Home

# Interplanetary Physics in Mainland China

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**Abstract**

During the past two years (2016–2018), great achievements have been made in the Chinese research of interplanetary physics, with nearly 100 papers published in the academic journals. The achievements are, including but not limited to the following topics: (1) solar corona; (2) solar wind and turbulence; (3) filament/prominence and jets; (4) solar flare; (5) radio bursts; (6) particle acceleration at coronal shocks; (7) magnetic flux ropes; (8) instability; (9) instrument; (10) Coronal Mass Ejections (CMEs) and their interplanetary counterparts; (11) Magnetohydrodynamic (MHD) numerical modeling; (12) solar energetic particles and cosmic rays. The progresses further improve our understanding the eruptions of solar activities, their evolutions and propagations in the heliosphere, and final geoeffects on our Earth. These results were achieved by the Chinese solar and space scientists independently or via international collaborations. This paper will give a brief review of these achievements.

**Key words**

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

## 1. Solar Corona

Slow-mode wave, as one of the three types of MHD waves, is prevalent in the solar and interplanetary plasmas. In the solar corona, the source region of solar wind, intensity disturbances were observed to propagate along the strands. Along with the intensity disturbance, there also exist oscillations of Doppler shift, line width, and blue-red wing asymmetry, which are newly discovered phenomena in the solar corona by the EIS instrument onboard Hinode satellite. There is a heated debate on the nature of the Propagating Intensity Disturbances (PIDs): (1) one argument is the slow-mode waves; (2) the other argument is the intermittent upflows superposed on the background static plasmas. Previously, these two arguments are apparently in contradiction to each other. To reconcile the seeming contradiction, He and his colleagues proposed a novel kinetic model to unify the slow mode waves and quasi-periodic beam flows in the same frame[1]. In this “wave+ flow” model, the beam flow is created by Landau resonance between semi-collisional plasmas and slow mode waves. Due to the generation of quasi-periodic beam flows, the synthetic spectral profiles illustrate blue-red wing asymmetry, the strongest blueward asymmetry of which is found to be ahead of that with strongest blueshift by about one quarter of period. The out-of-phase relation between asymmetry and Dopper shift is consistent with the observations, which cannot be explained by previous scenarios. Moreover, the slow mode waves are found to



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damp to its 1/e level over about three wavelengths in the semi-collisional solar corona.

## 2. Solar Wind and Turbulence

To reproduce the fast and slow solar wind, many theoretical and computational models have been proposed. In these models, the acceleration of the slow solar wind was understood in terms of thermal expansion of hot coronal plasma into the interplanetary space, *i.e.* Parker's thermal expansion model, with an additional source of momentum or energy introduced to explain the fast solar wind. Yang *et al.*[2] presented self-consistent modeling of the global solar wind driven by the unified nonlinear Alfvén wave. In this model, the low-frequency Alfvén waves with a broadband spectrum are globally injected at the base of the corona, with the amplitude independent of latitude. The numerical results show that the presence of the Alfvén waves is identified overall in a region away from the equatorial plane, and the waves significantly accelerate the plasma therein to form the fast wind. Near the equatorial plane, a slow wind is generated, and the slowness can be attributed to the absence of Alfvén waves owing to the strong damping at lower altitude. The velocity ratio of both modes, if extrapolated to 1 AU, conforms to the measurements. However, far from the Sun, the temperature of the fast wind is lower than that of its surroundings.

The anisotropy of solar wind turbulence seems to be related with its intermittency. To has a comprehensive understanding of the influence of intermittency on the turbulence anisotropy, Pei *et al.*[3] conducted an innovative research. In this work, they compared the angular dependence of scaling exponents of various orders of structure functions ($\zeta(p,\theta_{RB})$) before and after eliminating the intermittency. It was found that, in contrast to the transition from monofractal to multifractal scaling laws with increasing angles for the original turbulence, the scaling exponents look basically monofractal at all angles for the case after removing the intermittency. Furthermore, they applied the extended structure-function model, illustrating the difference of two key parameters ($\alpha$ as a proxy of the power spectral index and $p_1$ as the fragmentation fraction) between before and after removing intermittency. It is therefore suggested the uneven fragmentation of energy transfer rate is mainly located in the intermittency, which causes the anisotropy of turbulence.

Observations of solar wind turbulence indicate the existence of multiscale Pressure-Balanced Structures (PBSs) in the solar wind. Yang *et al.*[4] conducted a numerical simulation to investigate formation of multiscale PBSs in compressive magnetohydrodynamic turbulence. With a higher-order Godunov code Athena, they simulated a driven compressible turbulence with an imposed uniform guide field. They found that both the magnetic pressure and the thermal pressure exhibit a turbulent spectrum with a Kolmogorov-like power law, and that in many regions of the simulation domain they are anti-correlated, with the total pressure balance. This indicates the existence of multi-scale PBSs in MHD turbulence, with the small PBSs being embedded in the large ones. Also, they found that these multi-scale PBSs are likely to be related to the highly oblique-propagating slow-mode waves. With the same model, they also investigated the influence of the intermittency on the quasi-perpendicular scaling in the inertial range.

By applying the wavelet technique to the magnetic field and velocity to identify intermittency, Yang *et al.*[5] found that as the scale decreases in the simulation, the calculated Probability Distribution Functions (PDF) of the wavelet coefficients become extended on both tails of the non-Gaussian distribution, with a rapid increase in flatness. After intermittency has been removed from the driven turbulence, the quasi-perpendicular scaling for both fluctuations becomes steeper and close to a Kolmogorov –5/3 scaling, which may be a result of the stronger intermittency in the quasi-perpendicular direction and at the smaller scales. Their results suggest that the “background” turbulence seems to have the Kolmogorov.

Yang *et al.*[6] also studied the formation and properties of Tangential Discontinuities (TDs) in compressive MHD turbulence. They first detected sharp interfaces of magnetic and thermal pressure to identify TDs, and got that TDs are seen to separate distinct plasma and magnetic field regions, behaving as the walls of different flux tubes. By analyzing temporal evolution of TD's 3D structure, they found that the mutual approaching, squeezing, and separating of two clumps of the turbulent plasma results in the formation and collapse of the identified TD, with its lifetime of about 4.5 h for typical solar wind parameters. They further isolated each of the formed TDs from the background, and tracked each of them through time. By a statistical analysis of TDs' properties, they found that for typical solar wind parameters, the lifetimes of TDs are far shorter than the time the solar wind takes from the Sun to 1AU, which indicates that TDs observed by in situ satellites at 1AU are more likely to be generated by local turbulence.

The power spectrum of magnetic field in the solar wind turbulence was reported to be anisotropic with respect to the angle ($\theta_{VB}$) between local mean magnetic field ($B_0$) and sampling direction. When the local $B_0$ is nearly parallel (perpendicular) to the sampling direction, the spectral index was found to be close to –2 (–5/3). This result was widely considered as observational evidence for the critical balance theory. However, it was also found that after intermittent structures were removed, the spectral index in the parallel direction turned out to be about –1.6, and the anisotropy disappeared. Wang *et al*.[7] presented a method to guarantee a nearly constant $\theta_{VB}$ in each local time window that is mainly influenced by the mother function of the Morlet wavelet. They find that the –2 spectral index at the parallel angular bin $\theta_{VB} < 6°$ disappears, and the spectral indices become close to –1.5 at all the $\theta_{VB}$ bins. Accordingly, they conclude that the –2 index is caused by the large variation of the local $B_0$, which supports the explanation of the spectral anisotropy as being caused by the intermittency.

At the frequency range from 0.01 Hz to 0.1 Hz, the power spectrum of the fluctuations in the solar wind turbulence was recently observed to be anisotropic with respect to the direction of $B_0$. These observations are considered as evidence for a "critical balance" style cascade. However, Wang *et al*.[8] found that the anisotropy of the spectral index seems to be very weak, if using continuous time series which are time-stationary and have nearly constant local $B_0$. They apply the Fast Fourier Transform (FFT) on these time series selected from the eight-year magnetic field ($B$) and flow velocity ($V$) data observed by the WIND spacecraft in the high-speed solar wind. The results show that the FFT spectral indices of the time series with $B_0$ nearly parallel and perpendicular to the Sun-to-Earth radial direction are not significantly different. This work provides new clues on the nature of the anisotropy of the solar wind turbulence and thus will improve their understanding of the turbulent energy cascade.

The slow solar wind turbulence has recently been considered as fully evolved turbulence which can be described by critical balance theory. However, Tu *et al*.[9] presented two cases of convecting structure that support a different understanding. By using the measurements from WIND spacecraft in the slow solar wind, they find that Elsässer variables $z^{\pm}$ of these two cases do not represent inward and outward Alfvén waves, but are determined mainly by the magnetic variations, including tangentially varying structures. They then propose that the slow wind turbulence may be composed of convecting magnetic-field tangential and directional turnings, as well as current sheets, which may be considered as left-over fossils from Kolmogorov fluid turbulence. The fluid kinetic energy has been damped out, and the remaining magnetic fluctuations thus tend to become force-free structures.

