonic Waves (FMWs) has been directly observed by the SDO/AIA. Yang *et al.*[11] performed a numerical investigation of the excitation of FMWs in the interchange reconnection scenario. The modelling results show that the hot ($\sim$10 MK) reconnection outflows and FMWs owing to the interaction between plasmiods and the ambient magnetic field in the outflow region, both appear under the interchange reconnection scenario. The estimated energy flux of FMWs is about 50 times smaller than the energy flux related to the tube-channeled reconnection outflow, indicating that the energetically and dynamically reconnection outflow is far more important than the waves in the energy and mass supply to the solar wind.

Superhalo electrons appear to be continuously present in the interplanetary medium, even during very quiet times, with a power-law spectrum at energies above ~2 keV. Yang *et al.*[12] investigated the generation of superhalo electrons by magnetic reconnection in the solar wind source region, using magnetohydrodynamics and test particle simulations for both single X-line reconnection and multiple X-line reconnection. They find that the direct current electric field, produced in the magnetic reconnection region, can accelerate electrons from an initial thermal energy of $T \approx 10^5$ K up to hundreds of keV. After acceleration, some of the accelerated electrons, together with the nascent solar wind flow driven by the reconnection, propagate upwards along the newly-opened magnetic field lines into interplanetary space, while the rest move downwards into the lower atmosphere. Similar to the observed superhalo electrons at 1 AU, the flux of upward-traveling accelerated electrons versus energy displays a power-law distribution at 2−100 keV, $f(E) \approx E^{-\delta}$, with a δ of 1.5−2.4. For single (multiple) X-line reconnection, the spectrum becomes harder (softer) as the anomalous resistivity parameter α (uniform resistivity η) increases. These modelling results suggest that the acceleration in the solar wind source region may contribute to superhalo electrons.

The wave-particle interaction processes occurring in the solar wind provide crucial information to understand the wave dissipation and simultaneous particle heating in plasma turbulence. One requires observations of both wave fluctuations and particle kinetics near the dissipation range, which have, however, not yet been analyzed simultaneously. He *et al.*[13] showed new evidence of waveparticle interactions by combining the diagnosis of wave modes with the analysis of particle kinetics on the basis of measurements from the WIND spacecraft with a high cadence of about 3 s. Solar wind protons appear to be highly dynamic in their velocity distribution consisting of varying anisotropic core and beam components. The basic scenario of solar wind proton heating through wave-particle interaction is suggested to be the following. Left-handed cyclotron resonance occurs continuously, and is evident from the observed proton core velocity distribution and the concurrent quasi-parallel left-handed Alfvén cyclotron waves. Landau and right-handed cyclotron resonances are persistent and indicated by the observed drifting anisotropic beam and the simultaneous quasi-perpendicular right-handed kinetic Alfvén waves in a general sense.

Traditionally, the energy in solar wind turbulence is considered to be cascaded by the nonlinear interaction between counter-propagating Alfvén Waves (AWs). However, the precise connection between the turbulent fluctuations and the particle kinetics has not yet been established. For the first time, He *et al.*[14] reported the simultaneous observation of counter-propagating magnetohydrodynamic waves in the solar wind turbulence and presented clear evidence of plasma turbulence heating. As opposed to the traditional paradigm with counter-propagating AWs, anti-sunward AWs are encountered by Sunward slow Magnetosonic Waves (SMWs) in this new type of solar wind compressible turbulence. The counter-propagating AWs and SMWs correspond, respectively, to the dominant and sub-dominant populations of the imbalanced Elsässer variables. Nonlinear interactions between the AWs and SMWs are inferred from the non-orthogonality between the possible oscillation direction of one wave and the possible propagation direction of the other. The associated protons are revealed to exhibit bi-directional asymmetric beams in their velocity distributions: sunward beams appear in short, narrow patterns and anti-sunward in broad extended tails. It is suggested that multiple types of wave-particle interactions, *i.e.*, cyclotron and Landau resonances with AWs and SMWs at kinetic scales, are taking place to jointly heat the protons perpendicular and in parallel.

The dissipation of SMWs may play a significant role in heating the solar wind and SMWs contribute essentially to the solar wind compressible turbulence. The interaction between anti-sunward AWs and sunward SMWs has been reported in the new type of solar wind compressible turbulence. It becomes important for people to investigate the role of the SMWs in simulation. Most previous identifications of slow waves utilized the characteristic negative correlation between $\delta|B|$ and $\delta\rho$. However, that criterion does not well identify quasi-parallel slow waves, for which $\delta|B|$ is negligible compared to $\delta\rho$. Zhang *et al.*[15] presented a new method of identification of slow waves, which is applicable for the three-dimensional (3D) compressible simulation. It is based on two criteria that (i) $v_{\rm p}B_0$ (phase speed projected along B_0) is around $v_{\rm A} > c_{\rm s}$, and that (ii) there exists a clear correlation of $\delta v_\parallel$ and $\delta\rho$. This research demonstrates that if $v_{\rm A} > c_{\rm s}$, slow waves possess correlation between $\delta v_\parallel$ and $\delta\rho$, with $\delta\rho/\delta v_\parallel \approx \pm\rho_0/c_{\rm s}$. This method helps to distinguish slow-mode waves from fast and Alfvén waves, both of which do not have this polarity relation. The criteria are insensitive to the propagation angle $\theta_{\rm kB}$, defined as the angle between wave vector k and $\boldsymbol{B}_0$; they can be applied with a wide range of β if only $v_{\rm A} > c_{\rm s}$. Four cases of slow wave trains are identified with this method in their numerical simulation. The slow wave trains seem to deform, probably be caused by interaction with other waves; as a result, fast or Alfvén waves may be produced during the interaction and seem to propagate bi-directionally away. Their identification and analysis of the wave trains provide useful methods for investigations of compressible turbulence in the solar wind or in similar environments, and will thus deepen understandings of slow waves in the turbulence.

Based on theories, the beam instability induced by shock-accelerated ions can generate Upstream-Propagating Alfvén Waves (UPAWs) with a power spectral bump near 0.03 Hz, while the nonlinear wave-wave interaction favors an inverse cascade to create a power law spectrum. Wang *et al.*[16] presented the first observational evidence for the Upstream-Propagating Alfvénic Fluctuations (UPAFs) with power law spectra. They totally found 35 UPAWs and 47 UPAFs with power law spectra, about 47% of which are associated with energetic ion events ($>$ 30 keV). These UPAWs and UPAFs are mostly observed in the slow solar wind. However, their occurrence rate and power behave differently in dependence on the radial distance from the Earth.

The UPAWs related to the Earth's bow shock is often reported. However, the really sunward propagating AWs is rarely reported. Using measurements from the WIND spacecraft, He *et al.*[17] report the observation of sunward propagating AWs in solar wind that is magnetically disconnected from the Earth's bow shock. In the sunward magnetic field sector, they find a period lasting for more than three days in which there existed (during most time intervals) a negative correlation between the flow velocity and magnetic field fluctuations, thus indicating that the related AWs are mainly propagating sunward. The simultaneous observations of counter-streaming suprathermal electrons and non-appearance of interplanetary coronal mass ejection suggest that these AWs are indeed sunward AWs not owing to the deflection of an open magnetic field line. As the scale goes from the magnetohydrodynamic down to the ion kinetic regime, the wave vector of magnetic fluctuations usually becomes more orthogonal to the mean magnetic field direction, and the fluctuations become increasingly compressible, which are both features consistent with quasi-perpendicular kinetic AWs. However, this case shows clear signatures of quasi-parallel sunward propagating ion cyclotron waves. Concurrently, the solar wind proton velocity distribution reveals a sunward field-aligned beam that drifts at about the local Alfvén speed. This beam is found to run in the opposite direction of the normally observed (anti-sunward) proton beam, and is apparently associated with sunward propagating Alfvén/ion cyclotron waves. The results and conclusions of this study enrich their knowledge of solar wind turbulence and foster their understanding of proton heating and acceleration within a complex magnetic field geometry.

MHD discontinuities are ubiquitous in the solar wind and are often found at the origin of turbulence intermittency. They may also play a key role in the turbulence dissipation and heating of the solar wind. How were the discontinuities formed or excited has not been yet well studied. Yang *et al.*[18] investigated how the discontinuities, especially Rotational Discontinuities (RDs), are formed in MHD turbulence. In a simulation of the decaying compressive Three-Dimensional (3D) MHD turbulence with an imposed uniform background magnetic field, they detect RDs with sharp field rotations and little variations of magnetic field intensity, as well as mass density. Based on the analysis of the magnetic field and plasma parameters of one of the identified RDs, the identified RD evolves from the steepening of the Alfvén wave with moderate amplitude, which is caused by the nonuniformity of the Alfvén speed in the ambient turbulence.

The Tangential Discontinuities (TDs) and Rotational Discontinuities (RDs) are found to be the two most important types of discontinuities. Recently, the connection between turbulence intermittency and proton thermodynamics has been observationally investigated. Zhang *et al.*[19] presented numerical results from a three-dimensional MHD simulation with pressure anisotropy and defined new methods for identifying and distinguishing TDs and RDs. Three statistical results obtained for the relative occurrence rates and heating effects were highlighted: (i) RDs tend to take up the majority of the discontinuities along with time, (ii) the thermal states embedding TDs tend to be associated with extreme plasma parameters or instabilities while RDs do not, (iii) TDs have a higher average T as well as perpendicular temperature $T_{\perp}$. The simulation shows that TDs and RDs evolve and contribute to solar wind heating differently.

The power-spectrum index of magnetic fluctuations is a crucial parameter for the characterization of nonlinear interactions affecting the solar wind turbulence. Most previous observations were made for large and moderate amplitude magnetic fluctuations, which include current sheets and intermittent structures. By using measurements from the WIND spacecraft, Wang *et al.*[20] presented magnetic spectral features derived by the fast Fourier transform method from six-minute time series of magnetic fluctuations with low relative amplitudes ($\delta|B|/B_0$) of only 0.05−0.11. When comparing their spectra with those of moderate-amplitude fluctuations ($\delta|B|/B_0 \approx 0.4$), they found that for the low-amplitude fluctuations, the averaged magnetic spectral indices are −1.67 and −1.46, respectively, for small and large sampling angles, *i.e.*, the angle between the Sun-to-Earth radial direction and the mean magnetic field direction. However, for the moderate-amplitude fluctuations, these two indices are −1.89 and −1.70, respectively. This result of the moderate amplitude fluctuations is consistent with that of previous analyses, which, by using the wavelet technique, revealed spectral anisotropy of magnetic fluctuations and yielded an index of −2 in the parallel direction and −5/3 in the perpendicular direction. However, the result found here for the low amplitude fluctuations has not been reported before, and thus will probably initiate new studies aiming to better understand the turbulent nature of such low-amplitude fluctuations. Future studies will help to understand why the spectral anisotropy differs for fluctuations of different amplitudes.

