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Research Progress of Interplanetary Physics in Mainland China*

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Abstract Significant progress has been made by Chinese scientists in research of interplanetary physics during the recent two years (2018–2020). These achievements are reflected at least in the following aspects: Activities in solar corona and lower solar atmosphere; solar wind and turbulence; filament/prominence, jets, flares, and radio bursts; active regions and solar eruptions; coronal mass ejections and their interplanetary counterparts; other interplanetary structures; space weather prediction methods; magnetic reconnection; Magnetohydrodynamic (MHD) numerical modeling; solar energetic particles, cosmic rays, and Forbush decreases; machine learning methods in space weather and other aspects. More than one hundred and forty papers in the academic journals have been published in these research directions. These fruitful achievements are obtained by Chinese scholars in solar physics and space physics either independently or through international collaborations. They greatly improve people's understanding of solar activities, solar eruptions, the corresponding space weather effects, and the Sun-Earth relations. Here we will give a very brief review on the research progress. However, it must be pointed out that this paper may not completely cover all achievements in this field due to our limited knowledge.

Key words Solar wind, Solar eruptions, Energetic particles, Interplanetary transients, Space weather

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1 Activities in Solar Corona and Lower Solar Atmosphere

Solar UV bursts are a new type of small-scale activity discovered with NASA's IRIS mission. Tian *et al.*[1] studied the temporal evolution of UV bursts in the earliest stage of solar flux emergence, and found that the appearance of UV bursts is a good indicator of local heating during flux emergence. They also found that the occurrence frequency of UV bursts is closely related to the rate of flux emergence. By investigating the 3D magnetic field topology through a magneto-hydrostatic model, they found that almost all UV bursts are located in regions of a large squashing factor at a height of about 1 Mm. The relationship between Elleman bombs and UV bursts is highly debated. Chen *et al.*[2] investigated the spatial and temporal relationship between Elleman bombs

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and UV bursts using joint near-limb observations of GST and IRIS. They find that many UV bursts tend to appear at the upper parts of their associated flame-like EBs. The intensity variations of most EB-related UV bursts and their corresponding EBs match well. These results suggest that UV bursts and EBs likely form at different heights during a common reconnection process.

Solar spicules are the most abundant small-scale dynamic features in the solar chromosphere. The origin of these small-scale jets is poorly understood. Using GST's high-resolution and high-sensitivity magnetic field measurements of the photosphere, Samanta *et al.*[3] found clear signatures of opposite-polarity magnetic fluxes at the footpoints of the jets. Interaction between these fluxes leads to the generation of the jets. These observations provide a strong evidence for the reconnection driven spicule mechanism. Their observations have also revealed obvious heating of these spicules to coronal temperatures, thus revealing the previously missing link between magnetic activities in the lower solar atmosphere and coronal heating. Through a detailed analysis of the coordinated GST and IRIS observations, Tian *et al.*[4] identified signatures of shock waves and unambiguous evidence of reconnection at light brights. They found frequently occurring inverted Y-shaped jets in the *Hα* wings and UV burst-type profiles of the transition region lines. This work demonstrated that the surge-like activity above light bridges has two components: the ever-present short and slow surges likely to be related to the upward leakage of magneto-acoustic waves from the photosphere, and the occasionally occurring long and fast surges that are obviously caused by the intermittent reconnection jets. Their study has solved the debate regarding the nature of these surge-like activities.

From the highest-resolution sunspot images obtained with GST, Zhang *et al.*[5] discovered a new type of fine structures in light bridges: striking knot-like dark structures within the central dark lane. These dark knots divide the central dark lane into multiple sections, and they appear to be very common in narrow light bridges. The evolution of these highly dynamic dark structures could provide detailed information about the magneto-convection in light bridges. IRIS Observations often reveal significantly broadened and non-reversed Mg II k and h line profiles at flare ribbons. Zhu *et al.*[6] performed plane-parallel radiative hydrodynamics modeling for the formation of the Mg II k and h lines in flares, and reproduced their significantly broadened and single-peak profiles observed with IRIS for the first time

Coronal loops interconnecting two Active Regions (Ars), called Interconnecting Loops (Ils), are prominent large-scale structures in the solar atmosphere. They carry a significant amount of magnetic flux and therefore are considered to be an important element of the solar dynamo process. Earlier observations showed that eruptions of Ils are an important source of Coronal Mass Ejections (CMEs). It is generally believed that Ils are formed through magnetic reconnection in the high corona (>150″~200″), and several scenarios have been proposed to explain their brightening in Soft X-rays (SXRs). However, the detailed IL formation process has not been fully explored, and the associated energy release in the corona still remains unresolved. Du *et al.*[7] reported the complete formation process of a set of Ils connecting two nearby Ars, with successive observations by STEREO-A on the far side of the Sun and by Solar Dynamics Observatory (SDO) and Hinode on the Earth side. They concluded that Ils are formed by gradual reconnection high in the corona, in line with earlier postulations. In addition, they showed evidence that Ils brighten in SXRs and EUVs through heating at or close to the reconnection site in the corona (*i.e.*, through the direct heating process of reconnection), a process that has been largely overlooked in earlier studies of Ils.

Extreme-Ultraviolet (EUV) waves are spectacular horizontally propagating disturbances in the low solar corona. They always trigger horizontal Secondary Waves (SWs) when they encounter the ambient coronal structure. Zheng *et al.*[8] presented the first example of upward SWs in a streamer-like structure after the passing of a EUV wave. This event occurred on 1 June 2017. The EUV wave happened during a typical solar eruption including a filament eruption, a CME, and a C6.6 flare. The EUV wave was associated with Quasi-periodic Fast Propagating (QFP) wave trains and a type II radio burst that represented the existence of a coronal shock. The EUV wave had a fast initial velocity of similar to 1000 km·s^{-1}, comparable to high speeds of the shock and the QFP wave trains. Intriguingly, upward SWs rose slowly (similar to 80 km·s^{-1}) in the streamer-like structure after the sweeping of the EUV wave. The upward SWs seemed to originate from limb brightenings that were caused by the EUV wave. All of the results show that the EUV wave is a fast-mode Magnetohydrodynamic (MHD) shock wave, likely triggered by the flare impulses. They suggested that part of the EUV wave was probably trapped in the closed magnetic fields of the streamer-like structure, and upward SWs possibly resulted from the release of slow-mode trapped waves. It was believed that the interplay of the strong compression of the coronal shock and the configuration of the streamer-like structure is crucial for the formation of upward SWs.

The morphologies of the wavefronts of EUV waves can shed light on their physical nature and driving mechanism, which are still strongly debated. In reality, the wavefronts always deform after interacting with ambient coronal structures during their propagation. Zheng *et al.*[9] studied the initial wavefront morphologies of four selected EUV waves that were closely associated with jets or flux-rope eruptions, using the high spatio-temporal resolution observations and different perspectives from SDO and STEREO. For the jet-driven waves, the jets originated from one end of the overlying closed loops, and the arc-shaped wavefront formed around the other, far end of the expanding loops. The extrapolated field lines of the Potential Field Source Surface model show the close relationships between the jets, the wavefronts, and the overlying closed loops. For the flux-rope-driven waves, the flux ropes (sigmoids) lifted off beneath the overlying loops, and the circular wavefronts had an intimate spatio-temporal relation with the expanding loops. All of the results suggest that the configuration of the overlying loops and their locations relative to the erupting cores are very important for the formation and morphology of the wavefronts, and two jet-driven waves and two flux-rope-driven waves were likely triggered by the sudden expansion of the overlying closed loops. They also proposed that the wavefront of EUV wave was possibly integrated by a chain of wave components triggered by a series of separated expanding loops.

Fast sausage modes in solar magnetic coronal loops are only fully contained in unrealistically short dense loops. Otherwise, they are leaky, losing energy to their surroundings as outgoing waves. This causes any oscillation to decay exponentially in time. Simultaneous observations of both period and decay rate therefore reveal the eigenfrequency of the observed mode, and potentially insight into the tubes' nonuniform internal structure. Cally and Xiong[10] presented a global spectral description of the oscillations in an implicit matrix eigenvalue equation where the eigenvalues were associated predominantly with the diagonal terms of the matrix. The off-diagonal terms vanish identically if the tube is uniform. A linearized perturbation approach, applied with respect to a uniform reference model, was developed that makes the eigenvalues explicit. The implicit eigenvalue problem was easily solved numerically though, and it was shown that knowledge of the real and imaginary parts of the eigenfrequency is sufficient to determine the width and density contrast of a boundary layer over which the tubes' enhanced internal densities drop to ambient values. Linearized density kernels were developed that show sensitivity only to the extreme outside of the loops for radial fundamental modes, especially for small density enhancements, with no sensitivity to the core. Higher radial harmonics did show some internal sensitivity, but these would be more difficult to observe. Only kink modes are sensitive to the tube centers. Variation in internal and external Alfvén speed along the loop was shown to have little effect on the fundamental dimensionless eigenfrequency, though the associated eigenfunction became more compact at the loop apex as stratification increases, or might even displace from the apex.

A new method to quantitatively and comprehensively diagnose shock waves responsible for heating and ionizing solar atmosphere is proposed. Shock wave is supposed to be one of the main energy sources of heating and ionizing the lower atmosphere of the sun. The longitudinal oscillation of the solar shock on the surface of the photosphere is the source of the shock wave. In order to understand the physical process of the lower atmosphere of the sun, it is necessary to conduct the comprehensive and quantitative diagnosis of shock wave. However, the remote sensing diagnosis of the shock wave in the partially ionized solar atmosphere is more difficult than the in-situ diagnosis of the shock wave in the interplanetary solar wind. Thanks to the IRIS space-based telescope, the spectroscopy + imaging observation of the low transition region of the sun provides necessary conditions for the comprehensive and quantitative diagnosis of shock waves. Ruan *et al.* [11] established a new method of shock analysis based on imaging spectroscopy (abbreviated as the shock-ABIS method). The steps of this method are as follows: (i) based on the imaging spectroscopic observation, five parameters of the upstream and downstream of the shock wave (the velocity in the line of sight direction, the radiation intensity of the upstream and downstream, and the propagation velocity in the sky plane projection) are given; (ii) these five parameters are used as known quantities to be substituted into the nonlinear equation with the propagation velocity in the line of sight direction as unknown quantities for the iterative solution; (iii) further use the propagation velocity in the direction of line of sight to calculate the density, temperature, velocity, Mach number and other residual parameters of the upstream and downstream. The remarkable features of this method are: (i) combining the imaging spectroscopic observation data with the RH jump to the greatest extent; (ii) considering the temperature response function of the spectroscopic observation; (iii) considering the heating ionization effect downstream of the shock wave; (iv) being able to provide a full set of parameters of quasi-parallel shock wave to realize the comprehensive and quantitative diagnosis. The validity of the diagnosis method is verified by forward simulation. The diagnosis results applied to the observation cases show that the temperature in the downstream of the shock wave in the low transition region is significantly higher than that in the upstream (more than 30000° higher), the compression ratio of the shock wave is generally less than 2, and the propagation speed of the shock wave is slightly higher than the local sound speed in the upstream.

2 Solar Wind and Turbulence

Magnetic holes are common features with a prominent dip of magnetic field strength in space plasma turbulence. As to their nature, there exists a dispute of explanations among discontinuities, magnetic reconnection, solitons, kinetic-scale electron vortexes, slow waves, and mirror-mode instability. As magnetic holes are often accompanied by thermal anisotropy, at MHD scales double-polytropic equations can serve as an appropriate description. The reason for the long-lasting dispute lies in the fact that both mirror-mode structures and oblique slow-mode waves are characterized by anti-correlation between plasma density (or temperature) and magnetic field strength, which, as often used in preceding works, is also the characteristic feature of magnetic holes. Therefore, to finally and unambiguously diagnose the nature of magnetic holes above ion scales, Zhang *et al.*[12] proposed to resort to other features, among which $v_{\parallel}$ and its phase relation with $|B|$ and n behave differently between mirror mode structures and slow-mode waves. Herewith they established a model with a superposition of both slow and mirror modes to reproduce the observed types of behaviors (n, $v_{\parallel}$, $|B|$, $T_{\parallel}$, $T_{\perp}$). This model inspires a new understanding of the nature of magnetic holes: the magnetic hole in reality is not solely contributed by only one mode, but a mixture of the two modes with an adjustable amplitude ratio.

The compressible component of solar wind turbulence displays a slow-mode feature. However, the nature of the slow-mode fluctuations remains open. Based on numerical simulations of the driven compressible MHD turbulence with a uniform mean magnetic field, Yang *et al.*[13] used polarization of the MHD modes to decompose turbulent velocity and magnetic fields into Alfvén modes, slow modes, and fast modes. The numerical results with different cross-helicity, plasma beta (β), and Alfvén Mach number noted that fast modes are a marginal component among the three decomposed modes, and the compressible component of the MHD turbulence behaves mainly as the slow modes. Both of the decomposed slow modes and Alfvén modes exhibit a Kolmogorov-like power-law spectrum and evident anisotropy, with wave vectors mainly distributing around the directions perpendicular to the uniform mean field. For the first time, it was found that the propagating slow magnetosonic waves as well as the non-propagating slow-mode structures are combined to contribute to the compressible fluctuations, and the propagating Alfvén waves, as well as the non-propagating Alfvén-mode structures, coexist for the non-compressible fluctuations. However, there is unlikely a one-to-one match between the identified slow waves and Alfvén waves, or between the identified slow-mode structures and Alfvén-mode structures. These findings provide a new perspective on the understanding of the compressible and non-compressible fluctuations.

Time History of Events and Macroscale Interactions during Substorms (THEMIS) data are used to investigate the magnetic field structures in the vicinity of the magnetopause. Generally, the tendency that the farther away is from the Earth, the weaker the detected magnetic field is expected inside the dayside magnetopause. Song *et al.*[14] showed two cases which conflict with the expectation that the magnetic field gradient direction reverses from inward to outward in a short time interval. After further analysis, it was found that the THEMIS probes encountered a magnetopause indentation moving along the magnetopause towards the dawn in one case, and for the other case, they crossed an evolutive indented magnetopause that was produced locally and then recovered to its normal state. These two magnetopause indentations may be related with the fast magnetosheath flow. Accordingly, they supposed that the fast magnetic gradient direction reverse was caused by the abnormal magnetic field distribution adjacent to the deformed magnetopause.

Structures and propagating waves are often observed in solar wind turbulence. Their origins and features remain to be uncovered. Yang *et al.*[15] used 3D driven, compressible MHD turbulence simulations to investigate the global signatures of the driven fluctuations in the whole spatial and temporal domain. With four-dimensional spatial-temporal (x, y, z, t) Fourier transformations implemented, they identified two distinct main populations: waves, which satisfy the ω-k dispersion relations and were propagating; and structures, which satisfied the polarization relations but non-propagating ($\omega=0$). Whereas the overall turbulent energy spectrum was still consistent with $k^{-5/3}$, the contributions from waves and structures showed very different behavior in k space, with structures dominating at small k but waves became comparable to structures at large k. Overall, the fluctuations in the directions perpendicular to the large-scale mean field $\boldsymbol{B}_0$ were a manifestation of structures, while along the parallel direction, the fluctuations were dominated by waves. Also, a significant portion of the incompressible structures was the Alfvénic nature, and with imbalanced increased, the waves predominantly propagated in one direction and nearly perpendicular to $\boldsymbol{B}_0$. Differentiating the relative contributions from waves and structures could have important implications for understanding the non-linear cascade processes in the inertial range as well as particle-fluctuation interactions at small scales.

The power spectrum of magnetic fluctuations has a break at the high-frequency end of the inertial range. Beyond this break, the spectrum becomes steeper than the Kolmogorov law $f^{-5/3}$. The break frequency was found to be associated with plasma beta (β). However, the full-range β dependence of the ion-scale spectral break has not been presented before in observational studies. Wang *et al.*[16] showed the continuous variation of the break frequency on full-range β in the solar wind turbulence. By using measurements from the WIND and Ulysses spacecraft, they showed the break frequency (f_b) normalized, respectively, by the frequencies corresponding to ion inertial length (f_{di}), ion gyroradius ($f_{\rho i}$), and cyclotron resonance scale (f_{ri}) as a function of β for 1306 intervals. Their β values spread from 0.005 to 20, which nearly cover the full β range of the observed solar wind turbulence. It was found that f_b/f_{di} ($f_b/f_{\rho i}$) generally decreases (increases) with β_γ while f_b/f_{ri} is nearly a constant. They performed a linear fit on the statistical result, and obtained the empirical formulas $f_b/f_{di} \approx \beta^{-1/4}$, $f_b/f_{\rho i} \approx \beta^{1/4}$, and $f_b/f_{ri} \approx 0.90$ to describe the relation between f_b and β. They also compared the observations with a numerical simulation and the prediction by ion cyclotron resonance theory. The result favors the idea that the cyclotron resonance is an important mechanism for energy dissipation at the spectral break. When $\beta \ll 1$ and $\beta \gg 1$, the break at f_{di} and $f_{\rho i}$ may also be associated with other processes.

The slow wind anisotropy has been observed as elongation along the magnetic field direction in the magnetic self-correlation contours calculated from data sets of two-day-long data and averaged for five years in 1998–2002, which is consistent with prediction by the critical balance cascade theory. More pronounced elongation at smaller scales than at larger scales has also been predicted by this theory. However, this prediction has not yet been checked by observations. Wang *et al.*[17] presented a check of the variation trend of the anisotropy with scales by presenting level contours of magnetic field and velocity self-correlations using intervals with durations varying from two days to one hour as observed by ACE during 1998–2002 in the slow wind. They found that the level contours elongate along the magnetic field direction at durations of two days and one day. But they become isotropic for shorter intervals from about 10 hours to 1 hour. They also found that in the fast wind, the variation of the anisotropy with the scale has the same trend as in the slow wind. The 2D isotropic feature of the solar wind fluctuations shown by these statistical results is not consistent with the existing theory and will open a new avenue for studying solar wind turbulence.