The spectral break ($f_b$) of magnetic fluctuations at the ion scale in the solar wind is considered to give important clue on the turbulence dissipation mechanism. Among several possible mechanisms, the most notable two are related respectively with proton thermal gyroradius ($\rho_i$) and proton inertial length ($d_i$). However, no definite conclusion has been given for which one is more reasonable because the two parameters have similar value when plasma beta $\beta \sim 1$. Wang *et al*.[10] did a statistical study to see if the two ratios $f_b / f\rho_i$ and $f_b / f_{di}$ have different dependence on β in the solar wind turbulence with $0.1 < \beta < 1.3$. From magnetic measurements by the Wind spacecraft, they select 141 data sets with each one longer than 13 h. It is found that the ratio $f_b / f_{di}$ is statistically not dependent on $\beta$, and the average value of it is 0.48±0.06. However, $f_b / f\rho_i$ increases with increasing $\beta$ clearly and is significantly smaller than $f_b / f_{di}$ when $\beta < 0.8$. These new results show that $f_b$ is statistically 0.48 $f_{di}$, and the influence of $\beta$ could be negligible in the studied $\beta$ range. It indicates a preference of the dissipation mechanism associated with $d_i$ in the solar wind with $0.1 < \beta < 0.8$. Further theoretical studies are needed to give detailed explanation.

It has been a long-standing debate on the nature of Elsässer variable $z^-$ observed in the solar wind fluctuations. It is widely believed that $z^-$ represents inward-propagating Alfvén waves and interacts non-linearly with $z^+$ (outward- propagating Alfvén waves) to generate energy cascade. However, $z^-$ variations sometimes show a feature of convective structures. Wang *et al*.[11] presented a new data analysis on auto-correlation functions of $z^-$ in order to get some definite information on its nature. It is found that there is usually a large drop on the $z^-$ auto-correlation function when the solar wind fluctuations are highly Alfvénic. The large drop observed by Helios 2 spacecraft near 0.3 AU appears at the first non-zero time lag tau = 81 s, where the value of the auto-correlation coefficient drops to 25% – 65% of that at tau = 0 s. Beyond the first non-zero time lag, the auto-correlation coefficient decreases gradually to zero. The drop of $z^-$ correlation function also appears in the WIND observations near 1 AU. These features of the $z^-$ correlation function may suggest that $z^-$ fluctuations consist of two components: high-frequency white noise and low-frequency pseudo structures, which correspond to flat and steep parts of $z^-$ power spectrum, respectively. This explanation is confirmed by doing a simple test on an artificial time series, which is obtained from the superposition of a random data series on its smoothed sequence. The results suggest that in the highly Alfvénic fluctuations, $z^-$ may not contribute importantly to the interactions with $z^+$ to produce energy cascade.

The physical parameters of the solar wind observed in-situ near 1 AU have been studied by Yang *et al.*[12] for several decades, and relationships between them, such as the positive correlation between the solar wind plasma temperature, $T$, and velocity, $V$, and the negative correlation between density, $N$, and velocity, $V$, are well known. However, the magnetic field intensity, $B$, does not appear to be well correlated with any individual plasma parameter. In this article, they discussed previously under-reported correlations between $B$ and the combined plasma parameters $(NV^2)^{0.5}$ as well as between $B$ and $(NT)^{0.5}$. These two correlations are strong during periods of corotating interaction regions and high-speed streams, and moderate during intervals of slow solar wind. The results indicate that the magnetic pressure in the solar wind is well correlated both with the plasma dynamic pressure and the thermal pressure.

Multi-order structure functions in the solar wind are reported to display a monofractal scaling when sampled parallel to the local magnetic field and a multifractal scaling when measured perpendicularly. Whether and to what extent will the scaling anisotropy be weakened by the enhancement of turbulence amplitude relative to the background magnetic strength. Based on two runs of the Magnetohydrodynamic (MHD) turbulence simulation with different relative levels of turbulence amplitude, Yang *et al.*[13] investigated and compare the scaling of multi-order magnetic structure functions and magnetic Probability Distribution Functions (PDFs) as well as their dependence on the direction of the local field. The numerical results show that for the case of large-amplitude MHD turbulence, the multi-order structure functions display a multifractal scaling at all angles to the local magnetic field, with PDFs deviating significantly from the Gaussian distribution and a flatness larger than 3 at all angles. In contrast, for the case of small-amplitude MHD turbulence, the multi-order structure functions and PDFs have different features in the quasi- parallel and quasi-perpendicular directions: a monofractal scaling and Gaussian-like distribution in the former, and a conversion of a monofractal scaling and Gaussian-like distribution into a multifractal scaling and non-Gaussian tail distribution in the latter. These results hint that when intermittencies are abundant and intense, the multifractal scaling in the structure functions can appear even if it is in the quasi-parallel direction; otherwise, the monofractal scaling in the structure functions remains even if it is in the quasi-perpendicular direction.

## 3. Filament / Prominence and Jets

Zhang *et al.*[14] investigated the evolutions of two prominences (P1, P2) and two bundles of coronal loops (L1, L2), observed with SDO/AIA near the east solar limb on 2012 September 22. It was found that there were large-amplitude oscillations in P1 and L1 but no detectable motions in P2 and L2. These transverse oscillations were triggered by a large-scale coronal wave, originating from a large flare in a remote active region behind the solar limb. By carefully comparing the locations and heights of these oscillating and non-oscillating structures, they concluded that the propagating height of the wave is between 50 Mm and 130 Mm. The wave energy deposited in the oscillating prominence and coronal loops are at least of the order of 1028 *erg*. Furthermore, local magnetic field strength and Alfvén speeds were derived from the oscillating periods and damping time scales, which were extracted from the time series of the oscillations. It was demonstrated that oscillations can be used in not only coronal seismology, but also to reveal the properties of the wave.

Wang *et al.*[15] report the tornado-like evolution of a quiescent prominence on 2014 November 1. The eastern section of the prominence first rose slowly, transforming into an arch-shaped structure as high as ~150 Mm above the limb; the arch then writhed moderately in a left-handed sense, while the original dark prominence material emitted in the Fe IX 171 Å passband, and a braided structure appeared at the eastern edge of the warped arch. The unraveling of the braided structure was associated with a transient brightening in the EUV and apparently contributed to the formation of a Curtain-Like Structure (CLS). The CLS consisted of myriad thread-like loops rotating counterclockwise about the vertical if viewed from above. Heated prominence material was observed to slide along these loops and land outside the filament channel. The tornado eventually disintegrated and the remaining material flew along a left-handed helical path constituting approximately a full turn, as corroborated through stereoscopic reconstruction, into the cavity of the stable, western section of the prominence. They suggest that the tornado-like evolution of the prominence was governed by the helical kink instability, and that the CLS formed through magnetic reconnections between the prominence field and the overlying coronal field.

Liu *et al.*[16] present detailed analysis of recurrent homologous jets originating from an emerging negative magnetic flux at the edge of an active region. The observed jets show multi-thermal features. Their evolution shows high consistence with the characteristic parameters of the emerging flux, suggesting that with more free magnetic energy, the eruptions tend to be more violent, frequent, and blowout-like. The average temperature, average electron number density, and axial speed are found to be similar for different jets, indicating that they should have been formed by plasmas from similar origins. Statistical analysis of the jets and their foot point region conditions reveals a strong positive relationship between the foot point region total 131 Å intensity enhancement and jets' length/width. Stronger linearly positive relationships also exist between the total intensity enhancement/thermal energy of the foot point regions and jets' mass/kinetic/thermal energy, with higher cross-correlation coefficients. All the above results together confirm the direct relationship between the magnetic reconnection and the jets and validate the important role of magnetic reconnection in transporting large amounts of free magnetic energy into jets. It is also suggested that there should be more free energy released during the magnetic reconnection of blowout than of standard jet events.

Liu *et al.*[17] present the first observation, analysis, and modeling of solar coronal twin jets, which occurred after a preceding jet. Detailed analysis on the kinetics of the preceding jet reveals its blowout-jet nature, which resembles the one studied in Liu *et al.*[16]. However, the erupting process and kinetics of the twin jets appear to be different from the preceding one. Lacking detailed information on the magnetic fields in the twin jet region, they instead used a numerical simulation using a three-dimensional (3D) MHD model and find that in the simulation a pair of twin jets form due to reconnection between the ambient open fields and a highly twisted sigmoidal magnetic flux, which is the outcome of the further evolution of the magnetic fields following the preceding blowout jet. Based on the similarity between the synthesized and observed emission, they propose this mechanism as a possible explanation for the observed twin jets. Combining their observation and simulation, they suggest that with continuous energy transport from the subsurface convection zone into the corona, solar coronal twin jets could be generated in the same fashion addressed above.

Solar filaments/prominences are one of the most common features in the corona, which may lead to energetic Coronal Mass Ejections (CMEs) and flares when they erupt. The physical connections among and formation mechanisms of various components of the prominence-horn cavity system remain elusive. Wang *et al.*[18] present observations of such a system, focusing on a section of the prominence that rises and separates gradually from the main body. This forms a configuration sufficiently simple to yield clues regarding the above issues. It is characterized by embedding horns, oscillations, and a gradual disappearance of the separated material. The prominence-horn structure exhibits a large-amplitude longitudinal oscillation with a period of about 150 minutes and an amplitude of ~30 Mm along the trajectory defined by the concave horn structure. The horns also experience a simultaneous transverse oscillation with a much smaller amplitude (about 3 Mm) and a shorter period (10–15 minutes), likely representative of a global mode of the large-scale magnetic structure. The gradual disappearance of the structure indicated that the horn, an observational manifestation of the field-aligned transition region separating the cool and dense prominence from the hot and tenuous corona, is formed due to the heating and diluting process of the central prominence mass; most previous studies suggested that it is the opposite process, i.e., the cooling and condensation of coronal plasmas, that formed the horn. This study also demonstrated how the prominence transports magnetic flux to the upper corona, a process essential for the gradual build-up of pre-eruption magnetic energy.