Turbulence in the solar wind was recently reported to be anisotropic, with the average power spectral index close to -2 when sampling is parallel to the local mean magnetic field B_0 and close to $-5/3$ when sampling is perpendicular to the local B_0. This result was widely considered to be observational evidence for the Critical Balance Theory (CBT), which is derived by making the assumption that the turbulence strength is close to one. However, this basic assumption has not yet been checked carefully with observational data. Wang *et al.*[21] presented for the first time the scale dependent magnetic-field fluctuation amplitude, which is normalized by the local B_0 and evaluated for both parallel and perpendicular sampling directions, using two 30-day intervals of Ulysses data. From the results, the turbulence strength is evaluated as much less than one at small scales in the parallel direction. An even stricter criterion is imposed when selecting the wavelet coefficients for a given sampling direction, so that the time stationarity of the local B_0 is better ensured during the local sampling interval. The spectral index for the parallel direction is then found to be -1.75, whereas the spectral index in the perpendicular direction remains close to -1.65. These two new results, namely that the value of the turbulence strength is much less than one in the parallel direction and that the angle dependence of the spectral index is weak, can not be explained by existing turbulence theories, like CBT, and thus will require new theoretical considerations and promote further observations of solar wind turbulence.

Intensive studies have been conducted to understand the anisotropy of solar wind turbulence. However, the anisotropy of Elsässer variables ($Z^{\pm}$) in 2D wave-vector space has yet to be investigated. Yan *et al.*[22] first verified the transformation based on the projection-slice theorem between the power spectral density $\mathrm{PSD_{2D}}$ ($k_{\parallel}$, $k_{\perp}$) and the spatial correlation function $\mathrm{CF_{2D}}$ ($k_{\parallel}$, $k_{\perp}$). Based on the application of the transformation to the magnetic field and the particle measurements from the WIND spacecraft, they investigate the spectral anisotropy of Elsässer variables ($Z^{\pm}$), and the distribution of residual energy E_{R}, Alfvén ratio R_{A}, and Elsässer ratio R_{E} in the ($\boldsymbol{k}_{\parallel}$, $\boldsymbol{k}_{\perp}$) space. The spectra $\mathrm{PSD_{2D}}$ ($\boldsymbol{k}_{\parallel}$, $\boldsymbol{k}_{\perp}$) of B, V, and Z_{major} (the larger of $Z^{\pm}$) show a similar pattern that $\mathrm{PSD_{2D}}$ ($\boldsymbol{k}_{\parallel}$, $\boldsymbol{k}_{\perp}$) is mainly distributed along a ridge inclined toward the $\boldsymbol{k}_{\perp}$ axis. This is probably the signature of the oblique Alfvénic fluctuations propagating outwardly. Unlike those of B, V, and Z_{major}, the spectrum $\mathrm{PSD_{2D}}$ ($\boldsymbol{k}_{\parallel}$, $\boldsymbol{k}_{\perp}$) of Z_{minor} is distributed mainly along the $\boldsymbol{k}_{\perp}$ axis. Close to the $\boldsymbol{k}_{\perp}$ axis, $|E_{\mathrm{R}}|$ becomes larger while R_{A} becomes smaller, suggesting that the dominance of magnetic energy over kinetic energy becomes more significant at small $\boldsymbol{k}_{\parallel}$. R_{E} is larger at small $\boldsymbol{k}_{\parallel}$, implying that $\mathrm{PSD_{2D}}$ ($k_{\parallel}$, $\boldsymbol{k}_{\perp}$) of Z_{minor} is more concentrated along the $\boldsymbol{k}_{\perp}$ direction as compared to that of Z_{major}. The residual energy condensate at small $\boldsymbol{k}_{\parallel}$ is consistent with simulation results in which E_{R} is spontaneously generated by Alfvén wave interaction.

The heliocentric orbits of STEREO-A and B with a separation in longitude increasing by about 45° per year provided Liu *et al.*[23] the unique opportunity to study the evolution of the Heliospheric Plasma Sheet (HPS) on a time scale of up to ~2 days and to investigate the relative locations of HPSs and Heliospheric Current Sheets (HCS). Previous work usually determined the HCS locations based only on the interplanetary magnetic field. A recent study showed that a HCS can be taken as a global structure only when it matches with a Sector Boundary (SB). Using magnetic field and suprathermal electron data, it was also shown that the relative location of HCS and SB can be classified into five different types of configurations. However, only for two out of these five configurations, the HCS and SB are located at the same position and only these will therefore be used for their study of the HCS/HPS relative location. They find that out of 37 SBs in their data set, there are 10 suitable HPS/HCS event pairs. They find that an HPS can either straddle or border the related HCS. Comparing the corresponding HPS observations between STEREO-A and B, they find that the relative HCS/HPS locations are mostly similar. In addition, the time difference of the HPS observations between STEREO-A and B match well with the predicted time delay for the solar wind coming out of a similar region of the Sun. They therefore conclude that HPSs are stationary structures originating at the Sun.

In general, the Heliospheric Current Sheet (HCS), which defines the boundary of sunward and anti-sunward magnetic field, is encased by the slow solar wind. The Stream Interface (SI) represents the boundary between the solar wind plasmas of different origin and/or characteristics. According to earlier studies using data of low time resolution, the SI and HCS get closer further away from the Sun, and the two structures coincide with each other around 5 AU. Huang *et al.*[24] used STEREO data of a much higher time resolution to reveal an unusual case where the SI and HCS are coincident near 1 AU and separated from the so-called True Sector Boundary (TSB) at which the suprathermal electrons change their relative propagation directions. Preliminary analysis suggests that the closed loops in pseudo-streamers continually have interchange reconnection with the open-field lines that lead them, resulting not only in the coincidence of HCS and SI but also in the separation of the TSB from the HCS/SI. They therefore conclude that the interchange reconnection plays an important role in the evolution of slow solar wind.

In general, near 1 AU the Heliospheric Current Sheet (HCS) will be separated from the Stream Interface (SI) by several hours. However, a recent study found a coincidence case of these two structures that differs from those in former studies. This paper presents a statistical study with multi-spacecraft data from 2007 to 2010 to investigate a classification scheme and the stability of the coincidence cases. Based on the relative locations of HCS and True Sector Boundary (TSB), which is defined by the suprathermal electrons Strahl changing pitch angles, and the existence of Heat Flux Dropouts (HFDs) that relate to disconnected magnetic field lines, Huang *et al.*[25] found eleven coincidence cases that can be classified into three categories (Type Ⅰ－Ⅲ). Among them, Type Ⅰ coincidence cases, which connect to ideal HCSs, are the majority (nine cases). Type Ⅱ, having separated TSB and HCS, may relate to complicated interchange reconnection processes (one case). Type Ⅲ has a close connection with HFDs (one case). The statistical results suggest: (i) from 2007 to 2010 they observed eleven coincidence cases near 1 AU that can be classified into three types; (ii) only three out of eleven coincidence cases are observed by several spacecraft with large separation distances, indicating that the coincidence structures may not be stable for a long time; (iii) interchange reconnection and pseudostreamers should play a role in forming these coincidence cases.

Dynamic Pressure Pulses (DPPs) in the solar wind are a significant phenomenon closely related to the solar terrestrial connection and physical processes of solar wind dynamics. In order to automatically identify DPPs from solar wind measurements, Zuo *et al.*[26] developed a procedure with a three-step detection algorithm that is able to rapidly select DPPs from the plasma data stream and simultaneously define the transition region where large dynamic pressure variations occur and demarcate the upstream and downstream region by selecting the relatively quiet status before and after the abrupt change in dynamic pressure. To demonstrate the usefulness, efficiency, and accuracy of this procedure, they have applied it to the WIND observations from 1996 to 2008 by successfully obtaining the DPPs. The procedure can also be applied to other solar wind spacecraft observation data sets with different time resolutions.

Zuo *et al.*[27] performed a statistical survey on the properties of DPPs near 1 AU based on nearly 20 years of observations from the WIND spacecraft. It was found that only a tiny fraction of DPPs (around 4.2%) can be regarded as interplanetary shocks. For most DPPs, the total pressure (the sum of the thermal pressure and magnetic pressure) remains in equilibrium, but there also exists a small fraction of DPPs that are not pressure balanced. The overwhelming majority of DPPs are associated with solar wind disturbances, including coronal mass ejection-related flows, corotating interaction regions, as well as complex ejecta. The annual variations of the averaged occurrence rate of DPPs are roughly in phase with the solar activity during solar cycle 23, and during the rising phase of solar cycle 24.

Turbulence is a chaotic flow regime filled by irregular flows. The dissipation of turbulence is a fundamental problem in the realm of physics. Theoretically, dissipation ultimately cannot be achieved without collisions, and so how turbulent kinetic energy is dissipated in the nearly collisionless solar wind is a challenging problem. Wave particle interactions and Magnetic Reconnection (MR) are two possible dissipation mechanisms, but which mechanism dominates is still a controversial topic. Wang *et al.*[28] analyzed the dissipation region scaling around a solar wind MR region. They found that the MR region shows unique multifractal scaling in the dissipation range, while the ambient solar wind turbulence reveals a monofractal dissipation process for most of the time. These results provide the first observational evidences for intermittent multifractal dissipation region scaling around a MR site, and they also have significant implications for the fundamental energy dissipation process.

3 Superhalo Electron and Energetic Particle in the Inner Heliosphere

Wang *et al.*[29] have derived the particle injections at the Sun for ten good electron/^{3}He-rich Solar Energetic Particle (SEP) events, using a 1.2 AU particle path length. The inferred solar injections of high-energy (10 to 300 keV) electrons and of ~MeV/nucleon ions (carbon and heavier) start with a delay of 17±3 min and 75±14 min, respectively, after the injection of low-energy (0.4 to 9 keV) electrons. The injection duration (averaged over energy) ranges from 200 to 550 min for ions, from 90 to 160 min for low-energy electrons, and from 10 to 30 min for high-energy electrons. Most of the selected events have no reported Hα flares or GOES SXR bursts, but all have Type Ⅲ radio bursts that typically start after the onset of a low-energy electron injection. All nine events with the coverage of the Large Angle and Spectrometric Coronagraph (LASCO) on Solar and Heliospheric Observatory (SOHO) have a relatively fast ($> 570\,\mathrm{km\cdot s^{-1}}$), mostly narrow (about 30°), west-limb Coronal Mass Ejection (CME) that launches near the start of the low-energy electron injection, and reaches an average altitude of ~1.0 and 4.7 R_s, respectively, at the start of the high-energy electron injection and of the ion injection.