The Quiet Sun (QS) and helmet Streamer (STR) are generally considered to account for sources of slow solar wind with low Alfvénicity and low proton temperature. The solar wind with high Alfvénicity is often associated with Coronal Holes (CHs). Recently, the solar wind measured by ACE spacecraft at 1 AU was mapped back to its magnetic footpoints. Depending on the proximity of the solar wind footpoints to a given coronal or heliospheric structure, Wang *et al.*[18] classified solar winds into different types based on their sources: QS, STR, Active Region (AR), and CH. They compared the properties of the solar winds originated from QS, STR, AR, and CH using 2 h data. It was found that at solar maximum 34% of the quiet-Sun-associated slow wind ($V_{sw} <$ 450 km·s^{-1}) has high Alfvénicity ($|\sigma_c| > 0.7$). This significantly higher proportion of Alfvénic fluctuations indicated that the quiet-Sun-associated wind at 1 AU has similar properties as fast wind, which originates from the CH. Accordingly, they speculate that this type of solar wind at 1 AU could come from open fields within the quiet-Sun region. This observational study will help us understand more about the coronal source regions of the solar wind in interplanetary space.

On the mechanism of the isotropy of the turbulent power spectral break position: the isotropy of the turbulent diffusion effect. The break point of the solar wind turbulence power spectra has an important physical meaning: it is the transition from the energy cascade region at the MHD scales to the kinetic scales. There is a great controversy about the physical process related with the scale of break point: is it the dissipation of the ion cyclotron wave or the dispersion of the kinetic Alfven wave. If one of them is dominant, then the break point frequency should have anisotropic characteristics. Duan *et al.*[19] developed a set of methods to fit the double power-law spectra and identify the location of spectral break points. It was found that the frequency of break points did not change with the angle, suggesting the isotropic characteristics. Why is the break point frequency isotropic? Therefore, they studied the relationship between three effects with their initials being "d" (diffusion, dissipation, and dispersion), and found that diffusion effect (a combination of both dissipation effect and dispersion effect) can better characterize the physics. It was found that the indicator for diffusion effect is quasi-isotropic in the wave vector space, which provides a physical explanation for the isotropic observation results of spectral break points.

The formula of energy conversion rate spectrum in wave number space was put forward, and it was applied to the dissipation diagnosis of plasma turbulence in space by He *et al.*[20]. The profile of the dissipation rate spectrum of ion cyclotron wave is observed for the first time, and the parallel and vertical dissipation rate spectra are compared. It is found that the vertical dissipation rate spectrum dominates, indicating that the turbulent energy dissipation is mainly used to heat plasma vertically. They theoretically gave two equivalent forms of the distribution of dissipation rate spectrum in the wavenumber space, and expounds that one of them is relatively intuitive but cannot be applied to the actual observation, while the other seems to be relatively indirect but can be applied to the actual observation. With regard to in which reference system turbulent electric field should be used to calculate the dissipation rate spectrum. They pointed out through demonstration that the electric field under the average flow reference frame rather than the local flow reference frame should be used, otherwise the dissipation rate spectrum will be obviously underestimated. The dissipation of ion cyclotron wave is supposed to be one of the main mechanisms of turbulence dissipation of solar wind, but there is no direct evidence. Through the proposed method, people can directly determine whether the turbulence including the ion cyclotron wave is dissipating rather than growing, and gives the dissipation rate spectrum of the turbulence. The results show that the dissipation rate spectrum of turbulence has the following characteristics: (i) at the MHD scales in the cascade inertial range, the dissipation rate spectrum is maintained near 0; (ii) at the ion and sub-ion scales in the kinetic range, the dissipation rate spectrum begins to rise to positive and has obvious protrusion; (iii) after the frequency integration, the dissipation rate spectrum is 0.5×10^6 J·kg^{-1}·s^{-1}.

A model has been established by He *et al.*[21] to describe the intermittent characteristics of the inertial and dissipative ranges of solar wind turbulence quantitatively. The reason and explanation are found for the multifractals of the inertial range and the mono-fractals of the dissipative range. They extended the function of the application of casting probability distribution function. Based on two parameters of Casting probability distribution (μ and λ^2: the most probable values and variances of logarithmic form of turbulent local standard deviation, respectively), the mathematical formulas describing multi-order structure functions, flatness and scaling law index were derived for the first time. They found that using the mathematical formula of casting function and multi-order structure function to perform joint fitting, compared with simply using the probability distribution as the object to fit, can better determine the change of μ and λ^2 with the scale (τ). It was found that only λ^2 controls the scale change trend of Flatness: λ^2 is saturated or even slightly decreased with the decrease of the scale, which leads to the flatness approaching saturation or even not rising or falling in the sub ion scale. More importantly, they revealed the formation reasons of multifractal in inertia range and mono-fractal in dissipation range: $\mathrm{d}\mu/\mathrm{d}(\ln\tau)$ and $\mathrm{d}\lambda^2/\mathrm{d}(\ln\tau)$ are the coefficients of linear term and second-order term of scaling law index with scale change, the existence of multifractal is due to $|\mathrm{d}\mu/\mathrm{d}(\ln\tau)|\sim|\mathrm{d}\lambda^2/\mathrm{d}(\ln\tau)|$, while the appearance of a single fractal is due to $|\mathrm{d}\mu/\mathrm{d}(\ln\tau)|\rangle|\mathrm{d}\lambda^2/\mathrm{d}(\ln\tau)|$. In addition, they also found that the kinks of μ and λ^2 appear at different scales: the kink of μ and the kink of power spectrum appear at a smaller scale, while the kink of λ^2 and the kink of flatness appear at a larger scale.

For the turbulence at the kinetic scales (from the ion scale to the sub-electron scale), a wide-band wave mode decomposition method has been proposed by Zhu *et al.*[22]. It was found that the wave modes from the ion scale to the sub-electron scale are multiple: the kinetic Alfvén wave, the quasi-parallel propagating whistler wave, and the ion acoustic wave. They used the data of MMS satellite with high precision and high time resolution to study the wave mode properties of these turbulences from the ion scale (about 1 Hz) to the sub electron scale (about 1000 Hz), and showed the new observation results. Based on the theory of two fluids, the energy ratio of different types of wave modes and their changes with scales are analyzed quantitatively for the first time. They found that the Kinetic Alfvén Wave (KAW) is dominant at 1~30 Hz. Whistler Wave (WW) causes the magnetic field power spectrum to rise above 30 Hz, while Ion Acoustic Wave (IAW) causes the electric field power spectrum to rise above 30 Hz. Furthermore, the quantitative analysis of the three-wave mode energy ratios shows that: (i) the vertical magnetic field disturbance is mainly contributed by KAW at <30 Hz and WW at >30 Hz; (ii) the parallel magnetic field disturbance and the vertical electric field disturbance are mainly contributed by KAW in the whole frequency range; (iii) the parallel electric field disturbance is mainly contributed by IAW in the whole frequency range.

3 Filament/Prominence, Jets, Flares and Radio Bursts

Awasthi *et al.*[23] studied the source region of a complex ejecta, focusing on a flare precursor with definitive signatures of magnetic reconnection, *i.e.*, non-thermal electrons, flaring plasma, and bidirectional outflowing blobs. Aided by nonlinear force-free field modeling, they concluded that the reconnection occurs within a system of multiple braided flux ropes with different degrees of coherency. This study signifies the importance of internal structure and dynamics in understanding CMEs and in predicting their impacts on Earth. Su *et al.*[24] studied flares occurring in an Arch Filament System (AFS) consisting of multiple bundles of dark filament threads enclosed by semicircular flare ribbons. They constructed coronal magnetic field models using two independent methods, *i.e.*, the nonlinear force-free field extrapolation and the flux rope insertion method, and concluded that these circular shaped flares were caused by 3D magnetic reconnection at the Quasi-Separatrix Layers (QSLs) associated with the AFS possessing mixed signs of helicity.

It is often envisaged that dense filament material lies in the dips of magnetic field lines belonging to either a sheared arcade or a magnetic flux rope. But it is also debated which configuration correctly depicts filaments' magnetic structure, due to the incapacity to measure the coronal magnetic field. Awasthi *et al.*[25] addressed this issue by employing mass motions in an active-region filament to diagnose its magnetic structure, using $H\alpha$ line-center and line wing (±0.4 Å) images obtained by the 1 m New Vacuum Solar Telescope (NVST). Filament material predominately exhibits two kinds of motions, namely, rotation about the spine and longitudinal oscillation along the spine, which indicates a double-decker host structure with mixed signs of helicity, comprising a flux rope atop a sheared-arcade system. Prominence bubbles are cavities rising into quiescent prominences from below. Not only the origin of prominence bubbles is poorly understood, but most of their physical characteristics are still largely unknown. Awasthi and Liu[26] investigated the dynamical properties of a prominence bubble, which was observed since its early emergence beneath the spine of a quiescent prominence in the $H\alpha$ line-center and line-wing (±0.4 Å) by NVST. Combining Doppler maps with flow maps in the plane of sky derived from a Nonlinear Affine Velocity Estimator, they obtained a comprehensive picture of mass motions revealing a counter-clockwise rotation inside the bubble; with blue shifted material flowing upward and red-shifted material flowing downward. This sequence of mass motions was interpreted to be either outlining a kinked flux rope configuration of the prominence bubble or providing observational evidence of the internal kink instability in the prominence plasma.

Wang *et al.*[27] analyzed high-resolution observations from the 1.6 m telescope at Big Bear Solar Observatory that cover an active region filament. Counter-streaming motions in the filament extend to a light bridge, forming a spectacular circulation pattern around a sunspot. They analyzed the power of oscillations with the image sequences of constructed Dopplergrams, and found that the counter-streaming motion in the filament was due to physical mass motion along fibrils, while in the light bridge due to oscillation along the line-of-sight. The disintegration of solar filaments via mass drainage is a frequently observed phenomenon during a variety of filament activities. It is generally considered that the draining of dense filament material is directed by both gravity and magnetic field, yet the detailed process remains elusive. Liu *et al.*[28] reported on a partial filament eruption during which filament material drained downward to the surface not only along the filament's legs, but to a remote flare ribbon through a fan-out curtain-like structure. It is the interaction of the filament with the overlying QSLs that led to the splitting and disintegration of the filament.

Plasma motions within flaring regions provide key information to understanding flare processes. Cheng *et al.*[29] constructed EVE plasma dynamic spectrum charts, a 2D map of Doppler shift against temperature and time and identified three kinds of plasma motions: chromospheric evaporation (100~200 $km\cdot s^{-1}$) above 1 MK, cooling inside post-flare loops (approximately 150 $km\cdot s^{-1}$) between 0.3 and 1 MK, and condensation at footpoints (<30 $km\cdot s^{-1}$) below 0.3 MK. The chromospheric evaporation and condensation at footpoints started in the impulsive phase almost simultaneously, while the cooling occurred later in the gradual phase, with a time delay of more than 10 min. The reversal temperature between blue/redshifts is close to 1 MK, implying that the boundary of upflowing/downflowing plasma is located at the lower corona or the upper transition region.

The second peak in extreme ultraviolet sometimes appears during the gradual phase of solar flares, which is known as EUV Late Phase (ELP). Stereotypically ELP is associated with two separated sets of flaring loops with distinct sizes, and it has been debated whether ELP is caused by additional heating or extended plasma cooling in the longer loop system. Chen *et al.*[30] carried out a survey of 55 M-and-above GOES-class flares with ELP during 2010–2014, which are categorized as circular-ribbon (19 events), two-ribbon (23 events), and complex-ribbon (13 events) flares, and found that additional heating is more likely present during ELP in two-ribbon than in circular-ribbon flares, but that cooling may be the dominant factor causing the delay of the ELP peak relative to the main-phase peak, because the loop system responsible for the ELP emission is generally larger than, and well separated from, that responsible for the main-phase emission. They suggested a composite “dome-plate” QSL as a general and robust structure characterizing circular-ribbon flares rather than a magnetic null point.

Small-scale solar wind transients looking like “blobs” or “ripples” are very common in the solar wind. They mostly appear to emerge from coronal streamers as clear density enhancements but eventually diffuse to become part of the slow solar wind. Li *et al.*[31] developed a new method to identify and locate the transients automatically from simultaneous images from the two inner telescopes, known as HI-1, based on a correlation analysis. Correlation Coefficient (CC) maps along the Sun-Earth line were constructed for the period from 1 January 2010 to 28 February 2011. From the maps, transients propagating along the Sun-Earth line were identified, and a 27-day periodic pattern was revealed, especially for small-scale transients. Besides, it was suggested by the cc map that small-scale transients along the Sun-Earth line are more frequent than large-scale transients by a factor of at least 2, and that they quickly diffused into background solar wind within about 40 R_S in terms of the signal-to-noise ratio of white-light emissions. The method provides a new tool to reconstruct inhomogeneous structures in the heliosphere from multiple perspectives.

Quiescent solar prominences are generally considered to have a stable large-scale structure. However, they consist of multiple small-scale structures that are often significantly dynamic. To understand the nature of prominence plasma dynamics, Ruan *et al.*[32] used the high spatial, temporal, and spectral resolution observations obtained by Interface Region Imaging Spectrograph (IRIS) during a coordinated campaign with the Multichannel Subtractive Double Pass spectrograph at the Meudon Solar Tower. Detailed analysis of the IRIS observations of Mg II lines, including the analysis of Doppler shift and line width obtained with two different methods (quantile method and Gaussian-fit method) were discussed in the frame of the dynamic nature of the structures. Large-scale coherent blue shift and redshift features were observed in Mg II lines and $H\alpha$ exhibiting a slow evolution during 100 min of observations. They explained the presence of several significantly asymmetric peaks in the observed Mg II line profiles by the presence of several prominence fine structures moving with different velocities located along the Line of Sight (LOS). In such a case, the decrease of the intensity of individual components of the observed spectra with the distance from the central wavelength can be explained by the Doppler dimming effect. They showed that C II line profiles may be used to confirm the existence of multi-components along the LOS.

Ruan *et al.*[33] also derived the physical conditions of the prominence observed on 30 March 2017. They used a unique set of data in Mg II lines obtained with the space-borne IRIS and in $H\alpha$ line with the ground-based Multi-Channel Subtractive Double Pass spectrograph operating at the Meudon solar tower. They analyzed the prominence spectra of Mg II h and k lines, and the $H\alpha$ line in the part of the prominence which is visible in both sets of lines. They computed a grid of 1D NLTE (*i.e.*, departures from the local thermo-dynamical equilibrium) models providing synthetic spectra of Mg II k and h, and $H\alpha$ lines in a large space of model input parameters (temperature, density, pressure, and micro-turbulent velocity). They compared Mg II and $H\alpha$ line profiles observed in 75 positions of the prominence with the synthetic profiles from the grid of models. With these models, they could compute the relationships between the integrated intensities and between the optical thickness in $H\alpha$ and Mg II k lines. The optical thickness $t_{H\alpha}$ is between 0.05 and 2, and $t_{\mathrm{MgII}k}$ is between 3 and 200. They showed that the relationship of the observed integrated intensities agrees well with the synthetic integrated intensities for models with a higher micro-turbulence (16 $\mathrm{km\cdot s^{-1}}$) and T around 8000 K, n_e=1.5×10^{10} $\mathrm{cm^{-3}}$, p=0.05 dyne. In this case, large micro-turbulence values could be a way to take into account the large mixed velocities existing in the observed prominence.

The magnetic orientation of CMEs near the Earth's magnetosphere is one major parameter that influences the geoeffectiveness of CMEs. The orientation often varies during the eruption and propagation from the Sun to the Earth due to the deflection and/or rotation of CMEs. It is common to observe the Counterclockwise (CCW) or Clockwise (CW) rotation (viewed from above) of solar prominences in the corona, which can be used to predict the space weather effect of associated CMEs. Song *et al.*[34] reported an intriguing failed prominence eruption that occurred on 10 December 2010, exhibiting the CCW and CW rotations sequentially in the corona. The eruption was recorded by both SDO/AIA and the Extreme Ultraviolet Imager on board STEREO. This stereoscopic combination makes it possible to reconstruct the three-dimensional structure and identify the rotation reversal without ambiguity. The prominence first rotates CCW about its ascending direction by 135° in 26 min and then reverses to the CW rotation by 45° in 15 min; *i.e.*, the average CCW and CW rotation speeds are 5.2 and 3.0(°)·$\mathrm{min^{-1}}$, respectively. The possible mechanisms leading to the rotation and reversal were discussed. The kinematics of the prominence was also analyzed, which indicates that an upward force acts on the prominence during the entire process.

Filament eruptions, one of the most energetic explosions on the Sun, release large quantities of magnetized plasma into the interplanetary space. Hence, the understanding of the initiation and evolution of filament eruptions can provide broader implications for space weather and geospace climate. Zheng *et al.*[35] presented a confined partial eruption of a double-decker structure that consisted of two vertically separated filaments on 16 April 2016. Only the upper filament erupted, and the eruption was closely associated with an episode of flux cancellation, surrounding transient brightenings, and unambiguous tether-cutting reconnections of the overlying sheared loops. However, the lower filament was nearly intact through the eruption. Interestingly, the erupting material moved along large-scale external loops and eventually arrived at remote sites, indicating a confined partial eruption. All the results show that the partial eruption involved two magnetic reconnections at least, and the bottom magnetic cancellation and internal tether-cutting reconnections between filaments both play critical roles in triggering the eruption. They conjectured that the newly formed low-lying loops due to tether-cutting reconnections and the flare loops resulting from the partial eruption likely contributed to maintaining the equilibrium of the lower filament. It was also suggested that the restriction of some large-scale external magnetic structures was crucial to turn the successful partial eruption into a confined event.

Coronal jets are always produced by magnetic reconnection between emerging flux and pre-existing overlying magnetic fields. When the overlying field is vertical/oblique or horizontal, the coronal jet will appear as anemone type or two-sided-loop type. Most observational jets are of the anemone type, and only a few two-sided-loop jets have been reported. Using the high-quality data from New Vacuum Solar Telescope, Interface Region Imaging Spectrograph, and Solar Dynamics Observatory, Zheng *et al.*[36] presented an example of two-sided-loop jets simultaneously observed in the chromosphere, transition region, and corona. The continuous emergence of magnetic flux brought in successively, the emergence of coronal loops and the slow rise of overlying horizontal filament threads. The following occurred sequentially: the deformation of the loops, the plasmoid ejection from the loop top, and pairs of loop brightenings and jets moving along the untwisting filament threads. All of the observational results indicate that magnetic reconnection exists between the emerging loops and the overlying horizontal filament threads, and it was the first example of two-sided-loop jets associated with ejected plasmoids and twisted overlying fields.