Zheng *et al*.[19] reported the interaction of two filaments (F1 and F2) in a long filament channel associated with twin CMEs on 2016 January 26. Before the eruption, a sequence of rapid cancellation and emergence of the magnetic flux has been observed, which likely triggered the ascending of the west filament (F1). The east footpoints of rising F1 moved toward the east far end of the filament channel, accompanied by post-eruption loops and flare ribbons. This likely indicated a large-scale eruption involving the long filament channel, which resulted from the interaction between F1 and the east filament (F2). Some bright plasma flew over F2, and F2 stayed at rest during the eruption, likely due to the confinement of its overlying lower magnetic field. Interestingly, the impulsive F1 pushed its overlying magnetic arcades to form the first CME, and F1 finally evolved into the second CME after the collision with the nearby coronal hole. They suggested that the interaction of F1 and the overlying magnetic field of F2 led to the merging reconnection that forms a longer eruptive filament loop. Their results also provide a possible picture of the origin of twin CMEs and show that the large-scale magnetic topology of the coronal hole is important for the eventual propagation direction of CMEs.

Filaments are about 100 times cooler and denser than the coronal material, and physical understanding of their material origin remains controversial. Two types of scenarios have been proposed: one argues that the filament plasma is brought into the corona from photosphere or chromosphere through a siphon or evaporation/injection process, while the other suggests that the material condenses from the surrounding coronal plasma due to thermal instability. The elemental abundance analysis is a reasonable clue to constrain the models, as the siphon or evaporation/injection model would predict that the filament material abundances are close to the photospheric or chromospheric ones, while the condensation model should have coronal abundances. Song *et al*.[20] analyzed the elemental abundances of a magnetic cloud that contains the ejected filament material. The corresponding filament eruption occurred on 1998 April 29, accompanying an M6.8 class soft X-ray flare located at the heliographic coordinates S18E20 (NOAA 08210) and a fast halo CME with the linear velocity of 1374 $km\cdot s^{-1}$ near the Sun. They found that the abundance ratios of elements with low and high first ionization potential such as Fe/O, Mg/O, and Si/O are 0.150, 0.050, and 0.070, respectively, approaching their corresponding photospheric values 0.065, 0.081, and 0.066, which does not support the coronal origin of the filament plasma.

The cold-dense plasma is occasionally detected in the solar wind with in situ data, but the source of the cold-dense plasma remains illusive. Interchange Reconnections (IRs) between closed fields and nearby open fields are known to contribute to the formation of solar winds. Zheng *et al*.[21] presented a confined filament eruption associated with a puff-like CME on 2014 December 24. The filament underwent successive activations and finally erupted, due to continuous magnetic flux cancelations and emergences. The confined erupting filament showed a clear untwist motion, and most of the filament material fell back. During the eruption, some tiny blobs escaped from the confined filament body, along newly formed open field lines rooted around the south end of the filament, and some bright plasma flowed from the north end of the filament to remote sites at nearby open fields. The newly formed open field lines shifted southward with multiple branches. The puff-like CME also showed multiple bright fronts and a clear southward shift. All the results indicated an intermittent IR existed between closed fields of the confined erupting filament and nearby open fields, which released a portion of filament material (blobs) to form the puff-like CME. They suggested that the IR provides a possible source of cold-dense plasma in the solar wind.

## 4. Solar Flare

The Solar Dynamics Observatory (SDO)/EUV Variability Experiment (EVE) provides rich information on the thermodynamic processes of solar activities, particularly on solar flares. Here, Wang *et al*.[22] develop a method to construct ThermoDynamic Spectrum (TDS) charts based on the EVE spectral lines. This tool could potentially be useful for Extreme UltraViolet (EUV) astronomy to learn about the eruptive activities on distant astronomical objects. Through several cases, they illustrate what they can learn from the TDS charts. Furthermore, they apply the TDS method to 74 flares equal to or greater than the M5.0 class, and reach the following statistical results. First, EUV peaks are always behind the Soft X-Ray (SXR) peaks and stronger flares tend to have faster cooling rates. There is a power-law correlation between the peak delay times and the cooling rates, suggesting a coherent cooling process of flares from SXR to EUV emissions. Second, there are two distinct temperature drift patterns, called Type I and Type II. For Type I flares, the enhanced emission drifts from high to low temperature like a quadrilateral, whereas for Type II flares the drift pattern looks like a triangle. Statistical analysis suggests that Type II flares are more impulsive than Type I flares. Third, for late-phase flares, the peak intensity ratio of the late phase to the main phase is roughly correlated with the flare class, and the flares with a strong late phase are all confined. They believe that the re-deposition of the energy carried by a flux rope, which unsuccessfully erupts out, into thermal emissions is responsible for the strong late phase found in a confined flare. Furthermore, they show the signatures of the flare thermodynamic process in the chromosphere and transition region in the TDS charts. These results provide new clues to advance their understanding of the thermodynamic processes of solar flares and associated solar eruptions, *e.g.*, coronal mass ejections.

The 2011 January 28 M1.4 flare exhibits two side-by-side candle-flame-shaped flare loop systems underneath a larger cusp-shaped structure during the decay phase, as observed at the northwestern solar limb by the Solar Dynamics Observatory. The northern loop system brightens following the initiation of the flare within the southern loop system, but all three cusp-shaped structures are characterized by about 10 MK temperatures, hotter than the arch shaped loops underneath. The “Ahead” satellite of the Solar Terrestrial Relations Observatory provides a top view, in which the post-flare loops brighten sequentially, with one end fixed while the other apparently slipping eastward. By performing stereoscopic reconstruction of the post-flare loops in EUV and mapping out magnetic connectivities, Gou *et al.*[23] found that the foot points of the post-flare loops are slipping along the footprint of a Hyperbolic Flux Tube (HFT) separating the two loop systems and that the reconstructed loops share similarity with the magnetic field lines that are traced starting from the same HFT footprint, where the field lines are relatively flexible. These results argue strongly in favor of slipping magnetic reconnection at the HFT. The slipping reconnection was likely triggered by the flare and manifested as propagative dimmings before the loop slippage is observed. It may contribute to the late-phase peak in Fe XVI 33.5 nm, which is even higher than its main-phase counterpart, and may also play a role in the density and temperature asymmetry observed in the northern loop system through heat conduction.

Typical solar flares display two quasi-parallel, bright ribbons on the chromosphere. In between is the Polarity Inversion Line (PIL) separating concentrated magnetic fluxes of opposite polarity in Active Regions (ARs). Intriguingly a series of flares exhibiting X-shaped ribbons occurred at the similar location on the outskirts of NOAA AR 11967, where magnetic fluxes were scattered, yet three of them were alarmingly energetic. The X shape, whose center coincided with hard X-ray emission, was similar in UV/EUV, which cannot be accommodated in the standard flare model. Mapping out magnetic connectivities in potential fields, Liu *et al.*[24] found that the X morphology was dictated by the intersection of two quasi-separatrix layers, *i.*e., a Hyperbolic Flux Tube (HFT), within which a separator connecting a double null was embedded. This topology was not purely local but regulated by fluxes and flows over the whole AR. The nonlinear force-free field model suggested the formation of a current layer at the HFT, where the current dissipation can be mapped to the X-shaped ribbons via field-aligned heat conduction. These results highlight the critical role of HFTs in 3D magnetic reconnection and have important implications for astrophysical and laboratory plasmas.

Corona structures and processes during the pre-impulsive stage of solar eruption are crucial to understanding the physics leading to the subsequent explosive energy release. Wu *et al.*[25] report the first microwave imaging study of a hot flux rope structure during the pre-impulsive stage of an eruptive M7.7 solar flare, with the Nobeyama Radioheliograph (NoRH) at 17 GHz. The flux rope is also observed by the SDO/AIA in its hot passbands of 94 and 131 Å. In the microwave data, it is revealed as an overall arcade-like structure consisting of several intensity enhancements bridged by generally weak emissions, with brightness temperatures ($T_B$) varying from 10 000 K to 20,000 K. Locations of microwave intensity enhancements along the structure remain relatively fixed at certain specific parts of the flux rope, indicating that the distribution of emitting electrons is affected by the large-scale magnetic configuration of the twisted flux rope. Wavelet analysis shows a pronounced 2-minute period of the microwave $T_B$ variation during the pre-impulsive stage of interest. The period agrees well with that reported for AIA sunward-contracting loops and upward ejective plasmoids (suggested to be reconnection outflows). This suggests that both periodicities are controlled by the same reconnection process that takes place intermittently at a 2-minute timescale. They inferred that at least a part of the emission is excited by non-thermal energetic electrons via the gyro-synchrotron mechanism. The study demonstrated the potential of microwave imaging in exploring the flux rope magnetic geometry and relevant reconnection process during the onset of solar eruption.

With the observations of the SDO, Zheng *et al*. [26] presented the slipping magnetic reconnections with multiple Flare Ribbons (FRs) during an X1.2 eruptive flare on 2014 January 7. A center negative polarity was surrounded by several positive ones, and three FRs appeared. The three FRs showed apparent slipping motions, and hook structures formed at their ends. Due to the moving foot points of the erupting structures, one tight semi-circular hook disappeared after the slippage along its inner and outer edges, and coronal dimmings formed within the hook. The east hook also faded as a result of the magnetic reconnection between the arcades of a remote filament and a hot loop that was impulsively heated by the under flare loops. Their results are accordant with the slipping magnetic reconnection regime in three-dimensional standard model for eruptive flares. They suggested that the complex structures of the flare are likely a consequence of the more complex flux distribution in the photosphere, and the eruption involves at least two magnetic reconnections.