Wang *et al.*[30] presented a statistical survey of 20−200 keV superhalo electrons measured at 1 AU by the WIND 3D Plasma and Energetic Particle instrument during quiet-time periods from January 1995 to December 2013. The observed omnidirectional differential flux of these quiet-time superhalo electrons generally fits to a power-law spectrum, with β ranging from 1.6 to 3.7 and the integrated density $\mathrm{n_{sup}}$ ranging from 10^{-8} to $10^{-5}\,\mathrm{cm^{-3}}$. In Solar Cycle 23 (24), the distribution of β has a broad maximum between 2.4 and 2.8 (2.0 and 2.4). Both β and the logarithm of n_sup show no obvious correlation with sunspot number, solar flares, solar wind core population, *etc.*

Yang *et al.*[31] presented a comprehensive study of the angular distribution of 20−200 keV superhalo electrons measured at 1 AU by the WIND 3DP instrument during quiet times from January 1995 to December 2005. They found that for ~96% of the selected quiet-time samples, superhalo electrons have isotropic angular distributions, while for ~3% (~1%) of quiet-time samples, superhalo electrons have outward anisotropic (inward-anisotropic) angular distributions. All three groups of superhalo electrons show no correlation with the local solar wind plasma, interplanetary magnetic field, turbulence, and energetic electrons accelerated/reflected at the terrestrial bow shock.

Tao *et al.*[32] presented a statistical survey of the energy spectrum of solar wind suprathermal (0.1−1.5 keV) electrons measured by the WIND 3DP instrument at 1 AU during quiet times at the minimum and maximum of solar cycles 23 and 24. They separate the halo and Strahl electrons based on their different angular behaviors and fit the energy spectrum of halo/Strahl to a kappa fuction. They find a strong positive correlation between kappa and effective temperature $T_{\rm eff}$ for both Strahl and halo-electrons, and a strong positive correlation between the Strahl number density and halo number density, likely reflecting the nature of the generation of these suprathermal electrons.

Wu *et al.*[33] reported observations of the acceleration and trapping of energetic ions and electrons between a pair of Corotating Interaction Regions (CIRs). The event occurred in Carrington Rotation 2060. Observed by the STEREO-B spacecraft, the two CIRs were separated by less than 5 days. In contrast to other CIR events, the fluxes of the energetic ions and electrons in this event reached their maxima between the trailing edge of the first CIR and the leading edge of the second CIR. The radial magnetic field ($B_{\rm r}$) reversed its sense and the anisotropy of the flux also changed from sunward to anti-sunward between the two CIRs. Furthermore, there was an extended period of counter streaming suprathermal electrons between the two CIRs.

Similar observations for this event were also obtained with the Advanced Composition Explorer and STEREO-A. They conjectured that these observations were due to a U-shaped, large-scale magnetic field topology connecting the reverse shock of the first CIR and the forward shock of the second CIR. Such a disconnected U-shaped magnetic field topology may have formed due to magnetic reconnection in the upper corona.

A rapid radiocarbon ^{14}C increase of 1.2% in AD774−775 has been reported in cedar and oak tree rings. So far, the origin of the ^{14}C increase is still uncertain and the possible origin is either supernova or solar particle event. The most possible origin of ^{14}C increase is strong solar flares and Coronal Mass Ejections (CMEs) with strong particles emission. Comprehensive approaches to identify the strong historical solar particle events based on the rapid ^{14}C/^{10}Be increase in tree/coral rings and ice cores, long duration strong auroras and geomagnetic storms are introduced. Evidence of the super auroras in AD775 was first found by Zhou *et al.*[34] in a Chinese Chronicle Jiutangshu and it supports the views that the rapid ^{14}C increase and strong auroras around AD775 are most possibly caused by strong solar storms with intense particles emission. It was identified that the solar event around AD775 would be the strongest solar particle event in the past 11 400 years. The discovery is significant for the research on the history of solar activities, space weather and forecast, radiation of solar energetic particles and protection.

Wang *et al.*[35] investigated the conditions for producing rapid variations of Solar Energetic Particle (SEP) intensity commonly known as dropouts. In particular, they used numerical model simulations based on solving the focused transport equation in the three-dimensional Parker interplanetary magnetic field to put constraints on the properties of particle transport coefficients in both directions perpendicular and parallel to the magnetic field. Their calculations of the temporal intensity profile of 0.5 and 5 MeV protons at the Earth show that the perpendicular diffusion must be small while the parallel mean free path is long in order to reproduce the phenomenon of SEP dropouts. When the parallel mean free path is a fraction of 1 AU and the observer is located at 1 AU, the perpendicular to parallel diffusion ratio must be below 10^{-5} if they want to see the particle flux dropping by at least several times within 3 h. When the observer is located at a larger solar radial distance, the perpendicular to parallel diffusion ratio for reproducing the dropouts should be even lower than that in the case of 1 AU distance. A shorter parallel mean free path or a larger radial distance from the source to observer will cause the particles to arrive later, making the effects of perpendicular diffusion more prominent and SEP dropouts disappear. All of these effects require the magnetic turbulence that resonates with the particles to be low everywhere in the inner heliosphere.

A fundamental statement in diffusion theory is provided by the so-called theorem on reduced dimensionality. The latter theorem is saying that if the dimensionality of the turbulence is reduced, charged particles are tied to a single magnetic field line. If there is pitch angle scattering and therewith parallel diffusion, this usually means that perpendicular transport is subdiffusive. Subdiffusive transport was found in numerous simulations for slab turbulence. However, it was unclear whether the theorem is valid for other models with reduced dimensionality such as the two-dimensional model. Qin and Shalchi[36] simultaneously traced magnetic field lines and energetic particles and they computed the distance between the particle and the initial field line. They confirm the aforementioned theorem for slab turbulence but they cannot confirm it for two-dimensional turbulence. They also showed that particles are not tied to field lines for two-component turbulence.

Wang *et al.*[37] investigated the onset time of Solar Energetic Particle (SEP) events with numerical simulations and analyzes the accuracy of the Velocity Dispersion Analysis (VDA) method. Using a three-dimensional focused transport model, they calculate the fluxes of protons observed in the ecliptic at 1 AU in the energy range between 10 MeV and 80 MeV. In particular, three models are used to describe different SEP sources produced by flare or coronal shock, and the effects of particle perpendicular diffusion in the interplanetary space are also studied. They have the following findings. When the observer is disconnected from the source, the effects of perpendicular diffusion in the interplanetary space and particles propagating in the solar atmosphere have a significant influence on the VDA results. As a result, although the VDA method is valid with impulsive source duration, low background, and weak scattering in the interplanetary space or fast diffusion in the solar atmosphere, the method is not valid with gradual source duration, high background, or strong scattering.

A gradual Solar Energetic Particle (SEP) event observed by multi-spacecraft has been simulated by Qin and Wang[38]. The time profiles of SEP fluxes accelerated by an interplanetary shock in the three-dimensional interplanetary space are obtained by solving numerically the Fokker-Planck focused transport equation. The interplanetary shock is modeled as a moving source of energetic particles. By fitting the 1 March 1979 SEP fluxes observed by Helios 1, Helios 2, and IMP 8 with their simulations, they obtain the best parameters for the shock acceleration efficiency model. And they also find that the particle perpendicular diffusion coefficient with the level of 1%−3% of parallel diffusion coefficient at 1 AU should be included. The reservoir phenomenon is reproduced in the simulations, and the longitudinal gradient of SEP fluxes in the decay phase, which is observed by three spacecraft at different locations, is more sensitive to the shock acceleration efficiency parameters than that is to the perpendicular diffusion coefficient.

The spatial and temporal invariance in the spectra of energetic particles in gradual solar events is reproduced in simulations. Based on a numerical solution of the focused transport equation, Wang and Qin[39] obtained the intensity time profiles of Solar Energetic Particles (SEPs) accelerated by an interplanetary shock in 3D interplanetary space. The shock is treated as a moving source of energetic particles with a distribution function. The time profiles of particle fluxes with different energies are calculated in the ecliptic at 1 AU. According to their model, they find that shock acceleration strength, parallel diffusion, and adiabatic cooling are the main factors in forming the spatial invariance in SEP spectra, and perpendicular diffusion is a secondary factor. In addition, the temporal invariance in SEP spectra is mainly due to the effects of adiabatic cooling. Furthermore, a spectra invariant region, which agrees with observations but is different from the one suggested by Reames *et al.* is proposed based on their simulations.

An approximate analytic description of a diffusion coefficient, including the effect of adiabatic focusing, has been developed by Wang and Qin[40]. This description is formulated with the aid of stochastic differential equations and the steady perturbation solution of the Fokker-Plank transport equation. The analytical formula is based on three important assumptions. First, the pitch-angle diffusion coefficient is set to be separable from the spatial coordinate and the pitch-angle cosine. Second, the spatial dependence of the ratio between the mean-free path and focusing length is assumed to be weak. Third, the pitch-angle distribution relaxes quickly to a steady state. The new analytic formula could be applied to calculate the spatial diffusion coefficient in the interplanetary and interstellar space.

Studying the access of the Cosmic Rays (CRs) into the magnetosphere is important to understand the coupling between the magnetosphere and the solar wind. Chu and Qin[41] numerically studied CRs' magnetospheric access with vertical geomagnetic cutoff rigidities. By the study of CRs' vertical geomagnetic cutoff rigidities at high latitudes, they obtain the CRs' Window (CRW) whose boundary is determined when the vertical geomagnetic cutoff rigidities drop to a value lower than a threshold value. Furthermore, they studied the area of CRWs and found out they are sensitive to different parameters, such as the z component of Interplanetary Magnetic Field (IMF), the solar wind dynamic pressure, AE index, and Dst index. It was found that both the AE index and Dst index have a strong correlation with the area of CRWs during strong geomagnetic storms. However, during the medium storms, only AE index has a strong correlation with the area of CRWs, while Dst index has a much weaker correlation with the area of CRWs. This result on the CRW can be used for forecasting the variation of the cosmic rays during the geomagnetic storms.

Experimental data from Cluster have shown that entropy density can be generated across Earth's bow shock. These new observations are a starting point for a more sophisticated analysis that includes computer modeling of a collisionless shock using observed shock parameters as input. Yang *et al.*[42] presented the first comparison between observations and particle-in-cell simulations of such entropy generation across a collisionless shock. The ion heating at the shock is dominated by the phase mixing of reflected and directly transmitted ions, which are separated from the incident ions. The electron heating is a nearly thermal process due to the conservation of their angular momentum. For both species, they calculate the entropy density across the shock, and obtain good consistency between observations and simulations on entropy generation across the shock. They also find that the entropy generation rate is reduced as the shock Mach number decreases.

Wei *et al.*[43] reviewed current models, which have been used to describe gradual SEP events and their applications. Generally, there are two major approaches to model gradual SEP events: some studies include the acceleration mechanisms of SEPs induced by CME driven shocks, while others assume a fixed particle injecting source at the shock. In addition, some researchers also consider the effects of perpendicular diffusion on SEPs propagation in 3D interplanetary magnetic fields. These models can partially reproduce the observed properties for SEP events. Then, they make a brief review of numerical MHD simulation models, such as Space Weather Modeling Frame (SWMF), Coronal and Heliospheric (CORHEL) model, Solar Inter-

Planetary-Conservative Element Solution Element (SIP-CESE) model, Coronal Interplanetary (COIN) model. All these models can be used to work out the propagation parameters of CME and CME-driven shocks, which are expected to provide inputs to the particle model. Finally, some discussions of the future work about how to combine MHD and particle models were presented.