Ruan *et al.*[37] reported on bidirectional coronal reconnection outflows reaching $\pm 200\ \mathrm{km\cdot s^{-1}}$ as observed in an active region with the Si IV and C II spectra of IRIS. The evolution of the active region with an emerging flux, a failed filament eruption, and a jet is followed in SDO/AIA filters from 304 to 94 Å, IRIS slit jaw images, and SDO/HMI movies. The bidirectional outflow reconnection is located at a bright point visible in multi-wavelength AIA filters above an arch filament system. This suggests that the reconnection occurs between rising loops above the emergence of magnetic bipoles and the longer, twisted magnetic field lines remnant of the failed filament eruption one hour before. The reconnection occurs continuously in the corona between quasi-parallel magnetic field lines, which is possible in a 3D configuration. The reconnection also triggers a jet with transverse velocities around $60\ \mathrm{km\cdot s^{-1}}$. Blueshifts and redshifts along its axis confirm the existence of a twist along the jet, which could have been transferred from the filament flux rope. The jet finally blows up the material of the filament before coming back during the second phase. In the $H\alpha$ Dopplergrams provided by the MSDP spectrograph, they saw more redshift than blueshift, indicating the return of the jet and filament plasma.

A complete understanding of the onset and subsequent evolution of confined flares has not been achieved. Earlier studies mainly analyzed disk events so as to reveal their magnetic topology and cause of confinement. Ning *et al.*[38] presented dynamic details of a confined flare observed on the northwestern limb of the solar disk on 24 July 2016, taking advantage of a tandem of instruments working at different wavelengths of X-rays, EUVs, and microwaves. The entire dynamic evolutionary process starting from its onset is consistent with a loop-loop interaction scenario. The X-ray profiles manifest an intriguing double-peak feature. From spectral fitting, it was found that the first peak is non-thermally dominated while the second peak is mostly multi-thermal with a hot (about 10 MK) and a super-hot (about 30 MK) component. This double-peak feature is unique in that the two peaks are clearly separated by 4 minutes, and the second peak reaches up to 25~50 keV; in addition, at energy bands above 3 keV the X-ray fluxes decline significantly between the two peaks. This, together with other available imaging and spectral data, manifest a two-stage energy release process. They carried out a comprehensive analysis to investigate the nature of this two-stage process, and conclude that the second stage with the hot and super-hot sources mainly involves direct heating through loop-loop reconnection at a relatively high altitude in the corona. The uniqueness of the event characteristics and complete data set make the study a nice addition to present literature on solar flares.

In solar flares, Hard X-Rays (HXRs) appear in the form of either footpoint sources or coronal sources. Each individual source provides its own critical information on the acceleration of non-thermal electrons and plasma heating. Earlier studies found that the HXR emission in some events manifests a broken-up power-law spectrum, with the break energy around a few hundred keV based on spatially-integrated spectral analysis, and it does not distinguish the contributions from individual sources. Ning *et al.*[39] reported the observation of the broken-up spectra of a coronal source studied using HXR data recorded by Reuven Ramaty High Energy Solar Spectroscopic Imager (RHESSI) during the GOES X8.2-class flare on 10 September 2017. The flare occurred behind the western limb and its footpoint sources were mostly occulted by the disk. They could clearly identify such broken-up spectra pertaining solely to the coronal source during the flare peak time and after. Since a significant pileup effect on the RHESSI spectra is expected for this intense solar flare, they have selected the pileup correction factor, p=2. In this case, they found the resulting RHESSI temperature (about 30 MK) to be similar to the GOES soft X-ray temperature and break energies of 45~60 keV. Above the break energy, the spectrum hardens with time from the spectral index of 3.4 to 2.7, and the difference in spectral indices below and above the break energy increases from 1.5 to 5 with time. However, they note that when p=2 is assumed, a single power-law fitting is also possible with the RHESSI temperature higher than the GOES temperature by about 10 MK. Possible scenarios for the broken-up spectra of the loop-top HXR source are briefly discussed.

Non-thermal loop-top sources in solar flares are the most prominent observational signature that suggests energy release and particle acceleration in the solar corona. Although several scenarios for particle acceleration have been proposed, the origin of the loop-top sources remains unclear. Kong *et al.*[40] presented a model that combines a large-scale MHD simulation of a two-ribbon flare with a particle acceleration and transport model for investigating electron acceleration by a fast-mode termination shock at the loop top. Their model provides spatially resolved electron distribution that evolves in response to the dynamic flare geometry. They found a concave-downward magnetic structure located below the flare termination shock, induced by the fast reconnection downflows. It acts as a magnetic trap to confine the electrons at the loop top for an extended period of time. The electrons are energized significantly as they cross the shock front, and eventually build up a power-law energy spectrum extending to hundreds of keV. They suggested that this particle acceleration and transport scenario driven by a flare termination shock is a viable interpretation for the observed non-thermal loop-top sources.

Solar radio spikes are narrowband, short duration radio bursts. Feng *et al.*[41] presented the latest observations from the newly built solar radio spectrograph at the Chashan Solar Observatory. On 18 July 2016, the spectrograph records a solar spike burst event, which has several episodes showing harmonic structures, with the second, third, and fourth harmonics. The lower harmonic radio spike emissions are observed later than the higher harmonic bands, and the temporal delay of the second (third) harmonic relative to the fourth harmonic is about 30~40 (10) ms. Based on the electron cyclotron maser emission mechanism, they analyzed possible causes of the temporal delay and further infer relevant coronal parameters, such as the magnetic field strength and the electron density at the radio source.

Solar radio spikes are excited by the energetic electrons accelerated during small scale magnetic reconnections. Spikes play an important role in diagnosing magnetic reconnections and studying electron accelerations. Feng[42] reported the solar radio spikes observed by the Chashan Solar Observatory (CSO) spectrograph combined with observations from SDO, to study the properties of spikes with harmonics. The CSO data show that the central frequency ratio of the third to the second harmonic is 1.35±0.01 and the third harmonic has a larger absolute and relative bandwidth, but a shorter duration than the second one. By studying the correlation between light curves of the solar radio spike and those of bright points at different EUV passbands, the best associated EUV bright point and passbands were determined. The spike source properties were discussed based on the extrapolated magnetic field around the associated EUV bright point.

Source imaging of solar radio bursts can be used to track energetic electrons and associated magnetic structures. Vasanth *et al.*[43] presented a combined analysis of data at different wavelengths for an eruption associated with a moving Type IV (T-IVm) radio burst. In the inner corona, the sources are correlated with a hot and twisted eruptive EUV structure, while in the outer corona, the sources are associated with the top front of the bright core of a white-light CME. This reveals the potential of using T-IVm imaging data to continuously track the CME by lighting up the specific component containing radio-emitting electrons. It was found that the T-IVm burst presents a clear spatial dispersion with observing frequencies. The burst manifests broken power law-like spectra in brightness temperature, which is as high as 10^7~10^9 K, while the polarization level is generally weak. In addition, the T-IVm burst starts during the declining phase of the flare with a duration as long as 2.5 h. From the differential emission measure analysis of AIA data, the density of the T-IVm source is found to be at the level of 10^8 cm^{-3} at the start of the burst, and the temperature may reach up to several MK. These observations do not favor gyro-synchrotron to be the radiation mechanism but are in line with a coherent plasma emission excited by energetic electrons trapped within the source. Further studies are demanded to elucidate the emission mechanism and explore the full diagnostic potential of T-IVm bursts.

Liu *et al.*[44] reported a stationary Type IV (IVs) radio burst observed on 24 September 2011. Observations from the Nançay Radio Heliograph (NRH) show that the Brightness Temperature (TB) of this burst is extremely high, over 10^{11} K at 150 MHz and over 10^8 K in general. The degree of circular polarization (q) is between $-60\%\sim-100\%$, which means that it is highly left-handed circularly polarized. The flux-frequency spectrum follows a power-law distribution, and the spectral index is considered to be roughly $-3\sim-4$ throughout the IVs. Radio sources of this event are located in the wake of the CMEs and are spatially dispersed. They line up to present a formation in which lower-frequency sources are higher. Based on these observations, it was suggested that the IVs were generated through electron cyclotron maser emission.

For the first time, Koval *et al.*[45] presented simulation results of the focusing effect of the ionospheric plasma density irregularities, namely, Medium-Scale Traveling Ionospheric Disturbances (MSTIDs), on solar radio emission by applying a ray tracing method to the Earth's ionosphere with MSTIDs. With this technique, they investigated the focusing effect that manifests itself in the form of peculiar spectral disturbances in intensity with specific morphology, so-called Spectral Caustics (SCs), occasionally appearing in dynamic spectra of different solar radio instruments operating in the meter-decameter wavelength range. They showed that the simulated spectral shapes of SCs are in good agreement with the ones detected in real solar radio spectrograms. In particular, SCs that are classified as inverted V-like, V-like, X-like, and fiber-like types have been reproduced. It was also found that the seasonal dependence in the occurrence of SCs, which has been discovered recently, can be understood through a strong relationship between the focusing frequency, the most important characteristic point in most SC patterns, and the elevation angle of the Sun. They found that under typical parameters of MSTIDs with spatial and temporal periods set to be 300 km and 40 min, respectively, the focusing frequency decreases with the growth of the elevation angle. Physical interpretations of the results and implications on the analysis of solar radio data with SCs are discussed.

Koval *et al.*[46] also presented the first direct observations of SCs induced by MSTIDs, using solar dynamic spectra with SCs obtained by different European radio telescopes on 8 January 2014 and simultaneous two-dimensional detrended Total Electron Content (dTEC) maps over Europe. Spatial examination of dTEC maps as well as precise timing analysis of the maps and the dynamic spectra have been performed. Firstly, they found several pairs of one-to-one (TID-SC) correspondences. The study provides strong observational evidence supporting the suggestion that MSTIDs are the cause of SCs.

It has been suggested that the Z-mode instability driven by energetic electrons with a loss-cone type velocity distribution is one candidate process behind the continuum and zebra pattern of solar type-IV radio bursts. Both the temperature of background plasma (T_0) and the energy of energetic electrons (v_e) is considered to be important to the variation of the maximum growth rate (γ_{max}). Li *et al.*[47] presented a detailed parameter study on the effect of T_0 and v_e, within a regime of the frequency ratio ($10 \leqslant \omega_{pe}/\Omega_{ce} \leqslant 30$). In addition to γ_{max}, they also analyzed the effect on the corresponding wave frequency (ω^r_{max}) and propagation angle (θ_{max}). They found that: (i) γ_{max} generally decreases with increasing v_e, while its variation with T_0 is more complex depending on the exact value of v_e; (ii) with increasing T_0 and v_e, ω^r_{max} presents stepwise profiles with jumps separated by gradual or very weak variations, and due to the warm plasma effect on the wave dispersion relation ω^r_{max} can vary within the hybrid band (the harmonic band containing the upper hybrid frequency) and the higher band; (iii) the propagation is either perpendicular or quasi-perpendicular, and θ_{max} presents variations in line with those of ω^r_{max}, as constrained by the resonance condition. They also examined the profiles of γ_{max} with ω_{pe}/Ω_{ce} for different combinations of T_0 and v_e to clarify some earlier calculations which show inconsistent results.

The latest observational reports of solar flares reveal some uncommon features of microwave spectra, such as unusually hard (or even positive) spectra and/or a super-high peak frequency. For a better understanding of these features, Wu *et al.*[48] conducted a parameter study to investigate the effect of broken-power-law spectra of energetic electrons on microwave emission on the basis of the gyro-synchrotron mechanism. The electron broken-power-law energy distribution is characterized by three parameters–the break energy (E_B) and the power-law indices below (d_1) and above (d_2) the break energy. They found that with the addition of the d_2 component of the electron spectra, the total flux density can increase by several times in the optically thick regime, and by orders of magnitude in the optically thin regime; the peak frequency (v_p) also increases and can reach up to tens of gigahertz; and the degree of polarization (r_c) decreases in general. They also found that (i) the variation of the flux density is much larger in the optically thin regime, and the microwave spectra around the peak frequency manifest various profiles with a softening or soft-hard pattern; (ii) the parameters d_1 and E_B affect the microwave spectral index (α) and the degree of polarization (r_c) mainly in the optically thick regime, while d_2 mainly affects the optically thin regime. The results are helpful in understanding the recently reported microwave bursts with unusual spectral features and indicate the demands for a more complete spectral coverage of microwave bursts, especially in the high-frequency regime, say >10~20 GHz.

Quasi-periodic oscillations are usually detected as spatial displacements of coronal loops in imaging observations or aperiodic shifts of line properties (*i.e.*, Doppler velocity, line width, and intensity) in spectroscopic observations. They are often applied for remote diagnostics of magnetic fields and plasma properties on the Sun. Li *et al.*[49] combined the imaging and spectroscopic measurements of available space missions, and investigated the properties of non-damping oscillations at flaring loops. They used the Interface Region Imaging Spectrograph (IRIS) to measure the spectrum over a narrow slit. The double-component Gaussian fitting method was used to extract the line profile of Fe XXI1354.08Å at the O I spectral window. The quasi-periodicity of loop oscillations was identified in the Fourier and wavelet spectra. A periodicity at about 40 s is detected in the line properties of Fe XXI 1354.08 Å, hard X-ray emissions in GOES 1~8 Å derivative, and Fermi 26~50 keV. The Doppler velocity and line width oscillate in phase, while a phase shift of about $\pi/2$ is detected between the Doppler velocity and peak intensity. The amplitudes of Doppler velocity and line width oscillation are about 2.2 $km\cdot s^{-1}$ and 1.9 $km\cdot s^{-1}$, respectively, while peak intensity oscillates with amplitude at about 3.6% of the background emission. Meanwhile, a quasi-period of about 155 s is identified in the Doppler velocity and peak intensity of the Fe XXI 1354.08 Å line emission, and AIA 131 Å intensity. The oscillations at about 40 s are not damped significantly during the observation; this might be linked to the global kink modes of flaring loops. The periodicity at about 155 s is most likely a signature of recurring downflows after chromospheric evaporation along with flaring loops. The magnetic field strengths of the flaring loops are estimated to be about 120~170 Gs using the MHD seismology diagnostics, which are consistent with the magnetic field modeling results using the flux rope insertion method.

Quasi-Periodic Pulsations (QPPs) are usually found in the light curves of solar and stellar flares; they carry the features of time characteristics and plasma emission of the flaring core, and could be used to diagnose the coronas of the Sun and remote stars. Yuan *et al.*[50] combined SDO/AIA and the Nobeyama Radio-heliograph (NoRH) to observe an M7.7 class flare that occurred at active region 11520 on 19 July 2012. A QPP was detected both in the AIA 131 Å bandpass and the NoRH 17 GHz channel; it had a period of about four minutes. In the spatial distribution of Fourier power, they found that this QPP originated from a compact source and that it overlapped with the X-ray source above the loop top. The plasma emission intensities in the AIA 131 Å bandpass were highly correlated within this region. The source region is further segmented into stripes that oscillated with distinctive phases. Evidence in this event suggests that this QPP was likely to be generated by intermittent energy injection into the reconnection region.

CMEs play a decisive role in driving space weather, especially the fast ones (*e.g.*, with speeds above 800 $km\cdot s^{-1}$). Understanding the trigger mechanisms of fast CMEs can help us gain important information in forecasting them. The filament eruptions accompanied with CMEs provide a good tracer in studying the early evolution of CMEs. Zou *et al.*[51] surveyed 66 filament-accompanied fast CMEs to analyze the correlation between the trigger mechanisms, namely either magnetic reconnection or ideal MHD process, associated flares, and CME speeds. Based on the data gathered from SDO, GONG, and STEREO, they found that: (i) Active Region (AR) filament and intermediate filament (IF) eruptions show a higher probability for producing fast CMEs than quiet Sun (QS) filaments, while the probability of Polar Crown (PC) filament eruptions is zero in their statistic; (ii) AR filament eruptions that produce fast CMEs are more likely to be triggered by magnetic reconnection, while QS filaments and IFs are more likely to be triggered by an ideal MHD process; (iii) for AR filaments and IFs, it seems that the specific trigger mechanism does not have a significant influence on the resulting CME speeds, while for the QS filaments, the ideal MHD mechanism can more likely generate a faster CME; (iv) comparing with previous statistical studies, the onset heights of filament eruptions and the decay indexes of the overlying field show some differences: for AR filaments and IFs, the decay indexes are larger and much closer to the theoretical threshold, while for QS filaments, the onset heights are higher than those obtained in previous results.

Two X-class solar flares occurred on 6 September 2017 from active region NOAA 12673: the first one is a confined X2.2 flare, and it is followed only 3 h later by the second one, which is the strongest flare in solar cycle 24, reaching X9.3 class and accompanied by a CME. Why did these two X-class flares occur in the same position with similar magnetic configurations, but one is eruptive while the other is not. Zou *et al.*[52] tracked the coronal magnetic field evolution via nonlinear force-free field extrapolations from a time sequence of vector magnetograms with a high cadence. A detailed analysis of the magnetic field shows that a Magnetic Flux Rope (MFR) forms and grows gradually before the first flare, and shortly afterward, the MFR's growth is significantly enhanced with a much faster rise in height, from far below the threshold of torus instability to above it, while the magnetic twist only increases mildly. Combining EUV observations and the magnetic field extrapolation, they found that overlying the MFR is a null-point magnetic topology, where recurrent brightening is seen after the first flare. They thus suggested a scenario to interpret the occurrence of the two flares. The first flare occurred since the MFR reached a high enough height to activate the null point, and its continuous expansion forces the null-point reconnection recurrently. Such reconnection weakens the overlying field, allowing the MFR to rise faster, which eventually crosses the threshold of torus instability and triggers the second, eruptive flare.