Double-coronal Hard X-Ray (HXR) sources are believed to be critical observational evidence of bi-directional energy release through magnetic reconnection in large-scale current sheets in solar flares. Chen *et al*.[27] presented a study on double-coronal sources observed in both HXR and microwave regimes, revealing new characteristics distinct from earlier reports. This event is associated with a footpoint-occulted X1.3-class flare (2014 April 25, starting at 00:17 UT) and a coronal mass ejection that were likely triggered by the magnetic breakout process, with the lower source extending upward from the top of the partially occulted flare loops and the upper source co-incident with rapidly squeezing-in side lobes (at a speed of 250 km·s$^{-1}$ on both sides). The upper source can be identified at energies as high as 70–100 keV. The X-ray upper source is characterized by flux curves that differ from those of the lower source, a weak energy dependence of projected centroid altitude above 20 keV, a shorter duration, and an HXR photon spectrum slightly harder than those of the lower source. In addition, the microwave emission at 34 GHz also exhibits a similar double-source structure and the microwave spectra at both sources are in line with gyro-synchrotron emission given by non-thermal energetic electrons. These observations, especially the co-incidence of the very-fast squeezing-in motion of side lobes and the upper source, indicated that the upper source is associated with (and possibly caused by) this fast motion of arcades. This shed new light on the origin of the corona double-source structure observed in both HXRs and microwaves.

Solar Post-Flare Loops (PFLs) are arcade-like loop systems that appear during the gradual phases of eruptive flares. The Extreme UltraViolet (EUV) observations from the Atmospheric Imaging Assembly (AIA) on board the Solar Dynamics Observatory (SDO) allow us to investigate the fine structures in PFLs. Song *et al*.[28] focused on studying the Dark Post-Flare Loops (DPFLs) during X-class flares, which are more evident in SDO/AIA data than in previous EUV data. They identified and analyzed the DPFLs observed by SDO and found that: (1) the DPFLs of an X5.4 flare have an average lifetime of 10.0±5.5minutes, an average width of 1022±339 km, and an average maximum length of 33±10 Mm, (2) blob-like falling features with a size close to the resolution of SDO/AIA are identified in the DPFLs and have an average velocity of 76±19 km·s$^{-1}$, and (3) the average widths of the DPFLs slightly increase with the characteristic temperatures in the AIA 304, 171, 193, and 211 Å channels. Their investigation showed that DPFLs are found in all of the 20 cases within this study, which suggests that they are a common phenomenon in X-class flares and are probably produced by the same mechanism that creates coronal rain.

Jiang *et al*.[29] studied the physical mechanism of a major X-class solar flare that occurred in the super NOAA Active Region (AR) 12192 using a data-driven numerical Magnetohydrodynamic (MHD) modeling complemented with observations. With the evolving magnetic fields observed at the solar surface as bottom boundary input, they drove an MHD system to evolve self-consistently in correspondence with the realistic coronal evolution. During a two-day time interval, the modeled coronal field has been slowly stressed by the photospheric field evolution, which gradually created a large-scale coronal current sheet, *i.e.*, a narrow layer with intense current, in the core of the AR. The current layer was successively enhanced until it became so thin that a tether-cutting reconnection between the sheared magnetic arcades was set in, which led to a flare. The modeled reconnecting field lines and their foot points match well the observed hot flaring loops and the flare ribbons suggesting that the model has successfully "reproduced" the macroscopic magnetic process of the flare. In particular, with simulation, they explained why this event is a confined eruption–the consequent of the reconnection is the shared arcade instead of a newly formed flux rope. They also found much weaker magnetic implosion effect comparing to many other X-class flares.

## 5. Radio Bursts

Solar coronal radio bursts are enhanced radio emission excited by energetic electrons accelerated during solar eruptions. Studying these bursts is important for investigating the origin and physical mechanism of energetic particles and further diagnosing coronal parameters. Earlier studies suffered from a lack of simultaneous high-quality imaging data of the radio burst and the eruptive structure in the inner corona. Feng *et al.*[30] presented a study on a complex solar radio eruption consisting of a type II burst and three reversely drifting type III bursts, using simultaneous EUV and radio imaging data. It is found that the type II burst is closely associated with a propagating and evolving CME-driven EUV shock structure, originated initially at the northern shock flank and later transferred to the top part of the shock. This source transfer is coincident with the presence of shock decay and enhancing signatures observed at the corresponding side of the EUV front. The electron energy accelerated by the shock at the flank is estimated to be ~0.3 c by examining the imaging data of the fast-drifting herringbone structure of the type II burst. The reverse-drifting type III sources are found to be within the ejecta and correlated with a likely reconnection event therein. The implications for further observational studies and relevant space weather forecasting techniques are discussed.

First-of-its-kind radio imaging of a decameter solar stationary type IV radio burst has been presented by Koval *et al.*[31]. On 2014 September 6 the observations of type IV burst radio emission were carried out with the two-dimensional heliograph based on the Ukrainian T-shaped radio telescope (UTR-2), together with other telescope arrays. Starting at ~09:55 UT and for ~3 h, the radio emission was kept within the observational session of UTR-2. The interesting observation covered the full evolution of this burst, "from birth to death." During the event lifetime, two C-class solar X-ray flares with peak times 11:29 UT and 12:24 UT took place. The time profile of this burst in radio has a double-humped shape that can be explained by injection of energetic electrons, accelerated by the two flares, into the burst source. According to the heliographic observations, they suggested that the burst source was confined within a high coronal loop, which was part of a relatively slow coronal mass ejection. The latter has been developed for several hours before the onset of the event. Through analysis of about $1.5\times10^6$ heliograms (3700 temporal frames with 4096 images in each frame that correspond to the number of frequency channels), the radio burst source imaging shows a fascinating dynamical evolution. Both space-based (GOES, SDO, SOHO, STEREO) data and various ground-based instrumentation (ORFEES, NDA, RSTO, NRH) records have been used for this study.

Type III and type-III-like radio bursts are produced by energetic electron beams guided along coronal magnetic fields. As a variant of type III bursts, Type N bursts appear as the letter "N" in the radio dynamic spectrum and reveal a magnetic mirror effect in coronal loops. Kong *et al.*[32] reported a well-observed N-shaped burst consisting of three successive branches at metric wavelength with both fundamental and harmonic components and a high brightness temperature ($>10^9$ K). They verified the burst as a true type N burst generated by the same electron beam from three aspects of the data. First, durations of the three branches at a given frequency increase gradually and may be due to the dispersion of the beam along its path. Second, the flare site, as the only possible source of non-thermal electrons, is near the western feet of large-scale closed loops.

Third, the first branch and the following two branches are localized at different legs of the loops with opposite senses of polarization. They also found that the sense of polarization of the radio burst is in contradiction to the O-mode and there exists a fairly large time delay (3—5 s) between the fundamental and harmonic components. Possible explanations accounting for these observations are presented. Assuming the classical plasma emission mechanism, they can infer coronal parameters such as electron density and magnetic field near the radio source and make diagnostics on the magnetic mirror process.

Hot-Channel (HC) structure, observed in the high-temperature passbands of the Atmospheric Imaging Assembly/Solar Dynamic Observatory, is regarded as one candidate of coronal flux rope that is an essential element of solar eruptions. Vasanth *et al*.[33] presented the first radio imaging study of an HC structure in the metric wavelength. The associated radio emission manifests as a moving type-IV (t-IVm) burst. They showed that the radio sources co-move outward with the HC, indicating that the t-IV emitting energetic electrons are efficiently trapped within the structure. The t-IV sources at different frequencies present no considerable spatial dispersion during the early stage of the event, while the sources spread gradually along the eruptive HC structure at later stage with significant spatial dispersion. The t-IV bursts are characterized by a relatively high brightness temperature ($10^7$—$10^9$K), a moderate polarization, and a spectral shape that evolves considerably with time. This study demonstrates the possibility of imaging the eruptive HC structure at the metric wavelength and provides strong constraints on the t-IV emission mechanism, which, if understood, can be used to diagnose the essential parameters of the eruptive structure.

Type-I bursts (*i.e.* noise storms) are the earliest-known type of solar radio emission at the meter wavelength. They are believed to be excited by non-thermal energetic electrons accelerated in the corona. The underlying dynamic process and exact emission mechanism still remain unresolved. With a combined analysis of Extreme UltraViolet (EUV), radio and photospheric magnetic field data of unprecedented quality recorded during a type-I storm on 30 July 2011, Li *et al*.[34] identified a good correlation between the radio bursts and the co-spatial EUV and magnetic activities. The EUV activities manifest themselves as three major brightening stripes above a region adjacent to a compact sunspot, while the magnetic field there presents multiple Moving Magnetic Features (MMFs) with persistent coalescence or cancelation and a morphologically similar three-part distribution. They found that the type-I intensities are correlated with those of the EUV emissions at various wavelengths with a correlation coefficient of 0.7–0.8. In addition, in the region between the brightening EUV stripes and the radio sources there appear consistent dynamic motions with a series of bi-directional flows, suggesting ongoing small-scale reconnection there. Mainly based on the induced connection between the magnetic motion at the photosphere and the EUV and radio activities in the corona, they suggested that the observed type-I noise storms and the EUV brightening activities are the consequence of small-scale magnetic reconnection driven by MMFs. This is in support of the original proposal made by Bentley *et al*.