Solar Energetic Particles (SEPs) pose one of the most serious hazards to spacecraft systems and constrain human activities in space. Thus, it is of importance to forecast SEP events. Several theories and numerical models are applied to simulate SEP events. Each model makes some assumptions to simplify the complex acceleration and transportation processes within such events. In general, SEP will interact with ambient solar wind and background magnetic field during transportation. It is recognized that interplanetary transport effects must be taken into account at any analysis of SEP propagation. In the previous simulation, it was always assumed Parker magnetic field and fixed solar wind speed as the input parameters. However, these assumptions are too simple when compared with the real conditions. In order to get better results, it is necessary to use more accurate background conditions. Recently, Wei *et al.*[44] changed the fixed solar wind speed into spatial dependent speed profile based on Parker's theory, and replaced the Parker magnetic field with another Parker like magnetic field based on in-situ data at 1 AU. By solving the focused transport equation with simulation of time-backward stochastic processes method, their results are shown below.

(1) Under fast solar wind speed assumption, it is clear that the omnidirectional flux decreases faster than that for the situation with slow solar wind speed in the decay phase. They suggest that it is due to the adiabatic cooling effect. Fast solar wind speed has a significant effect on the adiabatic cooling, which leads the SEPs to lose energy more quickly during transportation. However, slow solar wind speed has less impact on the time profiles of SEP flux and anisotropy. They also compare the time profiles of SEP event observed at different observatories and energies, the results remain the same as previous.

(2) When applying in-situ data of magnetic field observed by WIND during different Carrington Rotations, the omnidirectional flux time profiles vary greatly, and the main results are as follows: the peak flux appears to be delayed, multi-peak occur, anisotropy also has some differences. They think it results from the magnetic field polarity, which affects the pitch angle, and furthermore, modulates the momentum. The characteristics are similar in solar minimum and solar maximum, while the peaks seem to be more when solar activity is active. They conclude that the real magnetic field polarity may exert a significant influence during the propagation of SEP.

In the future, they will try to use the real-time background conditions obtained from MHD models in their simulations, in order to make a thorough study of the SEP propagation.

Voyager 2 (V2) observed multiple crossings of the heliospheric Termination Shock (TS) on 31 August to 1 September 2007 at a distance of 84 AU from the Sun. Here, for the first time, Yang *et al.*[45] presented two-dimensional Particle-in-Cell (PIC) simulations of the TS self-consistently including Pickup Ions (PUIs), and compared the simulation results with V2 observations. They find the following results.

(1) PUIs play a key role in the energy dissipation of the TS, and most of the incident ion kinetic energy is transferred to the thermal energy of PUIs. The PIC simulation indicates that, for the upstream parameters chosen for V2 conditions, the density of PUIs is about 25% and the PUIs gain the largest fraction (approximately 86.6%) of downstream thermal pressure.

(2) The simulated heliosheath ion distribution function is a superposition of a cold core formed by transmitted Solar Wind Ions (SWIs), with the shoulders contributed by the hot reflected SWIs and direct-

ly transmitted PUIs, and the wings of the distribution dominated by the very hot reflected PUIs. The V2 Faraday cups observed the cool core of the distribution, and so they only saw the tip of the iceberg.

(3) The nonstationarity of the shock front is mainly caused by ripples along the shock front which form even if the percentage of PUIs is high. These simulation results agree reasonably well with the V2 experimental data.

The relevance of the shock front ripples to the multiple TS crossings observed by V2 is also discussed in this paper.

Based on a hybrid galactic cosmic-ray transport model, which incorporated MHD global heliospheric data into Parker's cosmic-ray transport equation, Luo *et al.*[46] studied the behavior of the transport of galactic cosmic rays and the corresponding gradients in their flux near the Heliopause (HP). Their findings are as below.

(1) by increasing the ratio of the parallel diffusion coefficient to the perpendicular diffusion coefficient in the interstellar magnetic field of the outer heliosheath, the simulated radial flux near the HP increases as well. As the ratio multiplying factor reached 10^{10}, the radial flux experienced a sudden jump near the HP, similar to what Voyager 1 observed in 2012.

(2) The effect of changing the diffusion coefficients' ratio on the radial flux variation depends on the energy of the cosmic rays, the lower the energy is, the more pronounced the effect is.

(3) The magnitude of the diffusion coefficients also affect the radial flux near the HP, the modulation beyond the HP varies by adjusting the magnitude multiplying factor.

4 Solar Flares and Radio Bursts

Ruan *et al.*[47] presented the observation of a major solar eruption that is associated with fast sunspot rotation. The event includes a sigmoidal filament eruption, a coronal mass ejection, and a GOES X2.1 flare from NOAA active region 11283. The filament and some overlying arcades were partially rooted in a sunspot. The sunspot rotated at $\sim 10^\circ \cdot h^{-1}$ during a period of 6 h prior to the eruption. In this period, the filament was found to rise gradually along with the sunspot rotation. Based on the Helioseismic and Magnetic Imager (HMI) observation, for an area along the polarity inversion line underneath the filament, they found gradual pre-eruption decreases of both the mean strength of the photospheric horizontal field (B_h) and the mean inclination angle between the vector magnetic field and the local radial (or vertical) direction. These observations are consistent with the pre-eruption gradual rising of the filament-associated magnetic structure. In addition, according to the nonlinear force-free field reconstruction of the coronal magnetic field, a pre-eruption magnetic flux rope structure is found to be in alignment with the filament, and a considerable amount of magnetic energy was transported to the corona during the period of sunspot rotation. Their study provides evidence that in this event sunspot rotation plays an important role in twisting, energizing, and destabilizing the coronal filament-flux rope system, and led to the eruption. They also proposed that the pre-event evolution of B_h may be used to discern the driving mechanism of eruptions.

Ruan *et al.*[48] presented a study of the persistent and gradual penumbral decay and the correlated decline of the photospheric transverse field component 10−20 h before a major flare (X1.8) eruption on 7 September 2011. This long-term pre-eruption behavior is corroborated by the well-imaged pre-flare filament rising, the consistent expansion of the coronal arcades overlying the filament, and the nonlinear force-free field modeling results in the literature. They suggested that both the long-term pre-flare penumbral decay and the transverse field decline are photospheric manifestations of the gradual rise of the coronal filament-flux rope system. They also suggested that the C3 flare and the subsequent reconnection process preceding the X1.8 flare play an important role in triggering the later major eruption.

Chen *et al.*[49] examined simultaneous radio and Extreme Ultraviolet (EUV)/white-light imaging data for a solar Type Ⅱ radio burst occurring on 18 March 2010 to deduce its source location. Using a bow-shock model, they reconstructed the three-dimensional EUV wave front (presumably the Type Ⅱ emitting shock) based on the imaging data of the two STEREO spacecraft. It is then combined with the Nancay radio imaging data to infer the three-dimensional position of the Type Ⅱ source. It is found that the Type Ⅱ source coincides with the interface between the Coronal Mass Ejection (CME) EUV wave front and a nearby coronal ray structure, providing evidence that the Type Ⅱ emission is physically related to the CME-ray interaction. This result, consistent with those of previous studies, is based on simultaneous radio and EUV imaging data for the first time.

Feng *et al.*[50] studied a multi-lane solar Type Ⅱ radio burst that was observed by several solar spectrographson 16 February 2011. The event was also recorded by the Nancay Radio Heliograph (NRH) at several metric wavelengths, by the AIA onboard the SDO, and by the EUVI onboard the STEREO in a number of EUV passbands. These multi-wavelength data provide a rare opportunity to reveal the emission source of the multiple Type Ⅱ lanes. Their study shows that all lanes are associated with a single EUV wave, presumably the radio-emitting shock. The EUV wave was driven by a CME associated with an M1.6 flare and a filament eruption. With the NRH data and the 3D bow-shock reconstruction that they built using the multi-viewpoint data of the EUV wave, they were able to deduce the 3D coordinates of the radio sources. They concluded that all the three Type Ⅱ lanes originated from the western flank of the shock, with two of them from closely adjacent locations on the southern part, the other one from a distinct location on the northern part. This case study demonstrates how the Type Ⅱ origin can be pinpointed by combining analyses of different data sets.

Kong *et al.*[51] examined two solar Type Ⅱ radio bursts, separated by ~24 h in time together. Both events are associated with CMEs erupting from the same active region (NOAA 11176) beneath a well-observed helmet streamer. They found that the Type Ⅱ emissions in both events ended once the CME/shock fronts passed the white-light streamer tip, which is presumably the magnetic cusp of the streamer. This leads them to conjecture that the closed magnetic arcades of the streamer may play a role in electron acceleration and Type Ⅱ excitation at coronal shocks.

To examine such a conjecture, they conducted a test-particle simulation for electron dynamics within a large-scale partially closed streamer magnetic configuration swept by a coronal shock. They found that the closed field lines play the role of an electron trap *via* which the electrons are sent back to the shock front multiple times and therefore accelerated to high energies by the shock. Electrons with an initial energy of 300 eV can be accelerated to tens of keV concentrating at the loop apex close to the shock front with a counter-streaming distribution at most locations. These electrons are energetic enough to excite Langmuir waves and radio bursts. Considering the fact that most solar eruptions originate from closed field regions, they suggested that the scenario may be important for the generation of more metric Type Ⅱs. This study also provides an explanation of the general ending frequencies of metric Type Ⅱs at or above 20−30 MHz and the disconnection issue between metric and interplanetary Type Ⅱs.

In many Type Ⅱ solar radio bursts, the fundamental and/or the harmonic branches of the bursts can split into two almost parallel bands with similar spectral shapes and frequency drifts. However, the mechanisms accounting for this intriguing phenomenon remain elusive. Du *et al.*[52] reported a special band-splitting Type Ⅱ event in which spectral features appear systematically earlier on the upper band (with higher frequencies) than on the lower band (with lower frequencies) by several seconds. Furthermore, the emissions carried by the splitting band are moderately polarized with the left-hand polarized signals stronger than the right-hand ones. The polarization degree varies in a range of -0.3 to -0.6. These novel observational findings provide important constraints on the underlying physical mechanisms of band-splitting of Type Ⅱ radio bursts.

One popular interpretation of band split of Type Ⅱ radio bursts is that the splitting bands are emitted from the shock upstream and downstream, respectively, with their frequency ratio γ determined by the shock compression ratio. This interpretation has been taken as the physical basis of many published references. Du *et al.*[53] reported on an observational analysis of Type Ⅱ events with a nice split selected from ground-based RSTN data from 2001 to 2014, in the metric-decametric wavelength. They investigated the temporal variation and distribution of γ, and conducted correlation analyses on the deduced spectral values. It is found that γ varies in a very narrow range with $> 80\%$ of γ (one-minute averaged data) between 1.15 and 1.25. For some well-observed and long-lasting events, γ does not show a systematic variation trend within observational uncertainties, from the onset to the termination of the splits. In addition, the parameters representing the propagation speed of the radio source (presumably the coronal shock) show a very weak or basically no correlation with γ. They suggested that these results do not favor the upstream-downstream scenario of band splits.