Using SDO/AIA, Samanta *et al.*[53] reported a wavelike or oscillating plasma flow propagating upward against the Sun's gravitational force. After carefully analyzing this event, they concluded that this phenomenon is likely a manifestation of vortex shedding in the supra-arcade region of a solar flare. The computed Strouhal number is also consistent with the prediction from previous simulations of vortex shedding in MHD environments. Song and Tian[54] performed the first statistical study of circular-ribbon flares. They used SDO/HMI observations from 2010 to 2017 and identified 90 circular-ribbon flares. Interestingly, they found that about 1/3 of these flares are white-light flares, which is much higher than previous thought. Compared to normal flares, these white-light flares tend to have a shorter duration, smaller size, stronger electric current, and more complicated magnetic field, suggesting that the timescale, spatial scale, and magnetic field complexity may play important roles in the generation of white-light emission.

4 Active Regions and Solar Eruptions

Ye *et al.*[55] presented a combined analysis of the applications of the weighted horizontal magnetic gradient (denoted as G_{M}) method and the magnetic helicity tool employed for three Active Regions (ARs), namely NOAA AR 11261, AR 11283 and AR 11429. They analyzed the time series of photospheric data from SDO taken between August 2011 and March 2012. During this period the three ARs produced a series of flares (eight M- and six X-class) and CMEs. AR 11261 had four M-class flares and one of them was accompanied by a fast CME. AR11283 had similar activities with two M- and two X-class flares, but only with a slow CME. Finally, AR 11429 was the most powerful of the three ARs as it hosted five compact and large solar flare and CME eruptions. For applying the G_{M} method they employed the Debrecen sunspot data catalogue, and, for estimating the magnetic helicity at a photospheric level they used the Space-weather HMI Active Region Patches (SHARP's) vector magnetograms from SDO/HMI (Helioseismic and Magnetic Imager). They followed the evolution of the components of the G_{M} and the magnetic helicity before the flare and CME occurrences. They found a unique and mutually shared behaviour, called the U-shaped pattern, of the weighted distance component of G_{M} and of the shearing component of the helicity flux before the flare and CME eruptions. This common pattern is associated with the decreasing-receding phases yet reported only known to be a necessary feature prior to solar flare eruption(s) but found now at the same time in the evolution of the shearing helicity flux. This result leads to the conclusions that (i) the shearing motion of photospheric magnetic field may be a key driver for a solar eruption in addition to the flux emerging process, and that (ii) the found decreasing-approaching pattern in the evolution of shearing helicity flux may be another precursor indicator for improving the forecasting of solar eruptions.

Wang *et al.*[56] reported the observations of a moderate but relatively intense geoeffective solar eruption on 4 November 2015 from the peripheral diffusive polarities of active region 12443. They used space-borne SDO and ACE observations. EUV images identified a helical pattern along a filament channel, and they regard this channel as flux-rope structure. Flow velocity derived from tracked magnetograms inferred converging motion along the polarity inversion line beneath the filament channel. An associated magnetic cancellation process was detected in the converging region. Further, the preeruptive EUV brightening was observed in the converging region, the most intense part of which appeared in the magnetic cancellation region. These observations implied that the converging and canceling flux probably contributed to the formation of the helical magnetic fields associated with the flux rope. A filament-height estimation method suggested that the middle part of the filament probably lies at a low altitude and was consistent with the initial place of the eruption. A thick current channel associated with the flux rope was also determined. For an expanding thick current channel, the critical height of the decay index for torus instability lied in the range of 37~47 Mm. Southward magnetic fields in the sheath and the ejecta induced a geomagnetic storm with a *Dst* global minimum of about −90 nT.

After that, Wang *et al.*[57] studied the magnetic field evolution in the AR 12673 that produced the largest solar flare in the past decade on 6 September 2017. Fast flux emergence was one of the most prominent features of this AR. They calculated the magnetic helicity from photospheric tangential flows that shear and braid field lines (shear helicity) and from normal flows that advected twisted magnetic flux into the corona (emergence helicity), respectively. Their results showed that the emergence helicity accumulated in the corona is $-1.6\times10^{43}\ Mx^2$ before the major eruption, while the shear helicity accumulated in the corona was $-6\times10^{43}\ Mx^2$, which contributed about 79% of the total helicity. The shear-helicity flux was dominant throughout the overall investigated emergence phase. Their results implied that the emerged fields initially contained relatively low helicity. Much more helicity was built up by shearing and converging flows acting on preexisting and emerging flux. Shearing motions were getting stronger with the flux emergence, and especially on both sides of the polarity inversion line of the core field region. The evolution of the vertical currents showed that most of the intense currents did not appear initially with the emergence of the flux, which implied that most of the emerging flux was probably not strongly current carrying. The helical magnetic fields (flux rope) in the core field region were probably formed by long-term photospheric motions. The shearing and converging motions were continuously generated, driven by the flux emergence. AR 12673 was representative, as photospheric motions contributed most of the non-potentiality in the AR with vigorous flux emergence.

Hu *et al.*[58] investigated a global Extreme-Ultraviolet (EUV) wave associated with a CME-driven shock on 10 September 2017. The EUV wave was transmitted by north- and south-polar Coronal Holes (CHs), which was observed by SDO and STEREO-A from opposite sides of the Sun. They obtained key findings on how the EUV wave interacted with multiple coronal structures, and its connection with the CME-driven shock: (i) the transmitted EUV wave was still connected with the shock that was incurvated to the Sun, after the shock had reached the opposite side of the eruption; (ii) the south CH transmitted EUV wave was accelerated inside an on-disk, low-density region with closed magnetic fields, which implies that an EUV wave can be accelerated in both open and closed magnetic field regions; (iii) part of the primary EUV wavefront turned around a Bright Point (BP) with a bipolar magnetic structure when it approached a dim, low-density filament channel near the BP; (iv) the primary EUV wave was diffused and apparently halted near the boundaries of remote active regions (ARs) that were far from the eruption, and no obvious AR related secondary waves were detected; (v) the EUV wave extended to an unprecedented scale of 360° in latitudes, which was attributed to the polar CH transmission. These results provide insights into the effects of coronal density and magnetic field distributions on the evolution of a EUV wave, and into the connection between the EUV wave and the associated CME-driven shock.

Solar eruptions occurring at different places within a relatively short time interval are considered to be sympathetic. However, it is difficult to determine whether there exist a cause and effect between them. Wang *et al.*[59] found slipping-like magnetic reconnection of the large-scale field in the quiet-Sun corona could continually transform magnetic fluxes overlying one filament to the other, which strengthened the strapping field of the filament that underwent a failed eruption but weakened the strapping field of the filament that erupted successfully. The effects of the slipping-like magnetic reconnection were manifested as serpentine flare ribbons extending along the chromospheric network, coronal dimmings, apparently growing hot loops, contracting cold loops, *etc*.

Large-scale propagating fronts are frequently observed during solar eruptions, yet whether or not they are waves is still an open question. Studying EUV fronts associated with three homologous CMEs from pseudo-multi-viewing angles, Liu *et al.*[60] found that each primary front directly associated with the CME consistently transmits through various coronal structures while producing slow and stationary fronts. The primary front also propagates along an arcade of coronal loops and slows down due to foreshortening at the far side, yielding local plasma heating. Based on these characteristics, the strength of the coronal magnetic field is estimated to be 2 Gs in the polar coronal hole and 4 Gs in the coronal arcade neighboring the AR. These observations substantiate the wave nature of the primary front and shed new light on slow fronts.

Solar eruptions, mainly eruptive flares with CMEs, represent the most powerful drivers of space weather. Due to the low plasma-β nature of the solar corona, solar eruption has its roots in the evolution of the coronal magnetic field. Although various theoretical models of the eruptive magnetic evolution have been proposed, they still oversimplify the realistic process in observation, which shows a much more complex process due to the invisible complex magnetic environment. Jiang *et al.*[61] studied a complex sigmoid eruption in solar active region11283, which is characterized by a multipolar configuration embedding a null-point topology and a sigmoidal magnetic flux rope. Based on extreme ultraviolet observations, it has been suggested that a three-stage magnetic reconnection scenario might explain the complex flare process. They reproduced the complex magnetic evolution during the eruption using a data-constrained high-resolution MHD simulation. The simulation clearly demonstrates three reconnection episodes, which occurred in sequence in different locations in the corona. Through these reconnections, the initial sigmoidal flux rope breaks one of its legs, and quickly gives birth to a new tornado-like magnetic structure that is highly twisted and has multiple connections to the Sun due to the complex magnetic topology. The simulated magnetic field configuration and evolution are found to be consistent with observations of the corona loops, filaments, and flare ribbons. Their study demonstrates that significant insight into a realistic, complex eruption event can be gained by a numerical MHD simulation that is constrained or driven by observed data.

Three-dimensional magnetic topology is crucial to understanding the explosive release of magnetic energy in the corona during solar flares. Much attention has been given to the pre-flare magnetic topology to identify candidate sites of magnetic reconnection, yet it is unclear how the magnetic reconnection and its attendant topological changes shape the eruptive structure and how the topology evolves during the eruption. Jiang *et al.*[62] employed a realistic, data-constrained MHD simulation to study the evolving magnetic topology for an X9.3 eruptive flare that occurred on 6 September 2017. The simulation successfully reproduces the eruptive features and processes in unprecedented detail. The numerical results reveal that the pre-flare corona contains multiple twisted flux systems with different connections, and during the eruption, these twisted fluxes form a coherent flux rope through tether-cutting-like magnetic reconnection below the rope. Topological analysis shows that the rising flux rope is wrapped by a quasi-separatrix layer, which intersects itself below the rope, forming a topological structure known as a hyperbolic flux tube, where a current sheet develops, triggering the reconnection. By mapping footpoints of the newly reconnected field lines, they were able to reproduce both the spatial location and, for the first time, the temporal separation of the observed flare ribbons, as well as the dynamic boundary of the flux rope's feet. Furthermore, the temporal profile of the total reconnection flux is comparable to the soft X-ray light curve. Such a sophisticated characterization of the evolving magnetic topology provides important insight into the eventual understanding and forecasting of solar eruptions.

Solar eruptions are manifestations of explosive release of magnetic energy in the Sun's corona. Large solar eruptions originate mostly within active regions, where strong magnetic fields concentrate on the solar surface. Jiang *et al.*[63] studied the magnetic field structure for an exception, which is a peculiar GOES X1.2 flare accompanied with a very fast coronal mass ejection taking place between two active regions, where the magnetic field is relatively weak. The pre-flare magnetic field is reconstructed from the SDO/HMI vector magnetogram, using a non-linear force-free field extrapolation method. It was found that prior to the flare, there is a highly twisted magnetic flux rope with magnetic field lines winding over 6 turns, which connects the border of a leading sunspot of one active region and the following polarity of the neighboring active region. The basic configuration of the flux rope is consistent with the observed sigmoidal coronal loops and filament channels by SDO/AIA. It resides rather low-lying between the active regions such that the torus instability is not able to be triggered. Thus, it is likely that, due to the strong magnetic twist, the kink instability of the flux rope triggers the eruption.

Magnetic Flux Ropes (MFRs) are thought to be the central structures of solar eruptions, and their ideal MHD instabilities can trigger the eruption. Duan *et al.*[64] performed a study of all the MFR configurations that led to major solar flares, either eruptive or confined, from 2011 to 2017 near the solar disk center. The coronal magnetic field was reconstructed from observed magnetograms, and based on magnetic twist distribution, they identified the MFR, which is defined as a coherent group of magnetic field lines winding an axis with more than one turn. It was found that 90% of the events possess pre-flare MFRs, and their 3D structures are much more complex in detail than theoretical MFR models. They further constructed a diagram based on two parameters, the magnetic twist number which controls the Kink Instability (KI), and the decay index which controls the Torus Instability (TI). It clearly shows lower limits for TI and KI thresholds, which are $n_{\rm crit}$=1.3 and $|T_w|_{\rm crit}$=2, respectively, as all the events above $n_{\rm crit}$ and nearly 90% of the events above $|T_w|_{\rm crit}$ erupted. Furthermore, by such criterion, over 70% of the events can be discriminated between eruptive and confined flares, and KI seems to play a nearly equally important role as TI in discriminating between the two types of flares. More than half of the events with both parameters are below the lower limits, and 29% are eruptive. These events might be triggered by magnetic reconnection rather than MHD instabilities.

Solar eruptions are the most powerful drivers of space weather. To understand their cause and nature, it is crucial to know how the coronal magnetic field evolves before the eruption. He *et al.*[65] studied the formation process of a relatively large-scale Magnetic Flux Rope (MFR) in active region NOAA 12371 that erupted with a major flare and CME on 21 June 2015. A data-driven numerical MHD model was employed to simulate 3D coronal magnetic field evolution of 1 day duration before the eruption. Comparison between the observed features and their modeled magnetic field discloses how the pre-eruption MFR forms. Initially, the magnetic field lines were weakly twisted as being simply sheared arcades. Then a long MFR was formed along the polarity inversion line due to the complex photospheric motion, which is mainly shearing rather than twisting. The presence of the MFR is evidenced by a coherent set of magnetic field lines with twist number above unity. Below the MFR a current sheet is shown in the model, suggesting that tether-cutting reconnection plays a key role in the MFR formation. The MFR's flux grows as more and more field lines are twisted due to continuous injection of magnetic helicity by the photospheric motions. Meanwhile, the height of the MFR's axis increases monotonely from its formation. By an analysis of the decay index of its overlying field, they suggested that this is because the MFR runs into the torus instability regime and becomes unstable, which finally triggers the eruption.

Miao *et al.*[66] reported a detailed observational study of two Quasi-periodic Fast-Propagating (QFP) magnetosonic wave events that occurred on 2011 March 9 and 10, respectively. Interestingly, both the events have two Wave Trains (WTs): a strong main one (WT-1) and a small and weak secondary one (WT-2). Peculiar and common characteristics of the two events are observed, namely, (i) the two QFP waves are accompanied with brightenings during the whole stage of the eruptions; (ii) both the two main WTs are nearly propagating along the same direction; (iii) extreme ultraviolet (EUV) waves were found to be associated with the two events. Investigating various aspects of the target events, they argued that: (i) the second event is accompanied with a flux rope eruption during the whole stage; (ii) the second event eruption produces a new filament-like dark feature; (iii) the ripples of the two WT-2 QFP waves seem to result from different triggering mechanisms. Based on the obtained observational results, they proposed that the funnel-like coronal loop system is indeed playing an important role in the two WT-1 QFP waves. The development of the second WT-2 QFP wave can be explained as due to the dispersion of the main EUV front. The coexistence of the two events offers thereby a significant opportunity to reveal what driving mechanisms and structures are tightly related to the waves.

Artifacts could mislead interpretations in astrophysical observations. A thorough understanding of an instrument will help in distinguishing physical processes from artifacts. Yuan *et al.*[67] investigated an artifact of AIA onboard SDO. Time-series data and wavelet spectra revealed periodic intensity perturbations in small regions over the entire image in certain AIA Extreme Ultraviolet (EUV) passbands at a period of about 45 seconds. These artificial intensity variations are prominently detected in regions with sharp intensity contrast, such as sunspot light bridges. This artifact was caused by a periodic pointing wobble of the two AIA telescopes ATA 2 (193 and 211 Å channels) and ATA 3 (171 Å and UV channels), to a lesser extent, while the other two telescopes were not found to be affected. The peak-to-peak amplitude of the wobble was about 0.2 pixels in ATA 2 and 0.1 pixels in ATA 3. This artifact was intermittent and affected the data of seven months from 18 January to 28 August 2012, as a result of a thermal adjustment to the telescopes. They recommended that standard pointing-correction techniques, such as local correlation tracking, should be applied before any detailed scientific analysis that requires sub-pixel pointing accuracy. Specifically, this artificial 45-second periodicity was falsely interpreted as abnormal sub-minute oscillations in a light bridge of a sunspot.

The Kelvin-Helmholtz (KH) instability is commonly found in many astrophysical, laboratory, and space plasmas. It could mix plasma components of different properties and convert dynamic fluid energy from large-scale structures to smaller ones. Yuan *et al.*[68] combined the ground-based New Vacuum Solar Telescope (NVST) and SDO/AIA to observe the plasma dynamics associated with active region 12673 on 9 September 2017. In this multi-temperature view, they identified three adjacent layers of plasma flowing at different speeds, and detected KH instabilities at their interfaces. They could unambiguously track a typical KH vortex and measure its motion. They found that the speed of this vortex suddenly tripled at a certain stage. This acceleration was synchronized with the enhancements in emission measure and the average intensity of the 193 Å data. They interpreted this as evidence that KH instability triggers plasma heating. The intriguing feature in this event is that the KH instability observed in the NVST channel was nearly complementary to that in the AIA 193 Å. Such a multi-thermal energy exchange process is easily overlooked in previous studies, as the cold plasma component is usually not visible in the extreme-ultraviolet channels that are only sensitive to high-temperature plasma emissions. Their finding indicates that embedded cold layers could interact with hot plasma as invisible matters. They speculated that this process could occur at a variety of length scales and could contribute to plasma heating.

Solar flares are often associated with coronal eruptions, but there are confined ones without eruptions, even for some X-class flares. How such large flares occurred and why they are confined are still not well understood. Zou *et al.*[69] studied a confined X2.2 flare in NOAA Active Region 12673 on 6 September 2017. It exhibits two episodes of flare brightening with rather complex, atypical ribbons. Based on topology analysis of the extrapolated coronal magnetic field, they revealed that there is a two-step magnetic reconnection process during the flare. Prior to the flare, there is a Magnetic Flux Rope (MFR) with one leg rooted in a rotating sunspot. Neighboring the leg is a magnetic null-point structure. The sunspot drives the MFR to expand, pushing magnetic flux to the null point, and reconnection is first triggered there. The disturbance from the null-point reconnection triggers the second reconnection, *i.e.*, a tether-cutting reconnection below the rope. However, these two reconnections failed to produce an eruption, because the rope is firmly held by its strapping flux. Furthermore, they compared this flare with an eruptive X9.3 flare in the same region 2 h later, which has a similar MFR configuration. The key difference between them is that, for the confined flare, the MFR is fully below the threshold of torus instability, whereas for the eruptive one, the MFR reaches entirely above the threshold. This study provides good evidence supporting that reconnection alone may not be able to trigger eruption; rather, MHD instability plays a more important role.