Koval *et al*.[35] presented an in-depth study into spectral perturbations appearing in solar dynamic spectra and being manifestations of the focusing effect of low-frequency solar emission by the Earth's ionosphere. Such perturbations are considered to be the result of radio waves focusing by Medium Scale Traveling Ionospheric Disturbances (MSTIDs). Using the Nançay Decametric Array (NDA) data set, they have conducted a statistical analysis of the spectral structures in solar dynamic spectra within 10–80 MHz. They have detected the spectral structures in the NDA spectral data for 129 observation days from 1999 to 2015. On spectrograms they appear as intensity variations different from well-known solar radio bursts. The sharp edges with enhanced intensity are distinctive characteristics of the structures for most events. Due to this spectral feature, they are termed as Spectral Caustics (SCs). Koval *et al*. have classified the SCs observed by the NDA as several types, based on their spectral morphology, namely: inverted V like, V like, X like, fiber like, and fringe like. They have found that the rate of occurrence of SCs in dynamic spectra depends on the phase of the solar cycle. About 81% of all days with detected SCs fall on active phases of solar cycles 23 and 24 (48% and 33%, respectively). They have also established the seasonal dependence in occurrence of the SCs. It was found that about 95% of days with SCs belong to autumn-winter months, whereas only near 5% of days with SCs belong to spring-summer months. This is well correlated with the reported dependence in MSTID occurrence rate.

Lv *et al.*[36] reported the well-observed event of a multi-lane type II solar radio burst with a combined analysis of radio dynamic spectra and radio and Extreme-UltraViolet (EUV) imaging data. The burst is associated with an EUV wave driven by a Coronal Mass Ejection (CME) that is accompanied by a GOES X-ray M7.9 flare on 5 November 2014. This type of event is rarely observed with such a complete data set. The type II burst presents three episodes (referred to as A, B, and C), characterized by a sudden change in spectral drift, and contains more than ten branches, including both Harmonic-Fundamental (H-F) pairs and split bands. The sources of the three episodes present a general outward propagating trend. There exists a significant morphology change from single source (Episode A) to double source (Episode B). Episode C maintains the double-source morphology at 150 MHz (no imaging data are available at a lower frequency). The double-source centroids are separated by about 300" to 500". The SouthEastern (SE) source is likely the continuation of the source of Episode A since both are at the same section of the shock (i.e. the EUV wave) and close to each other. The Northwestern (NW) source is coincident with (thus, possibly originates from) the interaction of the shock with a nearby mini-streamer-like structure. Comparing the simultaneously observed sources of the F and H branches of Episode A, they found that their centroids are separated by less than 200". The centroids of the split bands of Episode B are co-spatial within the observational uncertainties. This study shows the source evolution of a multi-lane type II burst and the source locations of different lanes relative to each other and to the EUV wave generated by a CME. The study indicates the intrinsic complexity underlying a type II dynamic spectrum.

## 6. Particle Acceleration at Coronal Shocks

Kong *et al.*[37] studied the effect of large-scale coronal magnetic field on the electron acceleration at a spherical coronal shock using a test-particle method. The coronal field is approximated by an analytical solution with a streamer-like magnetic field featured by partially open magnetic field and a current sheet at the equator atop the closed region. It showed that the closed field plays the role of a trapping agency of shock-accelerated electrons, allowing for repetitive reflection and acceleration, therefore can greatly enhance the shock-electron acceleration efficiency. It was found that, with an *ad hoc* pitch-angle scattering, electron injected in the open field at the shock flank can be accelerated to high energies as well. In addition, if the shock is faster or stronger, a relatively harder electron energy spectrum and a larger maximum energy can be achieved.

Using a test-particle simulation, Kong *et al.*[38] investigated the effect of large-scale coronal magnetic fields on electron acceleration at an outward-propagating coronal shock with a circular front. The coronal field is approximated by an analytical solution with a streamer-like magnetic field featuring a partially open magnetic field and a current sheet at the equator atop the closed region. They showed that the large-scale shock-field configuration, especially the relative curvature of the shock and the magnetic field line across which the shock is sweeping, plays an important role in the efficiency of electron acceleration. At low shock altitudes, when the shock curvature is larger than that of the magnetic field lines, the electrons are mainly accelerated at the shock flanks; at higher altitudes, when the shock curvature is smaller, the electrons are mainly accelerated at the shock nose around the top of closed field lines. The above process reveals the shift of the efficient electron acceleration region along the shock front during its propagation. They also found that, in general, the electron acceleration at the shock flank is not as efficient as that at the top of the closed field because a collapsing magnetic trap can be formed at the top. In addition, they found that the energy spectra of electrons are power-law-like, first hardening then softening with the spectral index varying in a range of –3 to –6. Physical interpretations of the results and implications for the study of solar radio bursts are discussed.

Earlier observations have shown that coronal shocks driven by coronal mass ejections can develop and accelerate particles within several solar radii in large Solar Energetic Particle (SEP) events. Motivated by this, Kong *et al.*[39] presented an SEP acceleration study that including the process in which a fast shock propagates through a streamer-like magnetic field with both closed and open field lines in the low corona region. The acceleration of protons is modeled by numerically solving the Parker transport equation with spatial diffusion both along and across the magnetic field. They showed that particles can be sufficiently accelerated to up to several hundred MeV within 2–3 solar radii. When the shock propagates through a streamer-like magnetic field, particles are more efficiently accelerated compared to the case with a simple radial magnetic field, mainly due to perpendicular shock geometry and the natural trapping effect of closed magnetic fields. Their results suggest that the coronal magnetic field configuration is an important factor for producing large SEP events. They further showed that the coronal magnetic field configuration strongly influences the distribution of energetic particles, leading to different locations of source regions along the shock front where most high-energy particles are concentrated. This work may have strong implications for SEP observations. The upcoming Parker Solar Probe will provide in situ observations for the distribution of energetic particles in the coronal shock region, and test the results of the study.

## 7. Magnetic Flux Ropes

The magnetic flux rope is among the most fundamental magnetic configurations in plasma. Although its presence after solar eruptions has been verified by spacecraft measurements near Earth, its formation on the Sun remains elusive, yet is critical to understand a broad spectrum of phenomena. Wang *et al.*[40] study the dynamic formation of a magnetic flux rope during a classic two-ribbon flare. Its feet are identified unambiguously with conjugate coronal dimmings completely enclosed by irregular bright rings, which originate and expand outward from the far ends of flare ribbons. The expansion is associated with the rapid ribbon separation during the flare main phase. Counting magnetic flux through the feet and the ribbon-swept area reveals that the rope's core is more twisted than its average of four turns. It propagates to the Earth as a typical magnetic cloud possessing a similar twist profile obtained by the Grad-Shafranov reconstruction of its three dimensional structure.

Magnetic Flux Ropes (MFRs) are one kind of fundamental structures in the solar/space physics and involved in various eruption phenomena. Twist, characterizing how the magnetic field lines wind around a main axis, is an intrinsic property of MFRs, closely related to the magnetic free energy and stableness. Although the effect of the twist on the behavior of MFRs had been widely studied in observations, theory, modeling, and numerical simulations, it is still unclear how much amount of twist is carried by MFRs in the solar atmosphere and in heliosphere and what role the twist played in the eruptions of MFRs. Contrasting to the solar MFRs, there are lots of in situ measurements of Magnetic Clouds (MCs), the large-scale MFRs in interplanetary space, providing some important information of the twist of MFRs. Thus, starting from MCs, Wang *et al.*[41] investigate the twist of interplanetary MFRs with the aid of a velocity-modified uniform-twist force-free flux rope model. It is found that most of MCs can be roughly fitted by the model and nearly half of them can be fitted fairly well though the derived twist is probably overestimated by a factor of 2.5. By applying the model to 115 MCs observed at 1 AU, they find that (1) the twist angles of interplanetary MFRs generally follow a trend of about 0.6 l/R radians, where l/R is the aspect ratio of a MFR, with a cutoff at about $12\pi$ radians AU−1, (2) most of them are significantly larger than $2.5\pi$ radians but well bounded by 2 1 /R radians, (3) strongly twisted magnetic field lines probably limit the expansion and size of MFRs, and (4) the magnetic field lines in the legs wind more tightly than those in the leading part of MFRs. These results not only advance their understanding of the properties and behavior of interplanetary MFRs but also shed light on the formation and eruption of MFRs in the solar atmosphere. A discussion about the twist and stableness of solar MFRs are therefore given.

Liu *et al.*[42] investigate the evolution of NOAA Active Region (AR) 11817 during 2013 August 10–12, when it developed a complex field configuration and produced four confined, followed by two eruptive, flares. These C-and-above flares are all associated with a Magnetic Flux Rope (MFR) located along the major polarity inversion line, where shearing and converging photospheric flows are present. Aided by the nonlinear force-free field modeling, they identify the MFR through mapping magnetic connectivities and computing the twist number for each individual field line. The MFR is moderately twisted and has a well-defined boundary of high squashing factor $Q$. They found that the field line with the extremum is a reliable proxy of the rope axis, and that the MFR's peak temporarily increases within half an hour before each flare while it decreases after the flare peak for both confined and eruptive flares. This pre-flare increase in twist number has little effect on the AR's free magnetic energy or any other parameters derived for the whole region, due to its moderate amount and the MF's relatively small volume, while its decrease after flares is clearly associated with the stepwise decrease in the whole region's free magnetic energy due to the flare. They suggest that twist number may serve as a useful parameter in forewarning the onset of eruption, and therefore, the consequent space weather effects. The helical kink instability is identified as the prime candidate onset mechanism for the considered flares.