Vasanth *et al.*[54] performed a statistical analysis of the geoeffectiveness of Coronal Mass Ejections (CMEs) that are associated with Interplanetary (IP) Type Ⅱ bursts in Solar Cycle 23 during the period of 1997−2008. About 47% (109 out of 232) of IP Type Ⅱ bursts are found to be associated with geomagnetic storms. Of these, 47%, 27% are associated with moderate, 14% with intense, and 6% with severe geomagnetic storms. They found that the IP Type Ⅱ bursts and their corresponding end frequencies can be used as indicators of CME geoeffectiveness: the lower the Type Ⅱ burst end frequency, the higher the possibility of having a stronger storm. In addition, they showed that various combinations of CME remote-sensing and IP Type Ⅱ parameters can be used to improve geomagnetic storm forecasting.

5 Coronal Mass Ejections and Their Interplanetary Counterparts

Cheng *et al.*[55] addressed the formation of a Magnetic Flux Rope (MFR) that erupted on 12 July 2012 and caused a strong geomagnetic storm event on 15 July. Through analyzing the long-term evolution of the associated active region observed by the Atmospheric Imaging Assembly and the Helioseismic and Magnetic Imager on board the Solar Dynamics Observatory, it is found that the twisted field of an MFR, indicated by a continuous S-shaped sigmoid, is built up from two groups of sheared arcades near the main polarity inversion line a half day before the eruption. The temperature within the twisted field and sheared arcades is higher than that of the ambient volume, suggesting that magnetic reconnection most likely works there. The driver behind the reconnection is attributed to shearing and converging motions at magnetic foot points with velocities in the range of $0.1-0.6\,\mathrm{km\cdot s^{-1}}$. The rotation of the preceding sunspot also contributes to the MFR buildup. Extrapolated three-dimensional non-linear force-free field structures further reveal the locations of the reconnection to be in a bald-patch region and in a hyperbolic flux tube. About 2 hours before the eruption, indications of a second MFR in the form of an S-shaped hot channel are seen. It lies above the original MFR that continuously exists and includes a filament. The whole structure thus makes up a stable double-decker MFR system for hours prior to the eruption. Eventually, after entering the domain of instability, the high-lying MFR impulsively erupts to generate a fast coronal mass ejection and X-class flare; while the low-lying MFR remains behind and continuously maintains the sigmoidicity of the active region.

It is generally accepted that CMEs are the results of eruptions of Magnetic Flux Ropes (MFRs). However, there is heated debate on whether MFRs exist prior to the eruptions or if they are formed during the eruptions. Several coronal signatures, *e.g.*, filaments, coronal cavities, sigmoid structures, and hot channels (or hot blobs), are proposed as MFRs and observed before the eruption, which support the pre-existing MFR scenario. There is almost no reported observation of MFR formation during the eruption. Song *et al.*[56] presented an intriguing observation of a solar eruptive event that occurred on 21 November 2013 with the AIA on board the SDO, which shows the formation process of the MFR during the eruption in detail. The process began with the expansion of a low-lying coronal arcade, possibly caused by the flare magnetic reconnection underneath. The newly formed ascending loops from below further pushed the arcade upward, stretching the surrounding magnetic field. The arcade and stretched magnetic field lines then curved in just below the arcade vertex, forming an X-point. The field lines near the X-point continued to approach each other and a second magnetic reconnection was induced. It is this high-lying magnetic reconnection that led to the formation and eruption of a hot blob (~10 MK), presumably an MFR, producing a CME. They suggested that two spatially separated magnetic reconnections occurred in this event, which were responsible for producing the flare and the hot blob (CME).

Song *et al.*[57] reported for the first time the detailed temperature evolution process of the magnetic flux rope in a failed solar eruption. Occurring on 5 January 2013, the flux rope was impulsively accelerated to a speed of $\sim$400 km·s^{-1} in the first minute, then decelerated and came to a complete stop in two minutes. The failed eruption resulted in a large-size high-lying (~100 Mm above the surface), high-temperature fire ball sitting in the corona for more than two hours. The time evolution of the thermal structure of the flux rope was revealed through the differential emission measure analysis technique, which produced temperature maps using observations of the SDO/AIA. The average temperature of the flux rope steadily increased from ~5 MK to ~10 MK during the first nine minutes of the evolution, which was much longer than the rise time (about three minutes) of the associated soft X-ray flare. They suggest that the flux rope is heated by the energy release of the continuing magnetic reconnection, different from the heating of the low-lying flare loops, which is mainly produced by the chromospheric plasma evaporation. The loop arcade overlying the flux rope was pushed up by ~10 Mm during the attempted eruption. The pattern of the velocity variation of the loop arcade strongly suggests that the failure of the eruption was caused by the strapping effect of the overlying loop arcade.

Hot Channels (HCs), high-temperature erupting structures in the lower corona of the Sun, have been proposed as a proxy of Magnetic Flux Ropes (MFRs) since their initial discovery. However, it is difficult to provide definitive proof given the fact that there is no direct measurement of the magnetic field in the corona. An alternative method is to use the magnetic field measurement in the solar wind from in-situ instruments. Song *et al.*[58] observed an HC prior to and during a Coronal Mass Ejection (CME) by the Atmospheric Imaging Assembly high temperature images. The HC is invisible in the EUVI low-temperature images, which only show the cooler Leading Front (LF). However, both the LF and an ejecta can be observed in the coronagraphic images. These are consistent with the high temperature and high density of the HC and support that the ejecta is the erupted HC. Meanwhile, the associated CME shock was identified ahead of the ejecta and the sheath through the COR2 images, and the corresponding ICME was detected by the Advanced Composition Explorer (ACE), showing the shock, sheath, and Magnetic Cloud (MC) sequentially, which agrees with the coronagraphic observations. Further, the MC average Fe charge state is elevated, containing a relatively low-ionization-state center and a high-ionization-state shell, consistent with the pre-existing HC observation and its growth through magnetic reconnection. All of these observations support that the MC detected near the Earth is the counterpart of the erupted HC in the corona for this event. The study provides strong observational evidence of the HC as an MFR.

A Hot Channel (HC) is a high temperature (~10 MK) structure in the inner corona first revealed by the SDO/AIA. Eruptions of HCs are often associated with flares and CMEs. Results of previous studies have suggested that an HC is a good proxy for a Magnetic Flux Rope (MFR) in the inner corona as well as another well known MFR candidate, the prominence-cavity structure, which has a normal coronal temperature (1−2 MK). In this paper, Song *et al.*[59] reported a high temperature structure (HTS, ~1.5 MK) contained in an interplanetary CME induced by an HC eruption. According to the observations of bidirectional electrons, high temperature and density, strong magnetic field, and its association with the shock, sheath, and plasma pile-up region, they suggest that the HTS is the interplanetary counterpart of the HC. The scale of the measured HTS is around 14 $R_{\rm s}$, and it maintained a much higher temperature than the background solar wind even at 1 AU. It is significantly different from the typical magnetic clouds, which usually have a much lower temperature. The study suggests that the existence of a corotating interaction region ahead of the HC formed a magnetic container to inhibit expansion of the HC and cool it down to a low temperature.

Filament eruptions often lead to CMEs, which can affect critical technological systems in space and on the ground when they interact with the geomagnetosphere at high speeds. Therefore, it is important to investigate the acceleration mechanisms of CMEs in solar/space physics. Based on observations and simulations, the resistive magnetic reconnection and the ideal instability of magnetic flux ropes have been proposed to accelerate CMEs. However, it remains uncertain whether both of them play a comparable role during a particular eruption. It has been extremely difficult to separate their contributions as they often work in a close time sequence during one fast acceleration phase. Song *et al.*[60] reported an intriguing filament eruption event, which shows two apparently separated fast acceleration phases and provides an excellent opportunity to address the issue. Through analyzing the correlations between velocity (acceleration) and soft (hard) X-ray profiles, they suggested that the instability and magnetic reconnection make a major contribution during the first and second fast acceleration phases, respectively. Further, they found that both processes have a comparable contribution to the filament acceleration in this event.

Among various factors affecting the space weather effects of a CME, its propagation trajectory in the interplanetary space is an important one determining whether and when the CME will hit the Earth. Many direct observations have revealed that a CME may not propagate along a straight trajectory in the corona, but whether or not a CME also experiences a deflected propagation in the interplanetary space is a question, which has never been fully answered. Here by investigating the propagation process of an isolated CME from the corona to interplanetary space during 12−19 September 2008, Wang *et al.*[61] present solid evidence that the CME was deflected not only in the corona but also in the interplanetary space. The deflection angle in the interplanetary space is more than 20° toward the west, resulting a significant change in the probability the CME encounters the Earth. A further modeling and simulation-based analysis suggests that the cause of the deflection in the interplanetary space is the interaction between the CME and the solar wind, which is different from that happening in the corona.

The dynamic process of CMEs in the heliosphere provides the key information for evaluating CMEs' geoeffectiveness and improving the accurate prediction of CME-induced shock arrival time at the Earth. Shen *et al.*[62] presented a data-constrained 3D Magnetohydrodynamic (MHD) simulation of the evolution of the CME in a realistic ambient solar wind for the 12−16 July 2012 event by using the 3D Corona Interplanetary Total Variation Diminishing (COIN-TVD) MHD code. A detailed comparison of the kinematic evolution of the CME between the observations and the simulation is carried out, including the usage of the time elongation maps from the perspectives of both STEREO-A and STEREO-B. In this case study, they find that their 3D COIN-TVD MHD model, with the magnetized plasma blob as the driver, is able to reproduce relatively well the real 3D nature of the CME in morphology and their evolution from the Sun to the Earth. The simulation also provides a relatively satisfactory comparison with the in-situ plasma data from the Wind spacecraft.

A geomagnetic storm is mainly caused by a frontside CME hitting the Earth and then interacting with the magnetosphere. However, not all frontside CMEs can hit the Earth. Thus, which CMEs hit the Earth and when they do so are important issues in the study and forecasting of space weather. In previous work, the deprojected parameters of the Full-Halo Coronal Mass Ejections (FHCMEs) that occurred from 1 March 2007 to 31 May 2012 were estimated, and there are 39 frontside events that could be fitted by the Graduated Cylindrical Shell model. In this work, Shen *et al.*[63] studied whether and when these Frontside FHCMEs (FFHCMEs) hit the Earth. It is found that 59% of these FFHCMEs hit the Earth, and for central events, whose deviation angles, which are the angles between the propagation direction and the Sun-Earth line, are smaller than 45°, the fraction increases to 75%. After checking the deprojected angular widths of the CMEs, they found that all of the Earth-encountered CMEs satisfy a simple criterion that the angular width is larger than twice the deviation angle. This result suggests that some simple criteria can be used to forecast whether a CME could hit the Earth. Furthermore, for Earth-encountered CMEs, the transit time is found to be roughly anti-correlated with the deprojected velocity, but some events significantly deviate from the linearity. For CMEs with similar velocities, the differences of their transit times can be up to several days. Such deviation is further demonstrated to be mainly caused by the CME geometry and propagation direction, which are essential in the forecasting of CME arrival.