5 Coronal Mass Ejections and Their Interplanetary Counterparts

Recent years have seen growing evidence of the existence of Alfvén waves within interplanetary magnetic flux ropes, which are believed to be an important aspect of dynamics connecting the Sun and the heliosphere. Previous studies, due to localized observation by single spacecraft, focused on sunward or anti-sunward Alfvén waves propagating along with magnetic field lines. Wang *et al.*[70] used multi-spacecraft observations to verify and analyze two large-scale Magnetic Clouds (MCs), when the spacecraft had quite different spatial separations. What surprises them was that not only unidirectional but bidirectional Alfvén waves existed in the large-scale MC, which was rooted to the Sun. They speculated that unidirectional Alfvén waves within an MC were generated by distortions produced within a pre-existing flux rope, and bidirectional Alfvén waves were emitted from the center of reconnection and then traveled outward along with two loop legs of an MC.

He *et al.*[71] investigated how a weak CME launched on 8 October 2016 without obvious signatures in the low corona produced a relatively intense geomagnetic storm. Remote sensing observations from SDO, STEREO, and SOHO and in situ measurements from WIND are employed to track the

CME from the Sun to the Earth. Using a graduated cylindrical shell model, they estimated the propagation direction and the morphology of the CME near the Sun. CME kinematics were determined from the wide-angle imaging observations of STEREO A and are used to predict the CME arrival time and speed at the Earth. They compared ENLIL MHD simulation results with in situ measurements to illustrate the background solar wind where the CME was propagating. They also applied a Grad-Shafranov technique to reconstruct the flux-rope structure from in situ measurements in order to understand the geoeffectiveness associated with the CME magnetic field structure. Key results were obtained concerning how a weak CME could generate a relatively intense geomagnetic storm: (i) there were coronal holes at low latitudes, which could produce High Speed Streams (HSSs) to interact with the CME in interplanetary space; (ii) the CME was bracketed between a slow wind ahead and an HSS behind, which enhanced the southward magnetic field inside the CME and gave rise to the unexpected geomagnetic storm.

Liu *et al.*[72] investigated the kinetic properties of a typical fast-mode shock inside an Interplanetary Coronal Mass Ejection(ICME) observed on 6 August 1998 at 1 AU, including particle distributions and wave analysis with the in situ measurements from WIND. Key results were obtained concerning the shock and the shock-ICME interaction at kinetic scales: (i) gyrating ions, which may provide energy dissipation at the shock in addition to wave-particle interactions, are observed around the shock ramp; (ii) despite the enhanced proton temperature anisotropy of the shocked plasma, the low plasma β inside the ICME constrains the shocked plasma under the thresholds of the ion cyclotron and mirror-mode instabilities; (iii) whistler heat flux instabilities, which can pitch-angle scatter halo electrons through a cyclotron resonance, were observed around the shock, and can explain the disappearance of Bi-Directional Electrons (BDEs) inside the ICME together with normal betatron acceleration; (iv) whistler waves near the shock are likely associated with the whistler heat flux instabilities excited at the shock ramp, which is consistent with the result that the waves may originate from the shock ramp; (vi) the whistlers share a similar characteristic with the shocklet whistlers, providing possible evidence that the shock is decaying because of the strong magnetic field inside the ICME.

An unexpected strong geomagnetic storm occurred on 26 August 2018, which was caused by a slow CME from a gradual eruption of a large quiet-region filament. Chen *et al.*[73] investigated the eruption and propagation characteristics of this CME in relation to the strong geomagnetic storm with remote sensing and in situ observations. Coronal magnetic fields around the filament were extrapolated and compared with extreme ultraviolet observations. They determined the propagation direction and tilt angle of the CME flux rope near the Sun using a Graduated Cylindrical Shell (GCS) model and the Sun-to-Earth kinematics of the CME with wide-angle imaging observations from STEREO A. They reconstructed the flux-rope structure using a Grad-Shafranov technique based on the in situ measurements at the Earth and compared it with those from solar observations and the GCS results. Their conclusions are as follows: (i) the eruption of the filament was unusually slow and occurred in the regions with relatively low critical heights of the coronal field decay index; (ii) the axis of the CME flux rope rotated in the corona as well as in interplanetary space, which tended to be aligned with the local heliospheric current sheet; (iii) the CME was bracketed between slow and fast solar winds, which enhanced the magnetic field inside the CME at1 AU; (iv) the geomagnetic storm was caused by the enhanced magnetic field and a southward orientation of the flux rope at 1 AU from the rotation of the flux rope.

A powerful CME occurred on 10 September 2017 near the end of the declining phase of the historically weak solar cycle 24. Liu *et al.*[74] obtained new insights concerning the geometry and kinematics of CME driven shocks in relation to their heliospheric impacts from the optimal, multi-spacecraft observations of the eruption. The shock, which together with the CME driver can be tracked from the early stage to the outer corona, shows a large oblate structure produced by the vast expansion of the ejecta. The expansion speeds of the shock along the radial and lateral directions are much larger than the translational speed of the shock center, all of which increase during the flare rise phase, peak slightly after the flare maximum and then decrease. The near simultaneous arrival of the CME-driven shock at the Earth and Mars, which are separated by 156.6° in longitude, is consistent with the dominance of expansion over translation observed near the Sun. The shock decayed and failed to reach STEREO A around the backward direction. Comparison between ENLIL MHD simulations and the multi-point in situ measurements indicates that the shock expansion near the Sun is crucial for determining the arrival or non-arrival and space weather impact at certain heliospheric locations. The large shock geometry and kinematics have to be taken into account and properly treated for accurate predictions of the arrival time and space weather impact of CMEs.

In order to have a comprehensive view of the propagation and evolution of CMEs from the Sun to deep interplanetary space beyond 1 AU, Zhao *et al.*[75] carried out a kinematic analysis of seven CMEs in solar cycle 23. The events are required to have coordinated coronagraph observations, interplanetary type II radio bursts, and multi-point in situ measurements at the Earth and Ulysses. A graduated cylindrical shell model, an analytical model without free parameters, and an MHD model were used to derive CME kinematics near the Sun, to quantify the CME/shock propagation in the Sun-Earth space, and to connect in situ signatures at the Earth and Ulysses, respectively. They found that each of the seven CME-driven shocks experienced a major deceleration before reaching 1 AU and thereafter propagated with a gradual deceleration from the Earth to larger distances. The resulting CME/shock propagation profile for each case was roughly consistent with all the data, which verifies the usefulness of the simple analytical model for CME/shock propagation in the heliosphere. The statistical analysis of CME kinematics indicates a tendency that the faster the CME, the larger the deceleration, and the shorter the deceleration time period within 1 AU. For several of these events, the associated geomagnetic storms were mainly caused by the southward magnetic fields in the sheath region. In particular, the interaction between a CME-driven shock and a preceding ejecta significantly enhanced the pre-existing southward magnetic fields and gave rise to a severe complex geomagnetic storm.

It is paramount from both scientific and societal perspectives to understand the generation of extreme space weather. Liu *et al.*[76] discussed the formation of solar superstorms based on a comparative study of the 23 July 2012 and 23 July 2017 eruptions. The first one is Carrington-class, and the second could rival the 1989 March event that caused the most intense geomagnetic storm of the space age. Observations of these events in the historically weak solar cycle 24 indicate that a solar superstorm can occur in any solar cycle and at any phase of the cycle. Recurrent patterns are identified in both cases, including the long-lived eruptive nature of the active region, a complex event composed of successive eruptions from the same active region, and in-transit interaction between the successive eruptions resulting in exceptionally strong ejecta magnetic fields at 1 AU. Each case also shows unique characteristics. Preconditioning of the upstream solar wind leading to unusually high solar wind speeds at 1 AU is observed in the first case, but not in the latter. This may suggest that the concept of “preconditioning” appears to be necessary for making a Carrington-class storm. They found a considerable deflection by nearby coronal holes in the second case, but not in the first. On the basis of these results, they proposed a hypothesis for further investigation that superstorms are “perfect storms” in nature, *i.e.*, a combination of circumstances that results in an event of unusual magnitude. Historical records of some extreme events seem to support their hypothesis.

The Sun’s atmosphere is frequently disrupted by CMEs, coupled with flares and energetic particles. The coupling is usually attributed to magnetic reconnection at a vertical current sheet connecting the flare and CME, with the latter embedding a helical magnetic structure known as flux rope. However, both the origin of flux ropes and their nascent paths toward eruption remain elusive. Gou *et al.*[77] presented an observation of how a stellar-sized CME bubble evolving continuously from plasmoids, mini flux ropes that are barely resolved, within half an hour. The eruption initiated when plasmoids springing from a vertical current sheet merged into a leading plasmoid, which rose at increasing speeds and expanded impulsively into the CME bubble, producing hard X-ray bursts simultaneously. This observation illuminates a complete CME evolutionary path capable of accommodating a wide variety of plasma phenomena by bridging the gap between microscale and macroscale dynamics.

Liu *et al.*[79] studied the twists released by 30 off-limb rotational solar coronal jets, and compare the observational findings with theoretical kink instability thresholds. The results suggest that the kink instability threshold in the solar atmosphere should not be a constant. They found the lower limit of a twist number of 1.3 turns should be merely a necessary but not a sufficient condition for a finite solar Magnetic Flux Rope (MFR) to become kink unstable. Wang *et al.*[79] investigated the continuous evolution of a pre-existing MFR in the corona, whose gradual expansion is associated with the development of a pair of coronal dimming regions on the surface, suggesting that the dimmings map the MFR's feet. Quantitative measurements indicate that the magnetic twist of the MFR increases from 1.0±0.5 to 2.0±0.5 turns during the five-hour expansion, and further increases to about 4.0 turns per AU when it is detected as a magnetic cloud at 1 AU. Besides, Magnetic Clouds (MCs) were also used to study the twist distribution inside the magnetic flux rope. Wang *et al.*[80] reported a rare event, in which a MC was observed sequentially by four spacecraft near Mercury, Venus, Earth, and Mars, respectively. With the aids of a uniform-twist flux rope model and a newly developed method that can recover a shock-compressed structure, they found that the axial magnetic flux and helicity of the magnetic cloud decreased when it propagated outward but the twist increased. Their analysis suggests that the "pancaking" effect and "erosion" effect may jointly cause such variations. The MC was eroded significantly leaving its inner core exposed to the solar wind at a far distance. The increase of the twist together with the presence of the erosion effect suggests that the post-eruption magnetic flux rope may have a high-twist core enveloped by a less-twisted outer shell. Besides, by peeling off equal azimuthal magnetic flux from both the front and rear boundary of an MC, just like peeling an onion, the average twist and the twist in each layer of the cross section of the MC were analyzed by Zhao *et al.*[81]. And they also found that the absolute value of twists exhibits a roughly monotonous decrease from the axis to the edge. Furthermore, Zhao *et al.*[82] showed that there's a clear positive correlation between the twist and the plasma poloidal angular velocity in peeled flux ropes or flux rope layers of the MC.

Similar to the Sun, other stars shed mass and magnetic flux via ubiquitous quasi-steady wind and episodic stellar CMEs. Mishra *et al.*[83] investigated the mass loss rate via solar wind and CMEs as a function of solar magnetic variability represented in terms of sunspot number and solar X-ray background luminosity during solar cycles 23 and 24. The study confirms a true physical increase in CME activity relative to the sunspot number in cycle 24, and shows that the CME occurrence rate and associated mass loss rate can be better predicted by X-ray background luminosity than the sunspot number. In contrast, the solar wind mass loss rate which is an order of magnitude more than the CME mass loss rate shows no obvious dependency on cyclic variation.

From 4–6 September 2017, heliospheric activity suddenly and drastically increased starting from a simple sunspot which transformed into a complex region with four X-class flares accompanied by several Earth-directed CMEs and largely disturbed the Earth's geomagnetic field. The two CMEs launched on 4 September 2017, 20:24 UT and 6 September 2017, 12:24 UT interacted with each other in the interplanetary space and formed a Shock-ICME complex structure. When the Shock-ICME arrived at Earth, it caused a strong multi-step magnetic storm. By recovering the shocked part of the Shock-ICME to an uncompressed state, and substituting both the observational data and recovered state into various *Dst* prediction models, Shen *et al.*[84] found that the compression of the shock enhanced the intensity of this geomagnetic storm by roughly a factor of two. For the first time, this work quantitatively analyzed the effects of shock compression on enhancing the geoeffectiveness of an ICME. In addition, in this case, the interaction between the shock and the host ICME increased the intensity of solar energetic particles by a factor of five.

For a deeper comprehension of the space weather effects of S-ICMEs, Xu *et al.*[85] analyzed 18 geomagnetic storms caused by shock-ICMEs since 1995. The results showed that due to the compression of the shock, the peak values of the southward magnetic field and the dawn-dusk electric field in ICMEs were increased by 2.0 and 2.2 times, respectively, and the intensity of the geomagnetic storm was increased by 1.4 times. Besides, Xu *et al.*[86] studied 12 ICMEs with extraordinary energetic particle enhancements, 9 of which were shock-interplanetary coronal mass ejection complex structures (shock-ICMEs), and 3 were Isolated Interplanetary Coronal Mass Ejections (I-ICMEs). Energetic-particle intensities increase more in the shock-ICMEs than in the I-ICMEs in all energy channels, especially in the high-energy channels. In addition, shocks inside energetic-particle-enhanced shock-ICMEs are relatively fast and strong. These results indicate that shock-ICME interaction may be an effective local acceleration mechanism.

CMEs are frequently associated with filament eruptions. Theoretical studies propose that both magnetic reconnection and ideal MHD instability of magnetic flux ropes can convert coronal magnetic energy into the filament/CME kinetic energy. Numerical simulations and analytical considerations demonstrate that both mechanisms can have significant contributions to the filament/CME acceleration. Many observational studies support that reconnection plays an important role during the acceleration, while the question on how to resolve observationally the contribution of the ideal instability to the acceleration remains open. On the other hand, it is difficult to separate and compare their contributions through observations as both mechanisms often work in a close time sequence. The above issues are addressed by Song *et al.*[87], through analyzing the eruption process of a quiescent filament. The filament started to rise from 00:00 UT on 25 December 2011, 20 min earlier than the starting time of the flare impulsive phase (00:20 UT), and reached the maximum velocity at the flare peak time (00:50 UT). They divided the acceleration process into two stages, corresponding to the pre-flare and flare impulsive phases, respectively. The analysis indicates that an ideal flux-rope instability is dominant in the first stage, while reconnection below the flux rope becomes important during the second stage, and both mechanisms may have comparable contributions to the net acceleration of the filament.

CMEs often exhibit the classic three-part structure in a coronagraph, *i.e.*, the bright front, dark cavity, and bright core, which are traditionally considered as the manifestations of coronal plasma pileup, Magnetic Flux Rope (MFR), and filament, respectively. However, a recent survey based on 42 CMEs all possessing the three-part structure found that a large majority (69%) do not contain an eruptive filament at the Sun. Therefore, a challenging opinion is proposed and claims that the bright core can also correspond to the MFR, which is supported by the CME simulation. Then what is the nature of the CME core. Song *et al.*[88] studied a CME associated with the eruption of a filament-hosting MFR on 29 September 2013. This CME exhibits the three-part morphology in multiple white-light coronagraphs from different perspectives. The new finding is that the bright core contains both a sharp and a fuzzy component. Through tracking the filament motion continuously from its source region to the outer corona, they conclude that the sharp component corresponds to the filament. The fuzzy component was suggested to result from the MFR that supports the filament against the gravity in the corona. The study can shed more light on the nature of CME cores, and explain the core whether or not the filament is involved with a uniform scenario. The nature of the CME cavity was also discussed.

So far, most studies on the structure of CMEs are conducted through white-light coronagraphs, demonstrating that about one-third of CMEs exhibit the typical three-part structure in the high corona (*e.g.*, beyond 2 R_S). Song *et al.*[89] reported the observation of the CME structure in the low corona (*e.g.*, below 1.3 R_S) through EUV passbands and found that the three-part CMEs in the white-light images can possess a similar three-part appearance in the EUV images, *i.e.*, a leading edge, a low-density zone, and a filament or hot channel. The analyses identified that the leading edge and the filament or hot channel in the EUV passbands evolve into the front and the core later within several solar radii in the white-light passbands, respectively. What is more, they found that the CMEs without an obvious cavity in the white-light images can also exhibit the clear three-part appearance in the EUV images, which means that the low-density zone in the EUV images (observed as the cavity in white-light images) can be compressed and/or transformed gradually by the expansion of the bright core and/or the reconnection of the magnetic field surrounding the core during the CME propagation outward. Their study suggests that more CMEs can possess the clear three-part structure in their early eruption stage. The nature of the low-density zone between the leading edge and the filament or hot channel was discussed.

Zhou *et al.*[90] performed a statistical study on the intermittency and the associated local heating in the front Boundary Layers (BLs) of 74 Magnetic Clouds (MCs). The intermittent structures are identified by the Partial Variance of Increments (PVI) method. The probability distribution function of PVI-values reveals that the BLs are more intermittent than adjacent sheath regions, and they contain a greater concentration of strong intermittencies. These strong intermittencies are accompanied by local enhancement of the proton temperature, while the enhancement is not prominent at weaker intermittencies inside the BLs. Since the strong intermittencies are associated with Magnetic Reconnection (MR) processes according to previous studies, these results indicate that MR processes may account for the local heating in the MCBLs to a large extent.

Coherent structures such as current sheets have been usually regarded to be sites of proton heating in the solar wind. Zhou *et al.*[91] statistically investigated the proton heating effects around the coherent structures within the turbulent sheath regions of Magnetic Clouds (MCs) based on WIND observations. It was found that the proton temperature enhancement near coherent structures in the MC sheath is not as remarkable as in the solar wind. Significant temperature increase only exists near coherent structures with great directional changes ($>45°$) in magnetic field or intensity changes ($\geqslant 10\%$ of the mean magnetic field magnitude), which merely account for 13% of the total of 12426 identified intermittent events in the 71 studied MC sheaths. The temperature increment is more evident near strong current sheets with great directional changes ($>45°$) at smaller scales than those at larger scales. It suggests that the heating effects in the MC sheath regions are likely to be highly localized. The local proton heating effects in the turbulent sheath are probably caused by the magnetic reconnection processes that are frequently associated with the strong current sheets.