Since only the magnetic conditions at the photosphere can be routinely observed in current observations, it is of great significance to determine the influences of photospheric magnetic conditions on solar eruptive activities. Previous studies about catastrophe indicated that the magnetic system consisting of a flux rope in a partially open bipolar field is subject to catastrophe, but not if the bipolar field is completely closed under the same specified photospheric conditions. In order to investigate the influence of the photospheric magnetic conditions on the catastrophic behavior of this system, Zhang *et al*.[43] expand upon the 2.5-dimensional ideal magnetohydrodynamic model in Cartesian coordinates to simulate the evolution of the equilibrium states of the system under different photospheric flux distributions. Their simulation results reveal that a catastrophe occurs only when the photospheric flux is not concentrated too much toward the polarity inversion line and the source regions of the bipolar field are not too weak; otherwise no catastrophe occurs. As a result, under certain photospheric conditions, a catastrophe could take place in a completely closed configuration, whereas it ceases to exist in a partially open configuration. This indicates that whether the background field is completely closed or partially open is not the only necessary condition for the existence of catastrophe, and that the photospheric conditions also play a crucial role in the catastrophic behavior of the flux rope system.

2.5-dimensional time-dependent ideal Magnetohydrodynamic (MHD) models in Cartesian coordinates were used in previous studies to seek MHD equilibria involving a magnetic flux rope embedded in a bipolar, partially open background field. As demonstrated by these studies, the equilibrium solutions of the system are separated into two branches: the flux rope sticks to the photosphere for solutions at the lower branch but is suspended in the corona for those at the upper branch. Moreover, a solution originally at the lower branch jumps to the upper, as the related control parameter increases and reaches a critical value, and the associated jump is here referred to as an upward catastrophe. Zhang *et al*.[44] advance these studies in three aspects. First, the magnetic field is changed to be force-free; the system still experiences an upward catastrophe with an increase in each control parameter. Second, under the force-free approximation, there also exists a downward catastrophe, characterized by the jump of a solution from the upper branch to the lower. Both catastrophes are irreversible processes connecting the two branches of equilibrium solutions so as to form a cycle. Finally, the magnetic energy in the numerical domain is calculated. It is found that there exists a magnetic energy release for both catastrophes. The Ampère's force, which vanishes everywhere for force-free fields, appears only during the catastrophes and does positive work, which serves as a major mechanism for the energy release. The implications of the downward catastrophe and its relevance to solar activities are briefly discussed.

A flux rope event observed in the magnetotail exhibits a double-peaked core field feature as reported by Liu *et al*.[45]. The generation of such double-peaked feature within the flux rope is explored with Hall-MHD simulations and theoretical analysis based on multiple X line reconnection. Simulations with a guide field produce flux ropes bounded by two active X lines in the thin current sheet. The guide field, combined with Hall-generated field, leads to a donut-shaped core field (having a double-peaked profile) near the magnetic separatrix. Subsequently, it rotates into the central region of the flux rope, which tends to be the force-free configuration. The analysis shows that there are three major factors affecting the evolution of the core field, including the guide field, convective, and Hall terms originating from the generalized Ohm's law. The convective term can become stronger near the central region of flux rope, and the Hall term dominates the region next to the separatrix during the early stages of the flux rope evolution. It implies that several different factors contribute to the generation of the double-peaked core field. The results may help explain a variety of core fields available in magnetotail flux ropes.

In the solar atmosphere, jets are ubiquitous at various spatial-temporal scales. They are important for understanding the energy and mass transports in the solar atmosphere. According to recent observational studies, the high-speed network jets are likely to be intermittent but continual sources of mass and energy for the solar wind. Yang *et al*.[46] conducted a 2D magnetohydrodynamics simulation to investigate the mechanism of these network jets. A combination of magnetic flux emergence and horizontal advection is used to drive the magnetic reconnection in the transition region between a strong magnetic loop and a background open flux. The simulation results show that not only a fast warm jet, much similar to the network jets, is found, but also an adjacent slow cool jet, mostly like classical spicules, is launched. Differing from the fast warm jet driven by magnetic reconnection, the slow cool jet is mainly accelerated by gradients of both thermal pressure and magnetic pressure near the outer border of the mass-concentrated region compressed by the emerging loop. These results provide a different perspective on their understanding of the formation of both the slow cool jets from the solar chromosphere and the fast warm jets from the solar transition region.

## 8. Instability

Using two-dimensional simulations, Tian & Chen[47] numerically explored the dependences of Kelvin-Helmholtz (KH) instability upon various physical parameters, including viscosity, the width of the sheared layer, flow speed, and magnetic field strength. In most cases, a multi-vortex phase exists between the initial growth phase and the final single-vortex phase. The parametric study shows that the evolutionary properties, such as phase duration and vortex dynamics, are generally sensitive to these parameters, except in certain regimes. An interesting result is that for supersonic flows, the phase durations and saturation of velocity growth approach constant values asymptotically as the sonic Mach number increases. They confirmed that the linear coupling between magnetic field and KH modes is negligible if the magnetic field is weak enough. The morphological behavior suggests that the multi-vortex coalescence might be driven by the underlying wave-wave interaction. Based on these results, they presented a preliminary discussion of several events observed in the solar corona. The numerical models need to be further improved to perform a practical diagnostic of the coronal plasma properties.

## 9. Instrument

Observation and research on solar radio emission have unique scientific value in solar and space physics and related space weather forecasting applications, since the observed spectral structures may carry important information about energetic electrons and underlying physical mechanisms. Du *et al*.[48] presented the design of a novel dynamic spectrograph that has been installed at the Chashan Solar Radio Observatory operated by the Laboratory for Radio Technologies, Institute of Space Sciences at Shandong University. The spectrograph is characterized by real-time storage of digitized radio intensity data in the time domain and its capability to perform off-line spectral analysis of the radio spectra. The analog signals received via antennas and amplified with a low-noise amplifier are converted into digital data at a speed reaching up to 32 k data points per millisecond. The digital data are then saved into a high-speed electronic disk for further off-line spectral analysis. Using different word lengths (1–32 k) and time cadences (5 ms–10 s) for off-line fast Fourier transform analysis, they can obtain the dynamic spectrum of a radio burst with different (user-defined) temporal (5 ms–10 s) and spectral (3–320 kHz) resolutions. This enables great flexibility and convenience in data analysis of solar radio bursts, especially when some specific fine spectral structures are under study.

## 10. Coronal Mass Ejection and Their Interplanetary Counterparts

Coronal mass ejection, as the most violent disturbance in the solar and heliosphere space, is found to be able to trigger and drive the turbulence developing in its ambient regions, *e.g*., the flank and wake regions of the CME. This new observation has recently been reported by Fan *et al*.[49]. The CME event is characterized with the ejection of a hot blob with the temperature as high as 10 MK. As impacted by the CME, the adjacent magnetic structures were strong distorted, leading to the initiation of turbulence featured by the enhancement of Doppler-shift oscillations from 3 km/s to 15 km/s and the effective thermal velocities from ±30 km/s to ±60 km/s. Moreover, the Doppler-shift maps from the CoMP instrument illustrate wave-like torsional oscillations at lower altitudes, and more random motions at higher altitudes. In association with the development of turbulence, the disturbed solar atmosphere gas was found to be heated significantly with the evidence from the time evolution of differential-emission-measure profiles, which indicates a drop-out of cool materials due to ejection and a significant increase of hot components probably due to heating process. This work hence sheds new light the turbulence-heating scenario of the solar corona and solar wind.

What happens during the impact of fast shock into the magnetic cloud is an interesting question but remains unclear at present. As motivated by this question, Mao *et al.*[50] conducted a numerical simulation to study the consequence of the impact. In their model, a pair of fast shocks is created due to the set of the boundary condition. The forward shock is propagating, relative to the background plasmas, at a speed about twice that of the perpendicular fast magnetosonic speed. Due to the high speed of propagation of fast shock, it catches up and takes over the MC during the simulation which lasts more than tens of hours in physical time. It is found that, due to the penetration of fast shock, the MC is highly compressed and significantly heated, leading to the increase of the temperature growth rate by a factor of 10 and the increased velocity to about half of the shock speed. The magnetic reconnection between the MC and the ambient magnetic fields is also sped up by a factor of two to four, leading to the significant erosion of the MC magnetic flux.

Solar Active Regions (ARs) are the major sources of two of the most violent solar eruptions, namely flares and Coronal Mass Ejections (CMEs). The largest AR in the past 24 years, NOAA AR 12192, which crossed the visible disk from 2014 October 17 to 30, unusually produced more than one hundred flares, including 32 M-class and 6 X-class ones, but only one small CME. Flares and CMEs are believed to be two phenomena in the same eruptive process. Why is such a flare-rich AR so CME-poor? Liu *et al.*[51] compared this AR with other four ARs; two were productive in both and two were inert. The investigation of the photospheric parameters based on the SDO/HMI vector magnetogram reveals that the flare-rich AR 12192, as with the other two productive ARs, has larger magnetic flux, current, and free magnetic energy than the two inert ARs but, in contrast to the two productive ARs, it has no strong, concentrated current helicity along both sides of the flaring neutral line, indicating the absence of a mature magnetic structure consisting of highly sheared or twisted field lines. Furthermore, the decay index above the AR 12192 is relatively low, showing strong constraint. These results suggest that productive ARs are always large and have enough current and free energy to power flares, but whether or not a flare is accompanied by a CME is seemingly related to (1) the presence of a mature sheared or twisted core field serving as the seed of the CME, or (2) a weak enough constraint of the overlying arcades.