Mass is one of the most fundamental parameters characterizing the dynamics of a CME. It has been found that CME apparent mass measured from the brightness enhancement in coronagraphs increases during its evolution in the corona. However, the physics behind it is not clear. Does the apparent mass gain come from the outflow from the dimming regions in the low corona, or from the pileup of the solar wind plasma around the CME? Feng *et al.*[64] analyzed the mass evolution of six CME events. Based on the coronagraph observations from STEREO, they find that their masses increased by a factor of 1.3−1.7 from $7\,R_{\rm s}$ to $15\,R_{\rm s}$, where the occulting effect is negligible. They then adopt the "snow-plow" model to calculate the mass contribution of the piled-up solar wind. The result gives evidence that the solar wind pileup probably makes a non-negligible contribution to the mass increase. In the height range from about $7\,R_{\rm s}$ to $15\,R_{\rm s}$, the ratio of the modeled to the measured mass increase is roughly larger than 0.55 though the ratios are believed to be overestimated. It is not clear yet whether the solar wind pileup is a major contributor to the final mass derived from coronagraph observations, but it does play an increasingly important role in the mass increase as a CME moves further away from the Sun.

Ding *et al.*[66] investigated the eruption and interaction of two CMEs during the large 22 May 2013 solar energetic particle event using multiple spacecraft observations. Two CMEs, having similar propagation directions, were found to erupt from two nearby Active Regions (ARs), AR11748 and AR11745, at ~08:48 UT and ~13:25 UT, respectively. The second CME was faster than the first CME. Using the graduated cylindrical shell model, they reconstructed the propagation of these two CMEs and found that the leading edge of the second CME caught up with the trailing edge of the first CME at a height of ~6 solar radii. After about two hours, the leading edges of the two CMEs merged at a height of ~20 solar radii. Type Ⅱ solar radio bursts showed strong enhancement during this two-hour period. Using the velocity dispersion method, they obtained the Solar Particle Release (SPR) time and the path length for energetic electrons. Further assuming that energetic protons propagated along the same interplanetary magnetic field, they also obtained the SPR time for energetic protons, which were close to that of electrons. These release times agreed with the time when the second CME caught up with the trailing edge of the first CME, indicating that the CME-CME interaction (and shock-CME interaction) plays an important role in the process of particle acceleration in this event.

Magnetic Clouds (MCs) are the interplanetary counterparts of CMEs, and usually modeled by a flux rope. By assuming the quasi-steady evolution and self-similar expansion, Wang *et al.*[66] introduced three types of global motion into a cylindrical force-free flux rope model and developed a new velocity-modified model for MCs. The three types of the global motion are the linear propagating motion away from the Sun, the expanding, and the poloidal motion with respect to the axis of the MC. The model was applied to 72 MCs observed by WIND spacecraft to investigate the properties of the plasma motion of MCs. They find that some MCs had a significant propagation velocity perpendicular to the radial direction and confirm the previous results that the expansion speed is correlated with the radial propagation speed and most MCs did not expand self-similarly at 1 AU. Most interestingly, they find that a significant poloidal motion did exist in some MCs. These findings advance their understanding of the MC's properties at 1 AU and the dynamic evolution of CMEs from the Sun to interplanetary space.

Space weather refers to dynamic conditions on the Sun and in the space environment of the Earth, which are often driven by solar eruptions and their subsequent interplanetary disturbances. It has been unclear how an extreme space weather storm forms and how severe it can be. Liu *et al.*[67] reported and investigated an extreme event with multi-point remote-sensing and in-situ observations. The formation of the extreme storm showed striking novel features. They suggest that the in-transit interaction between two closely launched coronal mass ejections resulted in the extreme enhancement of the ejecta magnetic field observed near 1 AU at STEREO-A. The fast transit to STEREO-A (in only 18.6 h), or the unusually weak deceleration of the event, was caused by the preconditioning of the upstream solar wind by an earlier solar eruption. These results provide a new view crucial to solar physics and space weather as to how an extreme space weather event can arise from a combination of solar eruptions.

In March 2012, the Sun exhibited extraordinary activities. In particular, the active region NOAA AR 11429 emitted a series of large Coronal Mass Ejections (CMEs) which were imaged by the STEREO as it rotated with the Sun from the east to west. The study of Liu *et al.*[68] demonstrated that these sustained eruptions are expected to generate a global shell of disturbed material sweeping through the heliosphere. A cluster of shocks and interplanetary CMEs were observed near the Earth, and are propagated outward from 1 AU using an MHD model.

The transient streams interact with each other, which erases memory of the source and results in a large Merged Interaction Region (MIR) with a preceding shock. The MHD model predicts that the shock and MIR would reach 120 AU around 22 April 2013, which agrees well with the period of radio emissions and the time of a transient disturbance in galactic cosmic rays detected by Voyager 1. These results are important for understanding the fate of CMEs in the outer heliosphere and provide confidence that the heliopause is located around 120 AU from the Sun.

From 30 September 2012 to 1 October, the Earth underwent a two-step geomagnetic storm. Liu *et al.*[69] examined the Sun-to-Earth characteristics of the Coronal Mass Ejections (CMEs) responsible for the geomagnetic storm with combined heliospheric imaging and in-situ observations. The first CME, which occurred on 25 September 2012, is a slow event and shows an acceleration followed by a nearly invariant speed in the whole Sun-Earth space. The second event, launched from the Sun on 27 September 2012, exhibits a quick acceleration, then a rapid deceleration, and finally a nearly constant speed, a typical Sun-to-Earth propagation profile for fast CMEs. These two CMEs interacted near 1 AU as predicted by the heliospheric imaging observations and formed a complex ejecta observed at WIND, with a shock inside that enhanced the pre-existing southward magnetic field. Reconstruction of the complex ejecta with the in-situ data indicates an overall left-handed flux-rope-like configuration with an embedded concave-outward shock front, a maximum magnetic field strength deviating from the flux rope axis, and convex-outward field lines ahead of the shock. While the reconstruction results are consistent with the picture of CME-CME interactions, a magnetic cloud-like structure without clear signs of CME interactions is anticipated when the merging process is finished.

The largest geomagnetic storms of solar cycle 24 so far occurred on 17 March 2015 and 22 June with *Dst* minima of −223 and −195 nT, respectively. Both of the geomagnetic storms show a multi-step development. Liu *et al.*[70] examined the plasma and magnetic field characteristics of the driving Coronal Mass Ejections (CMEs) in connection with the development of the geomagnetic storms. A particular effort is to reconstruct the in-situ structure using a Grad-Shafranov technique and compare the reconstruction results with solar observations, which gives a larger spatial perspective of the source conditions than one-dimensional in-situ measurements. Key results are obtained concerning how the plasma and magnetic field characteristics of CMEs control the geomagnetic storm intensity and variability: (i) a sheath-ejecta-ejecta mechanism and a sheath-sheath-ejecta scenario are proposed for the multi-step development of the 17 March 2015 and 22 June geomagnetic storms, respectively; (ii) two contrasting cases of how the CME flux-rope characteristics generate intense geomagnetic storms are found, which indicates that a southward flux-rope orientation is not a necessity for a strong geomagnetic storm; and (iii) the unexpected 17 March 2015 intense geomagnetic storm resulted from the interaction between two successive CMEs plus the compression by a high-speed stream from behind, which is essentially the perfect storm scenario proposed by Liu *et al.* (*i.e.*, a combination of circumstances results in an event of unusual magnitude), so the perfect storm scenario may not be as rare as the phrase implies.

As a follow-up study on Sun-to-Earth propagation of fast Coronal Mass Ejections (CMEs), Liu *et al.*[71] examined the Sun-to-Earth characteristics of slow CMEs combining heliospheric imaging and in-situ observations. Three events of particular interest, the 16 June 2010, 25 March 2011, and 25 September 2012 CMEs, were selected for this study. They compared slow CMEs with fast and intermediate-speed events, and obtained key results complementing the attempt of Liu *et al.* to create a general picture of CME Sun-to-Earth propagation: (i) the

Sun-to-Earth propagation of a typical slow CME can be approximately described by two phases, a gradual acceleration out to about 20—30 solar radii, followed by a nearly invariant speed around the average solar wind level; (ii) comparison between different types of CMEs indicates that faster CMEs tend to accelerate and decelerate more rapidly and have shorter cessation distances for the acceleration and deceleration; (iii) both intermediate-speed and slow CMEs would have speeds comparable to the average solar wind level before reaching 1 AU; (iv) slow CMEs have a high potential to interact with other solar wind structures in the Sun-Earth space due to their slow motion, providing critical ingredients to enhance space weather; and (v) the slow CMEs studied here lack strong magnetic fields at the Earth but tend to preserve a flux-rope structure with an axis generally perpendicular to the radial direction from the Sun. They also suggest a best strategy for the application of a triangulation concept in determining CME Sun-to-Earth kinematics, which helps to clarify confusions about CME geometry assumptions in the triangulation and to improve CME analysis and observations.

Wang *et al.*[72] examined two successive flare eruptions (X5.4 and X1.3) on 7 March 2012 in the NOAA active region 11429 and investigate the magnetic field reconfiguration associated with the two eruptions. Using an advanced non-linear force-free field extrapolation method based on the SDO/HMI vector magnetograms, they obtained a stepwise decrease in the magnetic free energy during the eruptions, which is roughly 20%—30% of the energy of the pre-flare phase. They also calculate the magnetic helicity and suggest that the changes of the sign of the helicity injection rate might be associated with the eruptions. Through the investigation of the magnetic field evolution, they find that the appearance of the implosion phenomenon has a strong relationship with the occurrence of the first X-class flare. Meanwhile, the magnetic field changes of the successive eruptions with implosion and without implosion were well observed.

Wang *et al.*[73] studied the role of the coronal magnetic field configuration of an Active Region (AR) in determining the propagation direction of a CME. The CME occurred in the AR 11944 (S09W01) near the disk center on 7 January 2014 and was associated with an X1.2 flare. A new CME reconstruction procedure based on a polarimetric technique is adopted, which shows that the CME changed its propagation direction by around 28° in latitude within $2.5\,R_{\rm s}$ and 43° in longitude within $6.5\,R_{\rm s}$ with respect to the CME source region. They use nonlinear force-free field and potential field source surface extrapolation methods to determine the configurations of the coronal magnetic field. They also calculate the magnetic energy density distributions at different heights based on the extrapolations. Their results show that the AR coronal magnetic field has a strong influence on the CME propagation direction. This is consistent with the channeling by the AR coronal magnetic field itself, rather than deflection by nearby structures. These results indicate that the AR coronal magnetic field configuration has to be taken into account in order to determine CME propagation direction correctly.