6 Other Interplanetary Structures

Small Flux Ropes (SFRs) have been studied for decades, but their source regions and formation mechanisms are still under debate. Huang *et al.*[92] focused on the formation mechanism of the twisted structures of SFRs. Current research on magnetic clouds suggests five-type distributions of the time structure of iron average charge states ($Q_{<\mathrm{Fe}>}$), which imply different formation mechanisms of twisted structures. They used a similar method to identify the $Q_{<\mathrm{Fe}>}$ types of 25 SFRs. However, only four of these five types of distributions were found among these SFRs. Because different origins of SFRs are characteristically affecting the formation of $Q_{<\mathrm{Fe}>}$ types, the possible source regions of these SFRs are distinguished. With additional compositional parameters, SFRs are reconfirmed to originate from two types of source regions: the solar corona and the interplanetary medium. Based on these results, their analysis indicates that the twisted structures of SFRs originating from the solar corona may be formed predominately during eruptions. SFRs originating from interplanetary space are related to complex magnetic reconnection processes, which may result in intricate $Q_{<\mathrm{Fe}>}$ distributions due to the reconstruction of magnetic field topology.

The global shape of the intersection of the Heliospheric Current Sheet (HCS) with the heliospheric equatorial plane is usually considered to be an Archimedean spiral, however, so far this has not been measured directly. Peng *et al.*[93] used multi-spacecraft measurements to determine its global shape. The time-shifted measured locations are fitted with Archimedean spirals. In most cases, the locations are fitted very well with Archimedean spirals, in addition to the direction of HCS determined by the Minimum Variation Analysis. However, there is one case in which the direction of the HCS does not fit well with the Archimedean spiral and therefore they fit it with a sinusoidal function in addition to an Archimedean spiral. The result showed that in some cases, the HCS is better described with an Archimedean spiral, superposed by small-scale ripples.

Liu *et al.*[94] reported on two small solar wind transients embedded in the corotating interaction region, characterized by surprisingly lower proton density compared with their surrounding regions. In addition to lower density, these two small solar wind transients showed other interesting features like higher proton temperature, higher alpha-proton ratios, and lower charge states (C^{+6}/C^{+5} and O^{+7}/O^{+6}). A synthesized picture for event one combining the observations by STEREO B, ACE, and WIND showed that this small solar transient has an independent magnetic field. Back-mapping links the origin of the small solar transient to a small coronal hole on the surface of the Sun. Considering these special features and the back-mapping, they concluded that such small solar wind transients may have originated from a small coronal hole at low latitudes.

Zhang *et al.*[95] presented a statistical study of the ion upflow associated with Sub-auroral Polarization Streams (SAPS) in the ionospheric sub-auroral region at different substorm times using three DMSP satellites (F16, F17, F18) data for five years (2010–2014) in the northern hemisphere. The results show similarities between SAPS and the ion upflow at a different intensity of substorms both in occurrence rate distribution and velocity distribution. In comparison to SAPS, the distribution of the ion upflow shows the smaller occurrence region and lower velocity. They also found that frictional heating plays an important role in ion upflow from the SAPS region. The intense substorms can trigger strong SAPS channels, enhanced frictional heating and large ion upflow. In addition, there is a moderate linear correlation between SAPS velocity and field-aligned velocity which is consistent with some previous findings. Their results also show that frictional heating can gradually dominate the ion upflow process in intense substorms, while it may not be the only factor to affect the whole upflow process.

7 Space Weather Prediction Methods

A solar magnetic flux transport model has the ability to demonstrate the magnetic evolution of the Sun, thus providing a foundation for space weather forecasting. Solar activities have close relationships with the Sun's magnetic fields. To predict the Sun's magnetic environment more precisely, many versions of magnetic flux rope models have been developed. Liu *et al.*[96] utilized two models that were created by Yeates *et al.* (hereinafter referred to as the Y model) and Worden and Harvey (hereinafter referred to as the WH model) to predict the short-term changes of 10.7 cm radio flux ($F_{10.7}$) during 2003–2014. Both models performed very well in estimating $F_{10.7}$ values. The statistical results of analyzing the correlation coefficient, mean absolute error, mean square error, relative error, frequency distribution, and so on, show that the Y model is superior to the WH model. The meridional flow and diffusion process used in the WH model do not agree with the observations. Such discrepancies may influence estimates of the global flux.

Qin and Wu[97] studied solar cycles with the Version 2 monthly smoothed international Sunspot Number (SSN), and found that the variations of SSN were well represented by a modified logistic differential equation with four parameters: maximum cumulative sunspot number or total sunspot number $x_{\rm m}$, initial cumulative sunspot number x_0, maximum emergence rate r_0, and asymmetry α. A two-parameter function was obtained by taking α and r_0 as fixed values. In addition, it was found that $x_{\rm m}$ and x_0 can be well determined at the start of a cycle. Therefore, a predictive model of sunspot number is established based on the two-parameter function. The prediction for Cycles 4~23 shows that the solar maximum can be predicted with an average relative error of 8.8% and a maximum relative error of 22% in Cycle 15 at the start of solar cycles if solar minima are already known. The quasi-online method for determining the moment of solar minimum shows that the solar minimum of 14 months can be obtained after the start of a cycle. Besides, their model can predict the cycle length with an average relative error of 9.5% and a maximum relative error of 22% in Cycle 4. Furthermore, they predicted the variations in sunspot number of Cycle 24 with the relative errors of the solar maximum and ascent time being 1.4% and 12%, respectively, and the predicted cycle length is 11.0 a (95% confidence interval is 8.3~12.9 a). A comparison to the observations of Cycle 24 shows that their predictive model has good effectiveness.

8 Magnetic Reconnection

Magnetic reconnection is prevalent in the solar wind and is usually associated with interplanetary coronal mass ejections. Zhou *et al.*[98] examined a Petschek-like Reconnection Exhaust (RE) in the front boundary of a magnetic cloud observed by the WIND spacecraft on 2 June 1998 and presented the first observation of a slow shock pair bounding the Petschek-like outflow jet in the interplanetary space. The whole structure contained an Alfvénic accelerated outflow and a pair of reverse slow shocks. The Alfvénic accelerated outflow was identified by Walén analysis. Rankine-Hugoniot relations were applied to confirm the slow shocks bounding the RE. Both shocks strictly satisfied the characteristics of slow shocks: (i) the intermediate Alfvén Mach numbers were both below unit in the up/downstream region; (ii) the slow Mach number was above unit in the upstream side but below unit in the downstream side. Plasma was compressed and heated across the trailing slow shock, especially in the shock jump layer that has a temperature 2.4 times that of the upstream.

As the Sun rotates, a fast stream can overtake a preceding slow stream, leading to the formation of a Stream Interaction Region (SIR). Two neighboring SIRs may eventually coalesce to produce a Merged Interaction Region (MIR) en route to the outer heliosphere. However, instances of significant interaction and merging of two neighboring SIRs within 1 AU are thought to be extremely rare. Wang *et al.*[99] presented a case report of two interacting and merging SIRs observed near 1 AU, which was associated with two adjacent low-latitude coronal holes. The two SIRs were filled with outward propagating Alfvénic fluctuations associated with MHD turbulence. A reconnection exhaust associated with a current sheet was identified. They suggested that magnetic reconnection represented a potentially important mechanism for the merging of two neighboring SIRs. This observation may shed light on the understanding of the structure and formation of a MIR within 1 AU.

Liu *et al.*[100] investigated the evolution of reconnection inflow using a fully kinetic approach. Three types of inflow were detailed, namely the collapse inflow, the vortex inflow, and the reverse inflow.

They were formed dynamically at different stages of reconnection *via* self-organizing processes, but were closely interrelated with each other. The reconnection starts from a small perturbation, which could trigger off a chain of pressure-induced collapses propagating into the inflow region. The pressure gradient resulted in the collapse inflow toward the reconnection site. Then due to the continuous injection of hot plasma carried by the reconnection outflows, the expanding exhaust caused its adjacent region to be compressed. The combined effects of the compression and the reflection of conducting walls led to the formation of the vortex inflow. Subsequently, the reverse inflow developed gradually within the exhaust. Under the modulation of these inflows, the reconnection rate showed a transient oscillation. They also discussed the possible occurrence of the self-organization inflow available in different contexts.

On the two-step energy conversion mechanism of the solar wind magnetic reconnection outflow region: Magnetic reconnection outflow/exhaust region is an important region of energy conversion, and its role in energy conversion is not less significant than that of magnetic reconnection diffusion region. Most of the energy conversion related to magnetic reconnection occurs in the outflow/exhaust region. The magnetic reconnection outflow region in the solar wind has the advantages for investigation, since it has a large extension scale and in-situ measurement compared with other reconnection outflow regions. By analyzing an event of WIND satellite passing through the magnetic reconnection outflow/exhaust region, He *et al.*[101] analyzed the changes of proton and electron velocity distribution in the upstream and downstream of reconnection in detail, and found that the proton and electron were heated obviously in the parallel direction. The reason for parallel heating may come from the fact that the back-to-back rotational discontinuities bend the particles upstream of both sides to flow counter stream in pairs, thus causing parallel heating. Further analysis shows that the solar wind particles heated in parallel are not stable, which makes the magnetic field line subject to the firehose instability. Moreover, they observed the excitation and emission of Alfven waves, which enhances the Alfven turbulence in the reconnection outflow region.

9 MHD Numerical Modeling

All kinds of upwind schemes can be combined very flexibly for different problems to achieve the perfect combination of Conservation Element and Solution Element (CESE) and Finite Volume Method (FVM). However, Yang *et al.*[102] pointed out that in many physical applications it needs to consider geometries that are more sophisticated. Hence, the main objective of their work was to extend the upwind CESE scheme to multi-dimensional MHD in general curvilinear coordinates by transforming the MHD equations from the physical domain (general curvilinear coordinates) to the computational domain (rectangular coordinates) and the new equations in the computational domain can be still written in the conservation form. For the three-dimensional (3D) case, the derivations of some formulas are much more abstract and complex in a 4D Euclidean hyperspace, and some technical problems need to be solved in the debugging process. Unlike in HD, keeping the magnetic field divergence-free for MHD problems is also a challenge especially in general curvilinear coordinates. These are the main obstacles they have overcome in their study. The test results of benchmarks demonstrate that they have successfully extended the upwind CESE scheme to general curvilinear coordinates for both 2D and 3D MHD problems.

Three-dimensional MHD numerical simulation is an important tool in the prediction of solar wind parameters. Shen *et al.*[103] improved their corona interplanetary total variation diminishing MHD model by using a new boundary applicable to all phases of solar cycles. This model used synoptic magnetogram maps from the Global Oscillation Network Group as the input data. The empirical Wang-Sheeley-Arge relation was used to assign solar wind speed at the lower boundary, while the temperature was specified accordingly based on its empirical relation with the solar wind speed. Magnetic field intensity and solar wind density at the boundary were obtained from observational data in the immediate past Carrington rotations, permitting the persistence of these two parameters in a short time period. The boundary conditions depended on only five tunable parameters when simulating the solar wind for different phases of the solar cycle. They applied this model to simulate the background solar wind from 2007 to 2017 and compare the modeled results with the observational data in the OMNI database. Visual inspection showed that their model could capture the time patterns of solar wind parameters well at most times. Statistical analysis showed that the simulated solar wind parameters were all in good agreement with the observations. This study demonstrated that the improved interplanetary total variation diminishing model could be used for predicting all solar wind parameters near the Earth.

Li *et al.*[104] employed a path-conservative HLLEM FVM to solve the solar wind MHD systems of Extended Generalized Lagrange Multiplier (EGLM) formulation with Galilean invariance (G-EGLM MHD equations). The governing equations of single-fluid solar wind plasma MHD were advanced by using a one-step MUSCL-type time integration with the logarithmic space time reconstruction. The code was programmed in FORTRAN language with Message Passing Interface parallelization in spherical coordinates with a six-component grid system. Then, the large-scale solar coronal structures during Carrington Rotations (CRs) 2048, 2069, 2097, and 2121 were simulated by inputting the line-of-sight magnetic field provided by the Global Oscillation Network Group (GONG). These four CRs belong to the declining, minimum, rising, and maximum phases of solar activity. Numerical results basically generated the observed characteristics of structured solar wind and thus show the code's capability of simulating solar corona with complex magnetic topology.

The MHD modeling of the steady solar wind is an essential and important ingredient in numerical space weather study. Numerically solving the MHD equation system is not an easy work due to its complexity by combining the Euler equations of gas dynamics with Maxwell's equations of electromagnetics and the solenoidal constraint. Moreover, the vast physical temporal and spatial scales of the solar wind simulation propose harsh requirements for computational efficiency and memory storage. Considering these factors, Wang *et al.*[105] developed an easily implemented Finite Volume (FV) scheme using the GMRES algorithm with an LU-SGS preconditioner for the 3D MHD-based simulation. The steady-state solar wind from 1 Rs to 20 Rs during Carrington Rotation (CR) 2051 was simulated for the validation of the proposed matrix-free implicit solver. Compared with the explicit solver, the implicit one could effectively enlarge the CFL number to 100 and achieved speedup ratios of 31.27 and 28.05, which reduced the computational time for the steady-state study from several days to only a few hours. The simulation captured the main features of the solar corona and the mapped in-situ solar wind measurements. The scheme proposed here provided a promising choice to conduct the 3D MHD simulation of the solar wind background from the Sun to the Earth beyond.

Deep-space exploration of the inner heliosphere is in an unprecedented golden age, with the recent and forthcoming launches of the Parker Solar Probe (PSP) and Solar Orbiter (SolO) missions, respectively. In order to both predict and understand the prospective observations by PSP and SolO, Xiong *et al.*[106] performed forward MHD modeling of the 3D inner heliosphere at solar minimum, and synthesized the White-Light (WL) emission that would result from Thomson scattering of sunlight from the coronal and heliospheric plasmas. Both solar rotation and spacecraft trajectory should be considered when reconstructing quiescent large-scale solar-wind streams from PSP and SolO WL observations. When transformed from a static coordinate system into a corotating one, the elliptical orbit of PSP becomes a multi-winding spiral. The innermost spiral winding of this corotating PSP orbit takes the form of a closed "heart shape" within around 80 R_s of the Sun.

PSP, when traveling along this "heart-shaped" trajectory, can cross a single Corotating Interaction Region (CIR) twice. This enables in situ measurements of the same CIR to be made in both the corona and heliosphere. As PSP approaches perihelion, the WL radiance from the corona increases. Polarization can be used to localize the main WL scattering region in the corona. Large-scale structures around PSP can be further resolved in the longitudinal dimension, using additional WL imagery from the out-of-ecliptic perspective of SolO. Coordinated observations between PSP and SolO are very promising in the quest to differentiate background CIRs from transient ejecta.

Zhang *et al.*[107] have used a 3D numerical MHD model to study the reconnection process between magnetic cloud and heliospheric current sheet. Within a steady-state heliospheric model that gives a reasonable large-scale structure of the solar wind near solar minimum, they injected a spherical plasmoid to mimic a magnetic cloud. When the magnetic cloud moves to the heliospheric current sheet, the dynamic process causes the current sheet to become gradually thinner and the magnetic reconnection begins. The numerical simulation can reproduce the basic characteristics of the magnetic reconnection, such as the correlated/anti-correlated signatures in $\boldsymbol{V}$ and $\boldsymbol{B}$ passing a reconnection exhaust. Depending on the initial magnetic helicity of the cloud, magnetic reconnection occurs at points along the boundary of the two systems where anti-parallel field lines are forced together. They found the magnetic field and velocity in the MC have an effect on the reconnection rate, and the magnitude of velocity can also effect the beginning time of reconnection. These results are helpful in understanding and identifying the dynamic process occurring between the magnetic cloud and the heliospheric current sheet.

Li and Feng[108] modified the CESE-HLL 3D MHD solar wind model to be able to work in a corona-heliosphere integrated approach and then simulated the evolution of solar wind from the solar surface to the Earth's orbit during the year 2008. Here high-cadence photospheric magnetic field data were used to drive the model at the solar surface via the projected normal characteristic boundary equations. The simulated results were analyzed and quantitatively evaluated by comparing the simulated results with solar and interplanetary observations. The analyses demonstrated that their model reproduces the main pattern and the evolutionary feature of large-scale coronal structures. The simulated results showed that the height of the pseudostreamer X point was positively correlated with the distance of the coronal holes connected by the pseudostreamer. During the year 2008, the helmet streamer belt was found to have a net southward displacement from the equator while the pseudostreamer belts were biased to the Northern Hemisphere. Both helmet streamer belt and pseudostreamer belts exhibited a general trend of becoming more concentrated along the equator throughout 2008. The evaluation of the simulated results at the L1 point showed that the general structures could be generated by the model, and that speed was the best among the solar wind parameters reproduced. However, the temperature of the fast solar wind and the magnitude of the interplanetary magnetic field were underestimated. The success rate of prediction and arrival time error was also calculated for magnetic field polarity reversals and stream interaction regions.

Yang *et al.*[109] successfully used their newly developed numerical method to study the process of the emergence of magnetic flux rope from the solar convection zone into the atmosphere with a stratified hydro-static equilibrium as the initial ambient state. Their simulation obtained some key characteristics revealed by observation or other researchers' simulations. To achieve the process from emergence until eruption required a numerical scheme with low numerical diffusion. Otherwise, the emergence process would be suppressed by the diffusion of magnetic flux during the long emergence period caused by the great gradient for density and pressure in the ambient state. The results demonstrated that their code can simulate the emergence process very well, which allows to explore flux emergence mechanisms.

Liu *et al.*[110] proposed a Hyperbolic Cell-centered Finite Volume Solver (HCCFVS) to obtain the potential magnetic field solutions prescribed by the solar observed magnetograms. By introducing solution gradients as additional unknowns and adding a pseudo-time derivative, HCCFVS transformed the second-order Poisson equation into an equivalent first-order pseudo-time-dependent hyperbolic system. Thus, instead of directly solving the Poisson equation, HCCFVS obtained the solution to the Poisson equation by achieving the steady-state solution to this first-order hyperbolic system. The code was established in FORTRAN 90 with Message Passing Interface parallelization. To preliminarily demonstrate the effectiveness and accuracy of the code, two test cases with exact solutions were first performed. The numerical results showed its second-order convergence. Then, the code was applied to numerically solve the solar potential magnetic field problem. The solutions demonstrated the capability of HCCFVS to adequately handle the solar potential field problem, and thus it could provide a promising method of solving the same problem, except for the spherical harmonic expansion and the iterative finite difference method. Finally, by using the potential magnetic fields from HCCFVS and the spherical harmonic expansion as initial inputs, they made a comparative study on the steady-state solar corona in Carrington rotation 2098 to reaffirm the HCCFVS's performance. Both simulations showed that their modeled results were similar and capture the large-scale solar coronal structures. The average relative divergence errors, controlled by solving the Poisson equation in the projection method with HCCFVS for both simulations, were kept at an acceptable level.