Liu *et al.*[52] identified the magnetic source locations of 142 Quasi-Homologous (QH) Coronal Mass Ejections (CMEs), of which 121 are from solar cycle (SC) 23 and 21 from SC 24. Among those CMEs, 63% originated from the same source location as their predecessor (defined as S-type), while 37% originated from a different location within the same active region as their predecessor (defined as D-type). Their distinctly different waiting time distributions, peaking around 7.5 and 1.5 h for S- and D-type CMEs, suggest that they might involve different physical mechanisms with different characteristic timescales. Through detailed analysis based on nonlinear forcefree coronal magnetic field modeling of two exemplary cases, they propose that the S-type QH CMES might involve a recurring energy release process from the same source location (by magnetic free energy replenishment), whereas the D-type QH CMEs can happen when a flux tube system is disturbed by a nearby CME.

Shen *et al.*[53] have proved the collision between solar Coronal Mass Ejections (CMEs) could be super-elastic from the observations and numerical simulations. This finding suggests that the CMEs' magnetic energy and thermal energy could be converted into kinetic energy through a more efficient way. However CME collisions are not always super-elastic, which means that this distinct property of plasmoids is probably excited conditionally. As the first attempt, they carry out a series of three-dimensional numerical experiments, and establish a diagram showing the dependence of the collision nature on the CME speed and k-number, the ratio of the CME's kinetic energy to the CME's total energy. It is found that the super-elastic nature of CMEs appears at the relatively low approaching speed, and most of the previous case studies are in agreement with this diagram. Their study firmly advances the understanding of the super-elastic property of plasmoids, and does give us new clues to deeply understand why and how the magnetic energy and/or thermal energy of the colliding plasmoids can be converted into kinetic energy in such an efficient way

Observational and numerical studies have shown that the kinematic characteristics of two or more Coronal Mass Ejections (CMEs) may change significantly after a CME collision. The collision of CMEs can have different natures, *i.e*. inelastic, elastic, and superelastic processes, depending on their initial kinematic characteristics. In this article, Shen *et al*.[54] first review the existing definitions of collision types including Newton's classical definition, the energy definition, Poisson's definition, and Stronge's definition, of which the first two were used in the studies of CME–CME collisions. Then, they review the recent research progresses on the nature of CME–CME collisions with the focus on which CME kinematic properties affect the collision nature. It is shown that observational analysis and numerical simulations can both yield an inelastic, perfectly inelastic, merging-like collision, or a high possibility of a superelastic collision. Meanwhile, previous studies based on a 3D collision picture suggested that a low approaching speed of two CMEs is favorable for a superelastic nature. Since CMEs are an expanding magnetized plasma structure, the CME collision process is quite complex, and they discuss this complexity. Moreover, the models used in both observational and numerical studies contain many limitations. All of the previous studies on collisions have not shown the separation of two colliding CMEs after a collision. Therefore the collision between CMEs cannot be considered as an ideal process in the context of a classical Newtonian definition. In addition, many factors are not considered in either observational analysis or numerical studies, e.g. CME-driven shocks and magnetic reconnections. Owing to the complexity of the CME collision process, a more detailed and in-depth observational analysis and simulation work are needed to fully understand the CME collision process.

Successive and interacting Coronal Mass Ejections (CMEs) directed earthward can have significant impacts throughout geospace. While considerable progress has been made in understanding their geomagnetic consequences over the past decade, elucidation of their atmospheric consequences remains a challenge. During 17–19 January 2005, a compound stream formed due to interaction of six successive halo CMEs impacted Earth's magnetosphere. Guo *et al.*[55] report one atmospheric consequence of this impact, namely, the prolonged multiple excitation of large-scale (>~1000 km) Traveling Atmospheric Disturbances (TADs). The TADs were effectively excited in auroral regions by sudden injections of energy due to the intermittent southward magnetic fields within the stream. They propagated toward the equator at speeds near 800 m/s and produced long-duration (~2.5 days) continuous large-scale density disturbances of order up ± 40% in the global thermosphere.

The largest geomagnetic storm so far, called 2015 St. Patrick's Day event, in the solar cycle 24 was produced by a fast Coronal Mass Ejection (CME) originating on 15 March 2015. It was an initially west-oriented CME and expected to only cause a weak geomagnetic disturbance. Why did this CME finally cause such a large geomagnetic storm? Wang *et al.*[56] try to find some clues by investigating its propagation from the Sun to 1 AU. First, they reconstruct the CME's kinematic properties in the corona from the SOHO and Solar Dynamics Observatory imaging data with the aid of the graduated cylindrical shell model. It is suggested that the CME propagated to the west ~33"±10" away from the Sun-Earth line with a speed of about 817 km·s$^{-1}$ before leaving the field of view of the SOHO/Large Angle and Spectrometric Coronagraph (LASCO) C3 camera. A Magnetic Cloud (MC) corresponding to this CME was measured in situ by the Wind spacecraft 2 days after the CME left LASCO's field of view. By applying two MC reconstruction methods, they infer the configuration of the MC as well as some kinematic information, which implies that the CME possibly experienced an eastward deflection on its way to 1 AU. However, due to the lack of observations from the STEREO spacecraft, the CME's kinematic evolution in interplanetary space is not clear. In order to fill this gap, they utilize numerical MHD simulation, Drag-Based CME propagation Model (DBM) and the model for CME Deflection in Inter-Planetary Space (DIPS) to recover the propagation process, especially the trajectory, of the CME from 30RS to 1 AU under the constraints of the derived CME's kinematics near the Sun and at 1 AU. It is suggested that the trajectory of the CME was deflected toward the Earth by about 12°, consistent with the implication from the MC reconstruction at 1AU. This eastward deflection probably contributed to the CME's unexpected geoeffectiveness by pushing the center of the initially west-oriented CME closer to the Earth.

Although the dynamical evolution of Magnetic

Clouds (MCs) has been one of the foci of interplanetary physics for decades, only few studies focus on the internal properties of large-scale MCs. Recent work by Wang *et al*. suggested the existence of the poloidal plasma motion in MCs. However, the main cause of this motion is not clear. In order to find it, Zhao *et al*.[57] identify and reconstruct the MC observed by the Solar Terrestrial Relations Observatory (STEREO)-A, Wind, and STEREO-B spacecraft during 19 – 20 November 2007 with the aid of the velocity-modified cylindrical force-free flux rope model. They analyze the plasma velocity in the plane perpendicular to the MC axis. It is found that there was evident poloidal motion at Wind and STEREO-B, but this was not clear at STEREO-A, which suggests a local cause rather than a global cause for the poloidal plasma motion inside the MC. The rotational directions of the solar wind and MC plasma at the two sides of the MC boundary are found to be consistent, and the values of the rotational speeds of the solar wind and MC plasma at the three spacecraft show a rough correlation. All of these results illustrate that the interaction with ambient solar wind through viscosity might be one of the local causes of the poloidal motion. Additionally, they propose another possible local cause: the existence of a pressure gradient in the MC. The significant difference in the total pressure at the three spacecraft suggests that this speculation is perhaps correct.

An interesting phenomenon, plasma poloidal motion, has been found in many Magnetic Clouds (MCs), and viscosity has been proposed as a possible mechanism. However, it is not clear how significant the role of viscosity is in generating such motion. Zhao *et al*.[58] conduct a statistical study of the MCs detected by the Wind spacecraft during 1995–2012. It is found that, for 19% of all the studied MCs (186), the poloidal velocities of the MC plasma near the MC boundaries are well correlated with those of the corresponding ambient solar wind plasma. A non-monotonic increase from inner to outer MCs suggests that the viscosity does play a role, albeit weak, on the poloidal motion in the MC statistically. The possible dependence on the solar wind parameters is then studied in detail for the nine selected crossings, which represent the viscosity characteristic. There is an evident negative correlation between the viscosity and the density, a weak negative correlation between the viscosity and the turbulence strength, and no clear correlation between the viscosity and the temperature.

As one of the most violent astrophysical phenomena, Coronal Mass Ejections (CMEs) have strong potential space weather effects. However, not all Earth-directed CMEs encounter the Earth and produce geo-effects. One reason is the deflected propagation of CMEs in interplanetary space. Although there have been several case studies clearly showing such deflections, it has not yet been statistically assessed how significantly the deflected propagation would influence the CME's arrival at Earth. Zhuang *et al*.[59] develop an integrated CME-Arrival Forecasting (iCAF) system, assembling the modules of CME detection, three-dimensional (3D) parameter derivation, and trajectory reconstruction to predict whether or not a CME arrives at Earth, and they assess the deflection influence on the CME-arrival forecasting. The performance of iCAF is tested by comparing the two-dimensional (2D) parameters with those in the Coordinated Data Analysis Workshop (CDAW) Data Center catalog, comparing the 3D parameters with those of the gradual cylindrical shell model, and estimating the success rate of the CME Earth arrival predictions. It is found that the 2D parameters provided by iCAF and the CDAW catalog are consistent with each other, and the 3D parameters derived by the ice cream cone model based on single-view observations are acceptable. The success rate of the CME-arrival predictions by iCAF with deflection considered is about 82%, which is 19% higher than that without deflection, indicating the importance of the CME deflection for providing a reliable forecasting. Furthermore, iCAF is a worthwhile project since it is a completely automatic system with deflection taken into account.