Wang *et al.*[74] presented an analysis of SDO observations of an X1.4 class flare on 12 July 2012 (SOL 2012-07-12T15:37L082C105), which was associated with a pronounced sunspot rotation in the associated active region. Based on the magnetograms taken with the SDO/HMI, they measured the rotational speed of the sunspot. They also used a technique, called the Differential Affine Velocity Estimator for Vector Magnetograms (DAVE4VM), to determine the horizontal velocities and the magnetic helicity flux transport. The helicity flux rate due to shearing motion changed sign after the onset of the eruption. A high correlation between the sunspot rotation speed and the change in the total accumulated helicity was found. They also calculated the net fluxes of the respective magnetic polarities and the net vertical currents. The net current in the region of interest showed a synchronous change with the sunspot rotation rate. The magnetic configurations of the sigmoid filament in the active region and the associated possible interaction between different structures were further investigated by means of a nonlinear force-free field extrapolation. They identified a possible magnetic reconnection region from the three-dimensional magnetic fields and its association with EUV structures. These results suggest that the major eruption of this active region was connected with the sunspot rotation.

It has been proved from the observations and numerical simulations that the collision between solar CMEs, the largest plasmoids in the heliosphere, could be super-elastic. Shen *et al.*[75] suggested that the CMEs' magnetic energy and thermal energy could be converted into kinetic energy through a more efficient way. However CME collisions are not always super-elastic, which means that this distinct property of plasmoids is probably excited conditionally. As the first attempt, they carry out a series of three-dimensional numerical experiments, and establish a diagram showing the dependence of the collision nature on the CME speed and k-number, the ratio of the CME's kinetic energy to the CME's total energy. It is found that the super-elastic nature of CMEs appears at the relatively low approaching speed, and most of the previous case studies are in agreement with this diagram. Their study firmly advances the understanding of the super-elastic property of plasmoids, and does give new clues to deeply understand why and how the magnetic energy and/or thermal energy of the colliding plasmoids can be converted into kinetic energy in such an efficient way.

6 MHD Numerical Modeling

Solar-interplanetary space involves many features, such as discontinuities and heliospheric current sheet, with spatial scales many orders of magnitude smaller than the system size. The scalable, massively parallel, block-based, Adaptive-Mesh Refinement (AMR) promises to resolve different temporal and spatial scales on which solar-wind plasma occurs throughout the vast solar-interplanetary space with even less cells but can generate a good enough resolution. Feng *et al.*[76] carried out the Adaptive Mesh Refinement (AMR) implementation of their Solar-Interplanetary space-time Conservation Element and Solution Element (CESE) Magnetohydrodynamic model (SIP-CESE MHD model) using a six-component grid system. The AMR realization of the SIP-CESE MHD model is naturalized directly in hexahedral meshes with the aid of the parallel AMR package PARAMESH available*. At the same time, the topology of the magnetic field expansion factor and the minimum angular separation (at the photosphere) between an open field foot point and its nearest coronal-hole boundary are merged into the model in order to determine the volumetric heating source terms. Their numerical results for the validation study of the solar-wind background of Carrington rotation 2060 show overall good agreements in the solar corona and in interplanetary space with the observations from the SOHO and spacecraft data from OMNI.

Feng *et al.*[77] introduced a new 3D MHD numerical model to simulate the steady state ambient solar wind from the solar surface to $215\,R_{\rm s}$ or beyond, and the model adopts a splitting finite-volume scheme based on a six-component grid system in spherical coordinates. By splitting the MHD equations into a fluid part and a magnetic part, a finite volume method can be used for the fluid part and a constrained-transport method able to maintain the divergence-free constraint on the magnetic field can be used for the magnetic induction part. This new second-order model in space and time is validated when modeling the large-scale structure of the solar wind. The numerical results for Carrington rotation

*http://sourceforge.net/projects/paramesh/

2064 show its ability to produce structured solar wind in agreement with observations.

The dynamic process of CMEs in the heliosphere provides the key information for evaluating CMEs' geoeffectiveness and improving the accurate prediction of CME-induced shock arrival time at the Earth. Shen *et al.*[78] presented a data-constrained 3D MHD simulation of the evolution of the CME in a realistic ambient solar wind for the 12—16 July 2012 event by using the 3D Corona Interplanetary Total Variation Diminishing (COIN-TVD) MHD code. A detailed comparison of the kinematic evolution of the CME between the observations and the simulation is carried out, including the usage of the time elongation maps from the perspectives of both STEREO-A and STEREO-B. In this case study, they find that their 3D COIN-TVD MHD model, with the magnetized plasma blob as the driver, is able to reproduce relatively well the real 3D nature of the CME in morphology and their evolution from the Sun to the Earth. The simulation also provides a relatively satisfactory comparison with the in-situ plasma data from the WIND spacecraft.

Zhang and Zhou[79] applied the MacCormack scheme to the time-independent MHD equations in spherical coordinates with a six-component grid for the 3D interplanetary solar wind simulation. The use of six-component grid system can better body-fit the spherical shell domain of interplanetary space as well as avoid the singularity and the mesh convergence near the poles. The radial coordinate is treated as a time-like coordinate, thus can significantly reduce the computational time. The inner boundary distribution is determined by the empirical relations and observation. Five kinds of inner boundary conditions used formerly by MHD modelers are comparatively used to simulate the Carrington Rotation (CR) 1922 solar wind background. The numerical results show that all these boundary conditions can produce consistent large-scale solar wind structure with the observation, and better result in agreement with observations can be achieved when adopting the following inner boundary condition: the radial speed is obtained by the empirical relationship proposed by McGregor *et al.* in 2011, the magnetic field is obtained by Horizontal Current Sheet (HCCS) model, an assumption of constant momentum flux is used to derive number density, and temperature is chosen to assure that the total pressure is uniform at the inner boundary.

Wang *et al.*[80] successfully applied the space-time Conservation Element and Solution Element (CESE) method in general curvilinear coordinates to the 3D MHD simulations of the interaction between the solar wind and Saturn's magnetosphere on a six-component grid system. As a new numerical model modified for the study of the interaction between the solar wind and Saturn's magnetosphere, they obtain the large-scale configurations of Saturn's magnetosphere under the steady solar wind with due southward Interplanetary Magnetic Field (IMF) conditions. The numerical results clearly indicate that the global structure of Saturn's magnetosphere is strongly affected by the rotation of Saturn as well as by the solar wind. The subsolar standoff distances of the magnetopause and the bow shock in their model are consistent with those predicted by the data-based empirical models. Their MHD results also show that a plasmoid forms in the magnetotail under the effect of the fast planetary rotation. However, somewhat differently from the previous models, they found that there are two flow vortices generated on the duskside under due southward IMF at Saturn. On the duskside, the clockwise one closer to the planet is excited by the velocity shear between the rotational flows and the sunward flows, while the anticlockwise one is generated from the velocity shear between the tailward flows along the magnetopause and the sunward flows.

The CME event on 3 April 2010 is the first fast CME observed by STEREO Sun-Earth Connection Coronal and Heliospheric Investigation (SECCHI)/Heliospheric Imager (HI) for the full Sun-Earth line. Such an event provides a good opportunity to study the propagation and evolution of CME from the Sun up to 1 AU. Zhou *et al.* [81] studied the time-dependent evolution and propagation of this event from the Sun to Earth using the 3D SIP-CESE MHD model. The CME is initiated by a simple spherical plasmoid model: a spheromak magnetic structure with high-speed, high-pressure, and high-plasma density plasmoid. The simulation performs a comprehensive study on the CME by comparing the simulation results with STEREO and WIND observations. It is confirmed from the comparison with observations that the MHD model successfully reproduces many features of both the fine solar coronal structure and the typical large-scale structure of the shock propagation and gives the shock arrival time at Earth with an error of ~2 h. Then they analyzed in detail the several factors affecting the CME's geo-effectiveness: the CME's propagation trajectory, span angle, and velocity.

Fu and Feng[82] proposed a new hybrid numerical scheme of combining an E-CUSP (Energy-Convective Upwind and Split Pressure) method for the fluid part and the Constrained Transport (CT) for the magnetic induction part. In order to avoid the occurrence of negative pressure in the reconstructed profiles and its updated value, a positivity preserving method is provided. Furthermore, the MHD equations are solved at each physical time step by advancing in pseudo time. The use of dual time stepping is beneficial in the computation since the use of dual time stepping allows the physical time step not to be limited by the corresponding values in the smallest cell and to be selected based on the numerical accuracy criterion. This newly established hybrid scheme combined with positivity preserving method and dual-time technique has demonstrated the accurateness and robustness through numerical experiments of benchmark problems such as the 2D Orszag-Tang vortex problem and the 3D shock-cloud interaction problem.

To model the steady state solar wind, Zhang and Feng[83] developed an implicit dual-time stepping scheme based on the finite volume method in spherical coordinates with a six-component grid system. By adding a pseudo-time derivative to the Magnetohydrodynamics equations for the solar wind plasma, the governing equations are solved implicitly at each physical time step by advancing in pseudo time. As a validation, ambient solar wind for Carrington rotation 2048 has been studied. Numerical tests with different Courant factors show its capability of producing structured solar wind and that the physical time step can be enlarged to be one hundred times that of the original one. Their numerical results have demonstrated overall good agreements with the observations.

Wang *et al.*[84] presented a newly developed global MHD model to study the responses of the Earth's magnetosphere to the solar wind. The model is established by using the space-time Conservation Element and Solution Element (CESE) method in general curvilinear coordinates on a six-component grid system. As a preliminary study, they present the model's numerical results of the quasi-steady state and the dynamics of the Earth's magnetosphere under steady solar wind flow with due northward Interplanetary Magnetic Field (IMF). The model results are found to be in good agreement with those published by other numerical magnetospheric models.

Feng *et al.*[85] presented a time-dependent 3D MHD solar wind simulation from the solar surface to the Earth's orbit driven by time-varying line-of-sight solar magnetic field data. The simulation is based on the 3D Solar-Interplanetary (SIP) Adaptive Mesh Refinement (AMR) space-time Conservation Element and Solution Element (CESE) MHD (SIP-AMR-CESE MHD) model. In this simulation, they first achieve the initial solar wind background with the time-relaxation method by inputting a potential field obtained from the synoptic photospheric magnetic field and then generate the time-evolving solar wind by advancing the initial 3D solar wind background with continuously varying photospheric magnetic field. The model updates the inner boundary conditions by using the projected normal characteristic method, inputting the high-cadence photospheric magnetic field data corrected by solar differential rotation, and limiting the mass flux escaping from the solar photosphere. They investigate the solar wind evolution from 1 July to 11 August 2008 with the model driven by the consecutive synoptic maps from the Global Oscillation Network Group. They compare the numerical results with the previous studies on the solar wind, the solar coronal observations from the Extreme ultraviolet Imaging Telescope (EIT) board on the SOHO, and the measurements from OMNI at 1 Astronomical Unit (AU). Comparisons show that the present data-driven MHD model's results have overall good agreement with the large-scale dynamical coronal and interplanetary structures, including the sizes and distributions of the coronal holes, the positions and shapes of the streamer belts, the heliocentric distances of the Alfvénic surface, and the transitions of the solar wind speeds. However, the model fails to capture the small-sized equatorial holes, and the modeled solar wind near 1 AU has a somewhat higher density and weaker magnetic field strength than observed. Perhaps better preprocessing of high-cadence observed photospheric magnetic field (particularly 3D global measurements), combined with plasma measurements and higher resolution grids, will enable the data-driven model to more accurately capture the time-dependent changes of the ambient solar wind for further improvements. In addition, other measures may also be needed when the model is employed in the period of high solar activity.