Temporal evolution of magnetic structures of the solar Active Region (AR) NOAA AR 11158, was simulated by Hayashi, Feng *et al.*[111] with their MHD simulation models using time-dependent solar-surface electric field or plasma flow data. Using the SDO/HMI vector magnetogram data, the solar surface boundary electric field maps are derived with their recently developed algorithm to reproduce the temporal evolution of solar-surface vector magnetic field as observed. The plasma motion velocity maps were calculated through the Differential Affine Velocity Estimator for Vector Magnetograms. In both data-driven models, the simulated evolutionary magnetic field structures at strong-field low-beta regions appeared near force-free state, as the current helicity density ($\boldsymbol{J}\cdot\boldsymbol{B}/B^2$) was roughly constant along each field line. Although the magnetic energy simulated with the newly developed plasma-velocity-driven model was about 10% of that by the electric-field driven model, the plasma-velocity-driven model could maintain the frozen-in condition, and evolution of current and free energy generated by the solar-surface plasma motions could be spatially and temporally traced. The present MHD simulation models for AR system could be a step toward better, more realistic data-driven evolutionary modeling, in particular, establishing boundary treatments for introducing the time-dependent observation data in a physically and mathematically consistent manner.

MHD simulations in the domain of spherical shell are a crucial and challenging subject in many fields such as geophysics and solar-terrestrial physics, due to the complication of the MHD equations and the specificity of the domain. Besides, due to the real-time requirement, accelerating the heavy computation is proposed in many practical problems, of which the space weather simulation and forecast from the Sun to Earth is a typical case. Considering these factors, Wang *et al.*[112] first developed a new, spatially second-order accurate Finite Volume (FV) solver for 3D MHD simulations with the multiple time steps strategy, which was based on the six-component grid for spherical shell domain. Then to speed up the simulation, they implemented the solver on multiple GPUs with optimizations of CUDA and established an effective multi-GPU FV solver on the spherical shell domain. An MHD manufactured solution was used to validate the solvers' spatial accuracy, and to measure their performances. Results showed that both solvers had nice scalability, and speedup ratios of $27.7^{\times}$ to $30.06^{\times}$ are obtained on GPUs. Then they utilized them to study the ambient solar wind for Carrington Rotation (CR)

2060. The multi-GPU FV solver could not only obtain speedup ratios of about 29.0, but captured main features of the solar corona and the mapped in-situ solar wind measurements.

Feng *et al.*[113] applied the rotated-hybrid scheme for the first time to 3D MHD equations in the finite-volume frame. This scheme was devised by decomposing a cell-face normal vector into two orthogonal directions and combining the Roe solver, a full-wave or complete Riemann solver, and the Rusanov solver, an incomplete Riemann solver, into one rotated-hybrid Riemann solver. To keep the magnetic field divergence-free, they proposed two kinds of divergence-cleaning approaches by combining the least-squares reconstruction of magnetic field with divergence-free constraints. One was the locally solenoidality-preserving method designed to locally maintain the magnetic solenoidality exactly, not just in a least-squares sense, and another was the globally Solenoidality-Preserving (SP) approach that was implemented by adding a global constraint but abandoned the exactness of the locally divergence-free condition. Both SP methods were employed for 3D MHD with a rotated-hybrid scheme in the finite-volume frame. To validate and demonstrate the capabilities of the rotated-hybrid scheme for MHD, they performed an Orszag-Tang MHD vortex problem and a numerical study for the steady-state coronal structures of Carrington rotation 2068 during the solar activity minimum. The numerical tests showed the robustness of the proposed scheme and demonstrated the capability of these two SP approaches to keep the magnetic divergence errors to the expected accuracy.

Liu *et al.*[114] presented a 3D numerical MHD data-driven model for the simulation of the CME that occurred on 22June 2015 in the active region NOAA12371. The numerical results showed two elbow-shaped loops formed above the Polarity Inversion Line (PIL), which was similar to the tether-cutting picture previously proposed. The temporal evolutions of magnetic flux showed that the sunspots underwent cancellation and flux emergence. The signature of velocity field derived from the tracked magnetograms indicated the persistent shear and converging motions along with the PIL. The simulation showed that two elbow-shaped loops were reconnected and formed an inverse S-shaped sigmoid, suggesting the occurrence of the tether-cutting reconnection, which was supported by observations of the AIA telescope. Analysis of the decline rate of the magnetic field indicated that the flux rope reached a region where the torus instability was triggered. They concluded that the eruption of this CME was caused by multiple factors, such as photosphere motions, reconnection, and torus instability. Moreover, their simulation successfully reproduced the three-component structures of typical CMEs.

Zhang *et al.*[115] performed a 3D time-dependent, numerical MHD simulation to investigate the propagation of a CME occurring on 12 December 2008. The background solar wind was obtained by using a splitting finite-volume scheme based on a six-component grid system in spherical coordinate, with Parker's one-dimensional solar wind solution and measured photospheric magnetic fields as the initial values. A spherical plasmoid was superposed on the realistic ambient solar wind to study the 12 December 2008 coronal mass ejection event. The plasmoid was assumed to have a Spheromak magnetic structure with a high-density, high-velocity, and high-pressure near the Sun. The dynamical interaction between the CME and the background solar wind flow was then investigated. They compared the model results with observations, and the model provided a relatively satisfactory comparison with the WIND spacecraft observations at 1 AU. They also investigated the numerical results assuming different parameters of the CME, and found that initial magnetic fields in the CME had a larger influence on the solar wind parameters at the Earth.

Previous research has shown that the deflection of CMEs in interplanetary space, especially fast CMEs, is a common phenomenon. The deflection caused by the interaction with background solar wind is an important factor to determine whether CMEs could hit Earth or not. As the Sun rotates, there will be interactions between solar wind flows with different speeds. When faster solar wind runs into slower solar wind ahead, it will form a compressive area corotating with the Sun, which is called a Corotating Interaction Region (CIR). These compression regions always have a higher density than the common background solar wind. When interacting with CME, will this make a difference in the deflection process of CME? Liu *et al.*[116] established a 3D flux-rope CME initialization model based on the Graduated Cylindrical Shell (GCS)model. Then this CME model was introduced into the background solar wind, which was obtained using a 3D IN (Interplanetary)-TVD-MHD model. The Carrington Rotation (CR) 2154 was selected as an example to simulate the propagation and deflection of fast CME when it interacted with background solar wind, especially with the CIR structure. The simulation results showed that: (i) the fast CME will deflect eastward when it propagates into the background solar wind without the CIR; (ii) when the fast CME hits the CIR on its west side, it will also deflect eastward, and the deflection angle will increase compared with the situation without CIR.

Wang *et al.*[117] presented a method of forced-field (*i.e.*, non-force-free field: NFFF) extrapolation of the global magnetic field in the corona, on the basis of single-layer vector magnetogram, by extending an extrapolation technique of local magnetic field. The forced coronal magnetic field is described by a system with the Minimum Dissipation Rate (MDR) which is appropriate for the corona as a forced and open system. The obtained solution of the magnetic field can be decomposed into three components including one potential field and two Linear Force-Free Fields (LFFF). Starting from the given single-layer vector magnetogram, the bottom boundary condition for each component is determined with an iterative method to achieve a minimum difference of the transverse component between the extrapolated field and the original magnetogram. The final extrapolated forced field is given by the sum of the three-component fields with the obtained bottom boundaries. The method was tested with an analytic Magnetohydrostatic (MHS) solution. It was shown that the extrapolated forced field is highly consistent with the MHS solution at least from the solar disk to the heliocentric distance of 1.5 solar radii. For instance, the complements of normalized and mean vector errors ($\boldsymbol{E}'_{\rm n}$, $\boldsymbol{E}'_{\rm m}$) are as high as about 97% and 95%, respectively. Further comparisons between magnetic strength, force, and field line distributions indicate that the MHS solution has been successfully reconstructed.

10 Solar Energetic Particles, Cosmic Rays, and Forbush Decreases

Lembège and Yang[118] analyzed self-consistently the impact of the non-stationarity of the heliospheric termination shock in the Presence of Pickup Ions (PUIs) on the energy partition between different plasma components by using a 1D particle-in-cell simulation code. Solar Wind Ions (SWIs) and PUIs were introduced as Maxwellian and shell distributions, respectively. For a fixed time, (i) with a percentage of 25% PUIs, a large part of the downstream thermal pressure was carried by reflected PUIs, in agreement with previous hybrid simulations; (ii) the total downstream distribution includes three main components: a low-energy component dominated by Directly Transmitted (DT) SWIs, a high-energy component dominated by reflected PUIs, and an intermediate-energy component dominated by reflected SWIs and DT PUIs. Moreover, results showed that the front non-stationarity (self-reformation) persisted even in presence of 25% PUIs, and had some impacts on both SWIs and PUIs: (i) the rate of reflected ions suffered some time fluctuations for both SWIs and PUIs; (ii) the relative percentage of downstream thermal pressure transferred to PUIs and SWIs also suffered some time fluctuations, but depended on the relative distance from the front; (ii) the three components within the total downstream heliosheath distribution persisted in time, but the contribution of the ion subpopulations to the low- and intermediate-energy components were redistributed by the front non-stationarity. Their results allowed clarifying the respective roles of SWIs and PUIs as a viable production source of energetic neutral atoms and were compared with previous results.

The solar eruption on 27 January 2012 resulted in a wide-spread solar energetic particle event observed by STEREO A and the near-Earth spacecraft (separated by 108°). The event was accompanied by an X-class flare, Extreme-Ultraviolet (EUV) wave, and fast coronal mass ejection. Zhu *et al.*[119] investigated the particle release by comparing the release times of particles at the spacecraft and the times when magnetic connectivity between the source and the spacecraft was established. The EUV wave propagating to the magnetic footpoint of the spacecraft in the lower corona and the shock expanding to the open field line connecting the spacecraft in the upper corona are thought to be responsible for the particle release. They tracked the evolution of the EUV wave and modeled the propagation of the shock using EUV and white-light observations. No obvious evidence indicates that the EUV wave reached the magnetic footpoint of either STEREO A or L1-observers. Their shock modeling showed that the release time of the particles observed at L1 was consistent with the time when the shock first established contacted with the magnetic field line connecting L1-observers. The release of the particles observed by STEREO A was delayed relative to the time when the shock was initially connected to STEREO A via the magnetic field line. They suggested that the particle acceleration efficiency of the portion of the shock connected to the spacecraft determined the release of energetic particles at the spacecraft.

Yang *et al.*[120] investigated electron dynamics at low-Mach-number collisionless shocks by using two-dimensional electromagnetic particle-in-cell simulations with various shock normal angles, and found the following results.

(1) The reflected ions and incident electrons at the shock front provide an effective mechanism for the quasi-electrostatic wave generation due to the charge-separation. A fraction of incident electrons can be effectively trapped and accelerated at the leading edge of the shock foot.

(2) At quasi-perpendicular shocks, the electron trapping and reflection is non-uniform due to the shock rippling along the shock surface and is more likely to take place at some locations accompanied by intense reflected ion-beams. The electron trapping process has a periodical evolution over time due to the shock front self-reformation, which is controlled by ion dynamics. Thus, this is a cross-scale coupling phenomenon.

(3) At quasi-parallel shocks, reflected ions can travel far back upstream. Consequently, quasi-electrostatic waves can be excited in the shock transition and the foreshock region. The electron trajectory analysis shows these waves can trap electrons at the foot region and reflect a fraction of them far back upstream. Simulation runs in this paper indicated that the micro-turbulence at the shock foot can provide a possible scenario for producing the reflected electron beam, which is a basic condition for the type II radio burst emission at low-Mach-number interplanetary shocks driven by CMEs.

Only a few days later, on 10 September 2017 starting at about 15:53 UT, the same region launched another extremely fast magnetic cloud accompanied by an intense shock which spread rapidly across the entire solar surface. The study by Guo *et al.*[121] reported that particles accelerated at the Sun arrived at Earth only 10~20 min later after the solar-surface eruption and caused a ground-level enhancement of radiation seen by multiple neutron monitors. A few hours later and shortly before 20:00 UT, the Radiation Assessment Detector (RAD) started detecting the biggest event since the landing of the Curiosity rover in August 2012 on the surface of Mars which is about 160° east from Earth in the heliosphere. This was the first SEP event seen on the surface of two planets. SEPs were also transported across magnetic field lines throughout the heliosphere and were detected at the back side of the Sun where the eruption was centered. Meantime, the intense and wide shock also propagated into the interplanetary space, reached Earth on its west edge after about 50.5 h and hit Mars on its east flank after about 59 h, causing the biggest depression of the galactic cosmic ray flux measured by RAD on Mars.

In particular, they combined both remote-sensing and in-situ observations of the 10 September 2017 eruptions at Earth, STEREO-A and also at Mars to study this event in a thorough manner. They addressed both the CME and shock propagation as well as the arrival of energetic protons at these locations using a data-constrained modeling approach to improve the understanding of the complexity of such extreme events in order to better forecast them and to mitigate their potential damages. First, they analyzed the event starting from the eruptions at the surface of the Sun and noticed the launch of 3 CMEs within hours from the same active region heading towards similar directions based on multi-viewpoint solar images. With the help of such stereoscopic images and 3D CME reconstruction techniques, they obtained the early kinematics of the 3 CMEs and modeled their propagation as they headed out from the Sun towards a direction more oriented towards Mars than to Earth (which are about 160° apart in heliospheric longitude). The CME-related shock was very wide and they derived it to be at least 220 degrees in its longitudinal extent in the solar equatorial plane. It impacted Earth in about 2 days after the launch. In the direction of Mars, it propagated faster and arrived at Mars (1.5 AU from the Sun) only about 10 hours later than its arrival at Earth. Using both an analytic drag-based model and the MHD ENLIL model, they simulated the propagation of 3 CMEs and the shock arrivals at two planets. In order to best match the modeled results with observations, they concluded that the shock experienced rather different interplanetary journeys in two directions. Towards Earth, the shock was not driven by a magnetic structure and experienced more deceleration on its way. Towards Mars, the very fast CME and its driven shock caught up with the previous 2 CMEs which likely swept the way for the successive one to experience less drag; all three CMEs had similar directions and speeds one faster than another and they likely merged as an entity and propagated further together. The arrival of the shock and the merged CME caused the biggest Forbush decrease in the Galactic Cosmic Ray flux RAD measures (about 23%).

The SEPs were widely spread and observed at 3 different locations in the heliosphere: Earth, Mars, and also STEREO-A spacecraft which was about 230° east from Earth. Upon the event onset at the Sun, Earth was already nicely connected to the central of the shock and flare region favoring high-energy particles triggering the Ground Level Enhancement (GLE) at multiple neutron monitors on the ground within tens of minutes. The high energy particle fluxes observed at Earth also had a rather gradual declining time profile especially after the shock passed Earth. This is likely caused by particles trapped by a Stream Interaction Region (SIR) before it reached Earth. Alternatively, STEREO-A was connected to the back side of the Sun where the eruption was centered and energetic proton fluxes only started gradually increasing 16 hours later. This delay was most probably attributed to cross-field diffusion of particles transported across the interplanetary magnetic field lines. More interestingly, the SEP onset at Mars was nearly 4 hours later than the eruption at the Sun. Their investigation suggested three scenarios for explaining the trigger of the GLE at Mars. (i) Particles were continuously accelerated and/or re-accelerated by the interplanetary shock as it was propagating outwards and started connecting to east-side interplanetary magnetic field lines. This magnetic connection was established upon/shortly after the SEP onset at Mars; (ii) particles were transported across the field lines and arrived at Mars similar to the situation at STEREO-A; (iii) an SIR structure (a different one from the previous one passing Earth) located closer to the central of the eruption was injected with SEPs at an earlier phase of the event and served as a reservoir of particles and favored the GLE onset at Mars when it passed by Mars. They believed that the 3 scenarios are not contradictory and could be complementary.

Their detailed study on the 10 September 2017 event suggested that in order to better predict the ICME and SEP arrival and their potential space weather impact at different heliospheric locations, it is important to consider (i) the eruption of the flare and CME at the Sun, (ii) the evolution of the ICME kinematics, especially during interactions of different CMEs and (iii) the dynamic heliospheric conditions at different locations in the heliosphere such as the varying solar wind speeds and the stream interaction regions. Besides, it is also necessary to include, as much as possible, both the remote-sensing and in-situ observations of the events in all possible aspects. If STEREO-B were still in service, it could have had the most head-on observation of the shock of the magnetic structure of the CMEs and people would learn in better detail how the 3 CMEs were merged/interacted and how fast the central part of the shock was propagating.

To better understand and forecast the potential radiation impacts induced by extreme SEP events, Guo *et al.*[122,123] developed a GEANT4-based particle transport model implemented with Martian atmospheric and regolith properties to transport Galactic Cosmic Ray (GCR) particles from deep space down to the surface of Mars. Guo *et al.*[124] also benchmarked this model using in-situ RAD measurements of charged particle spectra on the surface of Mars. Recently, Guo *et al.*[125] used this validated model to calculate the surface radiation for different input spectra at the top of the atmosphere. It is well known that the deep-space SEP differential energy spectrum at high energies is often given by a power law. They calculated the induced Martian surface radiation by a variety of SEP events with different properties such as their energy range, intensity, power-law index, and studied the correlation between the induced radiation and their properties statistically. For the first time, they found a pivot energy (about 300 MeV) at which the SEP flux alone can be used to determine the Martian surface dose rate for large SEP events with proton energy extending above about 500 MeV. In other words, with a fixed flux at this pivot energy, the variation of the power-law spectral index does not affect the surface radiation. This finding advances understanding of the radiation risks during possibly adverse space weather conditions. Together with SEP injection and interplanetary transport models, people can provide instantaneous and quantitative alerts for future human missions at Mars upon the onset of large SEP events at the Sun.