Solar Active Region (AR) 11283 is a very magnetically complex region and it has produced many eruptions. However, there exists a non-eruptive filament in the plage region just next to an eruptive one in the AR, which gives Jiang *et al.*[86] an opportunity to perform a comparison analysis of these two filaments. The coronal magnetic field extrapolated using the CESE-MHD-NLFFF code reveals that two Magnetic Flux Ropes (MFRs) exist in the same extrapolation box supporting these two filaments, respectively. Analysis of the magnetic field shows that the eruptive MFR contains a Bald-Patch Separatrix Surface (BPSS) cospatial very well with a pre-eruptive EUV sigmoid, which is consistent with the BPSS model for coronal sigmoids. The magnetic dips of the non-eruptive MFRs match Hα observation of the non-eruptive filament strikingly well, which strongly supports the MFR-dip model for filaments. Compared with the non-eruptive MFR/filament (with a length of about 200 Mm), the eruptive MFR/filament is much smaller (with a length of about 20 Mm), but it contains most of the magnetic free energy in the extrapolation box and holds a much higher free energy density than the non-eruptive one. Both the MFRs are weakly twisted and can not trigger kink instability. The AR eruptive MFR is unstable because its axis reaches above a critical height for torus instability, at which the overlying closed arcades can no longer confine the MFR stably. On the contrary, the quiescent MFR is very firmly held by its overlying field, as its axis apex is far below the torus-instability threshold height. Overall, this comparison investigation supports that an MFR can exist prior to eruption and the ideal MHD instability can trigger an MFR eruption.

In the solar corona, the magnetic flux rope is believed to be a fundamental structure that accounts for magnetic free energy storage and solar eruptions. Up to the present, the extrapolation of the magnetic field from boundary data has been the primary way to obtain fully three-dimensional magnetic information about the corona. As a result, the ability to reliably recover the coronal magnetic flux rope is important for coronal field extrapolation. Jiang and Feng[87] examined their coronal field extrapolation code with an analytical magnetic flux rope model, which consists of a bipolar magnetic configuration holding a semi-circular line-tied flux rope in force-free equilibrium.

By only using the vector field at the bottom boundary as input, they test their code with the model in a representative range of parameter space and find that the model field can be reconstructed with high accuracy. In particular, the magnetic topological interfaces formed between the flux rope and the surrounding arcade, *i.e.*, the hyperbolic flux tube and bald patch separatrix surface, are also reliably reproduced. By this test, they demonstrate that their CESE-MHD-NLFFF code can be applied to recovering the magnetic flux rope in the solar corona as long as the vector magnetogram satisfies the force-free constraints.

Wu *et al.*[88] presented a 3D MHD model based on an observed eruptive twisted flux rope (sigmoid) deduced from solar vector magnetograms. This model is a combination of their two very well tested MHD models: (i) data-driven 3D MHD Active Region Evolution (MHD-DARE) model for the reconstruction of the observed flux rope and (ii) 3D MHD Global Coronal-Heliosphere Evolution (MHD-GCHE) model to track the propagation of the observed flux rope. The 6 September 2011, AR11283, event is used to test this model. First, the formation of the flux rope (sigmoid) from AR11283 is reproduced by the MHD-DARE model with input from the measured vector magnetograms given by SDO/HMI. Second, these results are used as the initial boundary condition for their MHD-GCHE model for the initiation of a CME as observed. The model output indicates that the flux rope resulting from MHD-DARE produces the physical properties of a CME, and the morphology resembles the observations made by STEREO/COR-1.

Zhang *et al.*[89] presented a comparative study of divergence cleaning methods of magnetic field in the solar coronal 3D numerical simulation. For such purpose, the diffusive method, projection method, generalized Lagrange multiplier method and constrained-transport method are used. All these methods are combined with a finite-volume scheme in spherical coordinates. In order to see the performance between the four divergence cleaning methods, solar coronal numerical simulation for Carrington rotation 2056 has been studied. Numerical results show that the average relative divergence error is around $10^{-4.5}$ for the constrained-transport method, while about $10^{-3.1}$—$10^{-3.6}$ for the other three methods. Although there exist some differences in the average relative divergence errors for the four employed methods, their tests show they can all produce basic structured solar wind.

7 CME/Shock Arrival Time Prediction

One of the major solar transients, CMEs and their related interplanetary shocks have severe space weather effects and become the focus of study for both solar and space scientists. Predicting their evolutions in the heliosphere and arrival times at Earth is an important component of the space weather predictions. Various kinds of models in this aspect have been developed during the past decades. In this paper, Zhao and Dryer[90] presented a view of the present status (during Solar Cycle 24 in 2014) of the space weather's objective to predict the arrival of coronal mass ejections and their interplanetary shock waves at Earth. This status, by implication, is relevant to their arrival elsewhere in the solar system. Application of this prediction status is clearly appropriate for operational magnetospheric and ionospheric situations including A→B→C... solar system missions. They review current empirical models, expansion speed model, drag-based models, physics-based models (and their real-time prediction's statistical experience in Solar Cycle 23), and MHD models. New observations in Solar Cycle 24, including techniques/models, are introduced as they could be incorporated to form new prediction models. The limitations of the present models and the direction of further development are also suggested.

Predicting the arrival times of CMEs and their related waves at Earth is an important aspect of space weather forecasting. The Shock Propagation Model (SPM) and its updated version (SPM2), which uses the initial parameters of solar flare-Type Ⅱ burst events as input, have been developed to predict the shock arrival time. Zhao and Feng[91] continued to investigate the influence of solar disturbances and their associated CMEs on the corresponding Interplanetary (IP) shock's arrival at Earth. It has been found that IP shocks associated with wider CMEs have a greater probability of reaching the Earth, and the CME speed obtained from coronagraph observations can be supplementary to the initial shock speed computed from Type Ⅱ radio bursts when predicting the shock's arrival time. Therefore, the third version of the model, *i.e.*, SPM3, has been developed based on these findings. The new version combines the characteristics of solar flare-Type Ⅱ events with the initial parameters of the accompanying CMEs to provide the prediction of the associated IP shock's arrival at Earth. The prediction test for 498 events of Solar Cycle 23 reveals that the prediction success rate of SPM3 is 70%−71%, which is apparently higher than that of the previous SPM2 model (61%−63%). The transit time prediction error of SPM3 for the Earth-encountered shocks is within 9 h (mean-absolute). Comparisons between SPM3 and other similar models also demonstrate that SPM3 has the highest success rate and best prediction performance.

Prediction of the Shocks' Arrival Times (SATs) at the Earth is very important for space weather forecast. There is a well-known SAT model, Shock Time of Arrival (STOA), which is widely used in the space weather forecast. However, the shock transit time from STOA model usually has a relative large error compared to the real measurements. In addition, STOA tends to yield too much "yes" prediction, which causes a large number of false alarms. Therefore, Liu *et al.*[92] worked on the modification of STOA model. First, they give a new method to calculate the shock transit time by modifying the way to use the solar wind speed in STOA model. Second, they develop new criteria for deciding whether the shock will arrive at the Earth with the help of the sunspot numbers and the angle distances of the flare events. It is shown that their work can improve the SATs prediction significantly, especially the prediction of flare events without shocks arriving at the Earth.

8 Magnetic Reconnection

Kinetic effects resulting from the two-fluid physics play a crucial role in the fast collisionless reconnection, which is a process to explosively release massive energy stored in magnetic fields in space and astrophysical plasmas. In-situ observations in the Earth's magnetosphere provide solid consistence with theoretical models on the point that kinetic effects are required in the collisionless reconnection. However, all the observations associated with solar wind reconnection have been analyzed in the context of MHD although a lot of solar wind reconnection exhausts have been reported. Because of the absence of kinetic effects and substantial heating, whether the reconnections are still ongoing when they are detected in the solar wind remains unknown. By dual-spacecraft observations, Xu *et al.*[93] reported a solar wind reconnection with clear Hall magnetic fields. Its corresponding Alfvénic electron outflow jet, derived from the decouple between ions and electrons, is identified, showing direct evidence for kinetic effects that dominate the collisionless reconnection. The turbulence associated with the exhaust is a kind of back-ground solar wind turbulence, implying that the reconnection generated turbulence has not much developed.

9 Solar Variability and Its Impact on Climate

Based on the well-calibrated systematic measurements of sunspot numbers, the reconstructed data of the Total Solar Irradiance (TSI), and the observed anomalies of the Earth's averaged surface temperature (global, ocean, land), Zhao and Feng[94] investigated the periodicities of both solar activity and the Earth's temperature variation as well as their correlations on the time scale of centuries using the wavelet and cross correlation analysis techniques. The main results are as follows.

(1) Solar activities (including sunspot number and TSI) have four major periodic components higher than the 95% significance level of white noise during the period of interest, *i.e.* 11-year period, 50-year period, 100-year period, and 200-year period. The global temperature anomalies of the Earth have only one major periodic component of 64.3-year period, which is close to the 50-year cycle of solar activity.

(2) Significant resonant periodicities between solar activity and the Earth's temperature are focused on the 22- and 50-year period.

(3) Correlations between solar activity and the surface temperature of the Earth on the long time scales are higher than those on the short time scales. As far as the sunspot number is concerned, its correlation coefficients to the Earth temperature are 0.31−0.35 on the yearly scale, 0.58−0.70 on the 11-year running mean scale, and 0.64−0.78 on the 22-year running mean scale. TSI has stronger correlations to the Earth temperature than sunspot number.

(4) During the past 100 years, solar activities display a clear increasing tendency that corresponds to the global warming of the Earth (including land and ocean) very well. Particularly, the ocean temperature has a slightly higher correlation to solar activity than the land temperature.

All these demonstrate that solar activity has a non-negligible forcing on the temperature change of the Earth on the time scale of centuries.

The solar impact on the Earth's climate change is a long topic with intense debates. Based on the reconstructed data of Solar Sunspot Number (SSN), the local temperature in Vostok (T), and the atmospheric CO_2 concentration data of Dome Concordia, Zhao *et al.*[95] investigated the periodicities of solar activity, the atmospheric CO_2 and local temperature in the inland Antarctica as well as their correlations during the past 11 000 years before AD 1895. They find that the variations of SSN and T have some common periodicities, such as the 208-year, 521-year, and ~1000-year cycles. The correlations between SSN and T are strong for some intermittent periodicities. However, the wavelet analysis demonstrates that the relative phase relations between them usually do not hold stable except for the millennium-cycle component. The millennial variation of SSN leads that of T by 30~40 years, and the anti-phase relation between them keeps stable nearly over the whole 11 000 years of the past. As a contrast, the correlations between CO_2 and T are neither strong nor stable. These results indicate that solar activity might have potential influences on the long-term change of Vostok's local climate during the past 11 000 years before modern industry.

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