Because of the precise measurements of the cosmic ray electron flux by the PAMELA and AMS02, electron Forbush decreases ($F_{\rm d}$) have recently been observed for the first time. This serves as motivation of Luo *et al.*[126] to perform a numerical study of electron Forbush decreases with an advanced time-dependent, three-dimensional (3D) stochastic differential equation model, developed earlier to study proton $F_{\rm d}$. The model includes a realistic interstellar electron spectrum reconstructed from Voyager observations, and diffusion and drift coefficients to reproduce the modulated spectrum observed by PAMELA in 2009. On the basis of this numerical model, electron $F_{\rm d}$ profiles for a range of rigidities are simulated. In addition, a systematic comparison between electron and proton $F_{\rm d}$ during different solar polarity epochs is performed. This approach gives insight into the rigidity dependence of the heliospheric diffusion coefficients and of drift effects over two magnetic field polarity cycles. They found that during an $A>0$ epoch, the recovery time of a 1 GV proton $F_{\rm d}$ is remarkably shorter than the 1 GV electrons, whereas the electron $F_{\rm d}$ displays a faster recovery during an $A<0$ epoch. This model clear predicts a charge-sign dependent effect in the recovery time of $F_{\rm d}$ but less so for their magnitude.

In modeling the transport process of Solar Energetic Particles (SEPs) in the heliosphere, the previous simulation works often simplify the solar wind velocity as radial and constant, and treat the magnetic field as Parker spiral. In order to fully understand the effect of solar wind velocity and interplanetary magnetic field on the particles' transport process, a realistic background solar wind and magnetic field are required. Wei *et al.*[127] used the focused transport model to investigate the transport of SEPs in the solar wind velocity and the magnetic field generated by the 3D high-resolution MHD model with a six-component grid. They found that in the uncompressed solar wind, the time intensity profiles of energetic particles showed a similar trend in both the MHD background and the Parker magnetic field assumption. However, the simulated SEP flux displayed an enhancement in the decay phase when a compression region swept past the local observer. Through investigating various effects, they found that the magnetic focusing effect was primarily responsible for the intensity enhancement, suggesting that the magnetic focusing effect had an important influence on the transport of SEPs. Further, they showed that the magnetic focusing could also be effective in large heliocentric distances.

Since May 2011, the Alpha Magnetic Spectrometer (AMS-02) on board the International Space Station has provided monthly cosmic proton fluxes for various low-rigidity levels ($P < 50$ GV). These precise measurements, in terms of high time and rigidity resolution, have provided a good opportunity to study cosmic ray modulation over a wide range of rigidities, together with transient events. Luo *et al.*[128] constructed a comprehensive numerical transport model, which was based on Parker's transport equation that included all known physical mechanisms: diffusion, convection, drift, and adiabatic cooling. Propagating diffusion barriers to simulate Forbush decreases (F_d) and Global Merged Interaction Regions (GMIRs) had also been incorporated: (i) utilizing a time-varying tilt angle of the heliospheric current sheet and interplanetary magnetic field, the general trend of the time variation of cosmic proton fluxes has been reproduced; (ii) the F_d events in October 2011 and March 2012 have been simulated, and the first GMIR event in solar cycle 24 has also been simulated and studied; and (iii) the rigidity dependence of the proton fluxes, as revealed by the AMS-02 data, had been reproduced with the appropriate chosen rigidity dependent diffusion coefficients. In order to reproduce the proton observations, they found that apart from the transient events, the derived mean free paths in interplanetary space also needed to be changed with time.

A 3D MHD solar wind model is an important tool for research and forecast of ambient solar wind. Employing boundary condition driven by solar photospheric magnetic field observation, Li *et al.*[129] developed a time-dependent 3D MHD interplanetary solar wind model. Using this model, they simulated the solar wind of Year 2008, and analyzed the evolution of global solar wind structures and the connection between interplanetary in-situ measurements and corona structures during that year. They realized a set of procedures, which evaluate the quality of predictions for both continuous solar wind parameters and characteristic structures of the solar wind. The evaluation results indicated that their model satisfactorily reproduced the large sale structure of the ambient solar wind during Year 2008. The correlation coefficient between observed and simulated speeds is higher than 0.6. The strength of simulated interplanetary magnetic field matched observation well. All interplanetary magnetic field reverses and 82.76% of the stream interaction regions were captured by their model. The false alarm rate of the interplanetary magnetic field reverse prediction is only 6.67% while that of the stream interaction region is only 11.11%. The errors in predicting the arrival time of these two structures were about one day.

Kong *et al.*[130] presented numerical modeling of particle acceleration at coronal shocks propagating through a streamer-like magnetic field by solving the Parker transport equation with spatial diffusion both along and across the magnetic field. They showed that the location on the shock where the high-energy particle intensity is the largest, depends on the energy of the particles and on time. The acceleration of particles to more than 100 MeV mainly occurs in the shock-streamer interaction region, due to perpendicular shock geometry and the trapping effect of closed magnetic fields. A comparison of the particle spectra to that in a radial magnetic field shows that the intensity at 100 MeV (200 MeV) is enhanced by more than one order (two orders) of magnitude. This indicates that the streamer-like magnetic field can be an important factor in producing large solar energetic particle events. They also showed that the energy spectrum integrated over the simulation domain consists of two different power laws. Further analysis suggested that it may be a mixture of two distinct populations accelerated in the streamer and open field regions, where the acceleration rate differs substantially. Their calculations also showed that the particle spectra are affected considerably by a number of parameters, such as the streamer tilt angle, particle spatial diffusion coefficient, and shock compression ratio. While the low-energy spectra agree well with standard diffusive shock acceleration theory, the break energy ranges from 1 MeV to 90 MeV and the high-energy spectra can extend to 1 GeV with a slope of 2~3.

Shock acceleration is considered one of the most important mechanisms for the acceleration of astrophysical energetic particles. Kong *et al.*[131] investigated the time evolution of the accelerated particle energy spectrum in the downstream of the shock, in order to understand the acceleration mechanism of energetic particles. From simulation results they obtained power-law energy spectra with bend-over energy, E_0, increasing with time. With the particle mean acceleration time and mean momentum change during each cycle of the shock crossing from the diffusive shock acceleration model (following Drury), a time-dependent differential equation for the maximum energy, $E_{\rm acc}$, of particles accelerated at the shock can be approximately obtained. They assumed the theoretical bend-over energy as $E_{\rm acc}$. It was found that the bend-over energy from simulations agrees well with the theoretical bend-over energy using the nonlinear diffusion theory, NLGCE-F, in contrast to that using the classic quasi-linear theory.

Using test particle simulations, Qin *et al.*[132] studied electron acceleration at collisionless shocks with a two-component model turbulent magnetic field with slab component including dissipation range. They investigated the importance of the shock-normal angle $\theta_{\rm Bn}$, magnetic turbulence level $(b/B_0)^2$, and shock thickness on the acceleration efficiency of electrons. It is shown that at perpendicular shocks the electron acceleration efficiency is enhanced with the decrease of $(b/B_0)^2$, and at $(b/B_0)^2$=0.01 the acceleration becomes significant due to a strong drift electric field with longtime particles staying near the shock front for Shock Drift Acceleration (SDA). In addition, at parallel shocks, the electron acceleration efficiency is increasing with the increase of $(b/B_0)^2$, and at $(b/B_0)^2$=10.0 the acceleration is very strong due to sufficient pitch-angle scattering for first-order Fermi acceleration, as well as due to the large local component of the magnetic field perpendicular to the shock-normal angle for SDA. On the other hand, the high perpendicular shock acceleration with $(b/B_0)^2$= 0.01 is stronger than the high parallel shock acceleration with b $(b/B_0)^2$=10.0, the reason might be the assumption that SDA is more efficient than first-order Fermi acceleration. Furthermore, for oblique shocks, the acceleration efficiency is small no matter whether the turbulence level is low or high. Moreover, for the effect of shock thickness on electron acceleration at perpendicular shocks, they showed that there exists the bend over thickness, $L_{\rm diff,b}$. The acceleration efficiency does not noticeably change if the shock thickness is much smaller than $L_{\rm diff,b}$. However, if the shock thickness is much larger than $L_{\rm diff,b}$, the acceleration efficiency starts to drop abruptly.

Shen and Qin[133] studied the 11- and 22-year modulation of Galactic Cosmic Rays (GCRs) in the inner heliosphere using a numerical model. Based on the numerical solutions of Parker's transport equations, the model incorporates a modified Parker heliospheric magnetic field, a locally static time-delayed heliosphere, and a time-dependent diffusion coefficients model in which an analytical expression of the variation of magnetic turbulence magnitude throughout the inner heliosphere is applied. Furthermore, during solar maximum, the solar magnetic polarity is determined randomly with the possibility of $A>0$ decided by the percentage of the solar north polar magnetic field being outward and the solar south polar magnetic field being inward. The computed results are compared at various energies with several GCR observations, *e.g.*, IMP 8, EPHIN on board SOHO, Ulysses, and Voyager 1 and 2, and they show good agreement. They showed that their model had successfully reproduced the 11- and 22-year modulation cycles.

Galactic Cosmic-Ray (GCR) helium and heavier ions are important sources of space radiation, and their elemental spectra and composition can help us better understand the transport in both the galaxy and the heliosphere. Shen *et al.*[134] used a model based on the numerical solution of Parker's transport equation to study the modulation of GCR helium and heavier ions in the inner heliosphere. The model incorporates a modified Parker heliospheric magnetic field, time-dependent diffusion and drift model, time-delayed heliosphere, and randomly determined solar magnetic polarity during solar maximum. They set the outer boundary of modulation at 85 AU, and the reference unmodulated GCR energy spectra for GCR helium and heavier ions, which are assumed to have a general form, are determined by fitting the numerical results to the selected GCR measurements, *e.g.*, BESS, ACE/CRIS, HEAO-3-C2, *etc.* In addition, they used the Sun's polar magnetic field data from NSO/NISP to determine the possibility of A>0 during the recent solar maximum, and it gives an improved numerical result during the period 2013–2015. Finally, the fitted unmodulated GCR energy spectra were used to study the long-term modulation of GCRs of helium and heavier ions, and the computed results show good agreement with various GCR measurements.

The equation $k_{zz}=\mathrm{d}\sigma^2/(2\mathrm{d}t)$ describing the relation of the parallel diffusion coefficient k_{zz} with the displacementvariance σ^2 (hereafter DCDV) is a well-known formula. Wang and Qin[135] found that DCDV is only applicable to two kinds of transport equations of the isotropic distribution function, one without cross-terms and the other without a convection term. Here, by employing the more general transport equation, *i.e.*, the variable coefficient differential equation derived from the Fokker-Planck equation, a new equation of k_{zz} as a function of σ^2 is obtained. They found that DCDV is the special case of the new equation. In addition, another equation of k_{zz} as a function of σ^2 corresponding to the telegraph equation is also investigated preliminarily.

It is very important to understand the stochastic diffusion of energetic charged particles in the non-uniform background magnetic field in plasmas of astrophysics and fusion devices. Using different methods considering an along-field adiabatic focusing effect, various authors derived a parallel diffusion coefficient $k_\parallel$ and its correction T to $k_{\parallel 0}$, where $k_{\parallel 0}$ is the parallel diffusion coefficient without an adiabatic focusing effect. Using the improved perturbation method developed by He and Schlickeiser and iteration process, Wang and Qin[136] obtained a new correction T' to $k_{\parallel 0}$. Furthermore, by employing the isotropic pitch-angle scattering model $D_{\mu\mu}=D(1-\mu^2)$, they found that T' has a different sign from that of T. In this paper, the spatial perpendicular diffusion coefficient $k_\perp$ with the adiabatic focusing effect is also obtained.

Interplanetary collisionless shocks are known to be a strong source of energetic charged particles up to tens of MeV (or even to a few hundred MeV). However, the acceleration of electrons at collisionless shocks is still not well understood, but it is suspected that the suprathermal electrons of the solar wind including the strahl, halo, and super halo populations could provide seed particles for the shock acceleration in the interplanetary medium. On the issue of ICME-driven Shock Acceleration of Solar Wind Suprathermal Electrons, Yang *et al.*[137-139] made a comprehensive study of in situ electron acceleration during 74 shocks driven by ICMEs with good suprathermal electron observations by the Wind 3DP instrument at 1 AU from 1995 through 2014. Among the selected 59 quasi-perpendicular (15 quasi-parallel) shock cases, about 86% (60%), 62% (36%), and 17% (7%) show significant electron flux enhancements of $J_\mathrm{D}/J_\mathrm{A}$>1.5 across the shock, respectively at 0.43, 1.95, and 40 keV, where J_D and J_A are the electron flux in the shock's downstream and the preceding ambient solar wind. For significantly shocked suprathermal electrons, the differential flux J_D positively correlates most with the magnetosonic Mach number, while the flux enhancement $J_\mathrm{D}/J_\mathrm{A}$ positively correlates most with the magnetic compression ratio, among the shock parameters. Both J_D and J_A generally fit well to a double-power-law spectrum at 0.4~100 keV, $J\propto E^{-\beta}$, with an index of $\beta_1 \approx$2~6 below break energy of e_b (which is typically about 2 keV) and an index of $\beta_2 \approx 2.0$~3.2 at energies above. Furthermore, J_D/J_A mostly peaks in the directions perpendicular to the interplanetary magnetic field at 0.4~50 keV. These results suggest that both quasi-parallel and quasi-perpendicular shocks accelerate electrons in situ at 1 AU mainly via shock drift acceleration, with an acceleration efficiency probably affected by the induced electric field at the shock surface.

Liu *et al.*[140] made a case study of the in situ acceleration of solar wind suprathermal electrons at the two quasi-perpendicular bow-shock crossings on 4 November 2015, combining the Wind 3D Plasma and Energetic Particle measurements of ambient solar wind suprathermal electrons and Magnetospheric Multiscale mission measurements of shocked suprathermal electrons. In both cases, the omnidirectional differential fluxes of shocked suprathermal electrons in the downstream exhibit a double-power-law energy spectrum with a spectral index of about 3 at energies below a downward break e_b near 40 keV and index of 6 at energies above, different from the unshocked suprathermal electrons observed in the ambient solar wind. At energies below (above) e_b, the observed electron flux ratio between the downstream and ambient solar wind, J_D/J_A, peaks near 90° PA (becomes roughly isotropic). Electrons at e_b have an average electron gyrodiameter (across bow shock) comparable to the shock thickness. These suggested that the bow-shock acceleration of suprathermal electrons is likely dominated by the shock drift acceleration mechanism. For electrons at energies below (above) e_b, their estimated drift time appears to be roughly energy independent (decrease with energy), leading to the formation of a double-power-law spectrum substantially steepening at a break that's determined by the shock thickness.

11 Machine Learning Methods in Space Weather and Other Aspects

A hybrid intelligent source surface model applying the artificial neural network tactic for solar wind speed prediction was given by Yang *et al.*[141]. The model was a hybrid system merging various observational and theoretical information as input. Different inputs were tested including individual parameters and their combinations in order to select an optimum. Then, the optimal model was implemented for prediction. The prediction was validated by both error analysis and event-based analysis from 2007 to 2016. The overall correlation coefficient is 0.74, and the root-mean-square error is 68 km·s^{-1}. The probability for detecting a high-speed-event is 0.68, the positive predicted value is 0.73, and the threat score is 0.55.

As arriving at the Earth, ICME will interact with the Earth's magnetosphere and cause geomagnetic storms. Ye and Feng[142] obtained the ICME event set from Richardson and Cane's near Earth ICME list, and the input features were extracted based on interplanetary solar wind and magnetic data during ICME disturbance. A total of 483 ICME events from 1996 to 2006 were chosen. 13 magnetic and kinetic features were finally selected for the training of the machine learning model. Rank of each feature's Fisher score indicated that the duration of the south-directed interplanetary magnetic field that was larger than 10 nT and the increase of solar wind speed at the upstream shock or wave disturbance was closely related to the geoeffectiveness of ICME events, which was consistent with those former statistical results. The trained Radial Basis Function Support Vector Machine (RBF-SVM) could determine whether an ICME event would trigger moderate or stronger geomagnetic storms ($Dst \leqslant -50$ nT) effectively with an accuracy of 0.78±0.08. The results showed that RBF-SVM could be used as a powerful tool in further analysis, and the better prediction of the geoeffectiveness of ICME would be obtained.

The global distribution of magnetic field and other plasma parameters on the source surface, which Yang and Shen[143] set at 2.5 solar radii, is important for coronal and heliospheric modeling. They introduced a new data-driven self-consistent method to obtain the global distribution of different parameters.

The magnetic and polarized Brightness (pB) observations were used to derive the magnetic field and electron density on the source surface, respectively. Then, an Artificial Neural Network (ANN) machine learning technique was applied to establish an empirical relation among the solar wind velocity, the magnetic field properties, and the electron density. The ANN was trained with global observational data, and is validated to be more reliable than the Wang-Sheeley-Arge (WSA) model for reconstructing the solar wind velocity, especially at high latitudes. The plasma temperature distribution was derived by solving a simplified 1D MHD equation system on the source surface. Using the method introduced above they obtained the global distribution for all the parameters self-consistently based on magnetic and polarized brightness observations. The modeling results of four Carrington rotations from different solar cycle phases were presented to validate the method.

Lu *et al.*[144] presented a kind of large area sub-wavelength cavity antenna with artificial permeability-negative metamaterials at GHz range. The antenna has the advantages of flatness, ultra-thin thickness, high gain, and good directivity. The optimal receiving area of the antenna is mainly determined by the size of the radiation source. Its directivity and side lobe cancellation mainly depend on the patterns of the patch array as the radiation source. It was found that the antenna with non-uniform distributed patch array as the radiation source has better performance than that with uniform distributed patch array patterns. Otherwise, this type of metamaterial antenna has nearly the same performance compared to that of parabolic antenna with equal radiation aperture, so it has potential applications to replace the traditional large aperture parabolic antenna.

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