Chi *et al*.[60] establish a catalog of Interplanetary Coronal Mass Ejections (ICMEs) during the period from 1995 to 2015 using the in-situ observations from the Wind and ACE spacecraft. Based on this catalog, they extend the statistical properties of ICMEs to the maximum phase of Solar Cycle 24. They confirm previous results that the yearly occurrence frequencies of ICMEs and shocks, the ratios of ICMEs driving shocks are correlated with the sunspot numbers. For the Magnetic Cloud (MC), they confirm that the yearly occurrence frequencies of MCs do not show any correlation with sunspot numbers. The highest MC ratio of ICME occurred near the solar minimum. In addition, they analyzed the yearly variation of the ICME parameters. They found that the ICME velocities, the magnetic-field strength, and their related parameters are varied in pace with solar-cycle variation. At the solar maximum, ICMEs move faster and carry a stronger magnetic field. By comparing the parameters between MCs and non-MC ejecta, they confirm the result that the magnetic-field intensities of MC are higher than those in non-MC ejecta. Furthermore, they also discuss the forward shocks driven by ICMEs. They find that one half of the ICMEs have upstream shocks and ICMEs with shocks have faster speed and higher magnetic-field strength than the ICMEs without shocks. The magnetic-field parameters and solar-wind plasma parameters in the shock sheath regions are higher than those in the ejecta regions of ICMEs from a statistical point of view.

The fundamental mechanism initiating Coronal Mass Ejections (CMEs) remains controversial. One of the leading theories is magnetic breakout, in which magnetic reconnection occurring high in the corona removes the confinement on an energized low-corona structure from the overlying magnetic field, thus allowing it to erupt. Chen *et al*.[61] reported critical observational evidence of this elusive breakout reconnection in a multi-polar magnetic configuration that leads to a CME and an X-class, long-duration flare. Its occurrence is supported by the presence of pairs of heated cusp-shaped loops around an X-type null point and signatures of reconnection inflows. Other peculiar features new to the breakout picture include sequential loop brightening, coronal hard X-rays at energies up to ~100 keV, and extended high-corona X-rays above the later restored multi-polar structure. These observations, from a novel perspective with clarity never achieved before, present crucial clues to understanding the initiation mechanism of solar eruptions

Jets are defined as impulsive, well-collimated upflows, occurring in different layers of the solar atmosphere with different scales. Their relationship with CMEs remains elusive. Using high-quality imaging data from the SDO/AIA, Zheng *et al*.[62] showed a well- observed coronal jet event, in which the part of the jet with embedding coronal loops runs into a nearby Coronal Hole (CH) and gets bounced in the opposite direction. This is evidenced by the flat shape of the jet front during its interaction with the CH and the V-shaped feature in the time-slice plot of the interaction region. About a half-hour later, a CME with an initially narrow and jet-like front is observed by the LASCO C2 coronagraph propagating along the direction of the post- collision jet. They also observed some 304 Å dark material flowing from the jet-CH interaction region toward the CME. They thus suggested that the jet and the CME are physically connected, with the jet-CH collision and the large-scale magnetic topology of the CH being important in defining the eventual propagating direction of this particular jet-CME eruption.

Magnetic Clouds (MCs) are the interplanetary counterparts of coronal magnetic flux ropes. They can provide valuable information regarding flux rope characteristics at their eruption stage in the corona, which is unable to be explored in situ at present. Song *et al*.[63] made a comprehensive survey of the average iron charge-state (<*Q*>Fe) distributions inside 96 MCs for solar cycle 23 using Advanced Composition Explorer (ACE) data. Since the (<*Q*>Fe) in the solar wind are typically around 9+ to 11+, the Fe charge state is defined as being high when the (<*Q*>Fe) is larger than 12$^+$, which implies the existence of a considerable amount of Fe ions with high charge states (*e.g.*, $\geqslant 16^+$). The statistical results show that the (<*Q*>Fe) distributions of 92 (~96%) MCs can be classified into four groups with different characteristics. In group A (11 MCs), the (<*Q*>Fe) shows a bi-modal distribution with both peaks being higher than 12+. Group B (4 MCs) presents a unimodal distribution of (<*Q*>Fe), with its peak being higher than 12+. In groups C (29 MCs) and D (48 MCs), the (<*Q*>Fe) remains higher and lower than 12$^+$ throughout ACE's passage through the MC, respectively. Possible explanations of these distributions are discussed.

CMEs often exhibit the typical three-part structure in the corona when observed with white-light coronagraphs, *i.e*., the bright leading front, dark cavity, and bright core, corresponding to a high-low-high density sequence. As CMEs result from eruptions of Magnetic Flux Ropes (MFRs), which can possess either lower (*e.g*., coronal-cavity MFRs) or higher (*e.g*., hot-channel MFRs) density compared to their surroundings in the corona, the traditional opinion regards the three-part structure as the manifestations of coronal plasma pileup (high density), coronal-cavity MFR (low density), and filament (high density) contained in the trailing part of MFR, respectively. Song *et al*.[64] demonstrated that filament-unrelated CMEs can also exhibit the classical three-part structure. The observations were made from different perspectives through an event that occurred on

2011 October 4. The CME cavity corresponds to the low-density zone between the leading front and the high-density core, and it is obvious in the low corona and gradually becomes fuzzy when propagating outward. The bright core corresponds to a high-density structure that is suggested to be an erupting MFR. The MFR is recorded from both edge-on and face-on perspectives, exhibiting different morphologies that are due to projection effects. They stressed that the zone (MFR) with lower (higher) density in comparison to the surroundings can appear as the dark cavity (bright core) when observed through white-light coronagraphs, which is not necessarily the coronal-cavity MFR (erupted filament).

Hu *et al.*[65] analyzed multi-spacecraft observations associated with the 2012 July 12 coronal mass (CME), covering the source region on the Sun from the Solar Dynamics Observatory, stereoscopic imaging observations from the Solar Terrestrial Relations Observatory (STEREO), magnetic field characteristics from Mercury Surface, Space Environment, Geochemistry, and Ranging (MESSENGER), and type II radio burst and in situ measurements from Wind. A triangulation method based on STEREO stereoscopic observations is employed to determine the kinematics of the CME, and the outcome is compared with the results derived from the type II radio burst using a solar wind electron density model. A Grad–Shafranov technique is applied to Wind in situ data to reconstruct the flux-rope structure and compare it with the observations of the solar source region, which helps in understanding the geo-effectiveness associated with the CME structure. Their conclusions are as follows: (1) the CME undergoes an impulsive acceleration, a rapid deceleration before reaching MESSENGER, and then a gradual deceleration out to 1 AU, which should be considered in CME kinematics models; (2) the type II radio burst was probably produced from a high-density interaction region between the CME-driven shock and a nearby streamer or from the shock flank with lower heights, which implies uncertainties in the determination of CME kinematics using solely type II radio bursts; (3) the flux-rope orientation and chirality deduced from in situ reconstructions at Wind agree with those obtained from solar source observations; (4) the prolonged southward magnetic field near the Earth is mainly from the axial component of the largely southward inclined flux rope, which indicates the importance of predicting both the flux-rope orientation and magnetic field components in geomagnetic activity forecasting.

Zhu *et al.*[66] studied the Solar Energetic Particle (SEP) event associated with the 2012 July 23 extreme solar storm, for which Solar Terrestrial Relations Observatory (STEREO) and the spacecraft at L1 provide multi-point remote sensing and in situ observations. The extreme solar storm, with a superfast shock and extremely enhanced ejecta magnetic fields observed near 1 au at STEREO A, was caused by the combination of successive Coronal Mass Ejections (CMEs). Meanwhile, energetic particles were observed by STEREO and near-Earth spacecraft such as the Advanced Composition Explorer and SOlar and Heliospheric Observatory, suggesting a wide longitudinal spread of the particles at 1 AU. Combining the SEP observations with in situ plasma and magnetic field measurements, they investigated the longitudinal distribution of the SEP event in connection with the associated shock and CMEs. Their results underscore the complex magnetic configuration of the inner heliosphere formed by solar eruptions. Examination of particle intensities, proton anisotropy distributions, element abundance ratios, magnetic connectivity, and spectra also gives important clues for particle acceleration, transport, and distribution.

The 2015 March 15 coronal mass ejection as one of the two that together drove the largest geomagnetic storm of solar cycle 24 so far was associated with sympathetic filament eruptions. Wang *et al.*[67] investigated the relations between the different filaments involved in the eruption. A surge-like small-scale filament motion is confirmed as the trigger that initiated the erupting filament with multi-wavelength observations and using a forced magnetic field extrapolation method. When the erupting filament moved to an open magnetic field region, it experienced an obvious acceleration process and was accompanied by a C-class flare and the rise of another larger filament that eventually failed to erupt. They measured the decay index of the background magnetic field, which presents a critical height of 118 Mm. Combining with a potential field source surface extrapolation method, they analyzed the distributions of the large-scale magnetic field, which indicates that the open magnetic field region may provide a favorable condition for $F_2$ rapid acceleration and have some relation with the largest solar storm. The comparison between the successful and failed filament eruptions suggests that the confining magnetic field plays an important role in the preconditions for an eruption.

As a follow-up study on Sun-to-Earth propagation of fast Coronal Mass Ejections (CMEs), Liu *et al*.[68] examined the Sun-to-Earth characteristics of slow CMEs combining heliospheric imaging and in situ observations. Three events of particular interest, the 2010 June 16, 2011 March 25, and 2012 September 25 CMEs, are selected for this study. They compared slow CMEs with fast and intermediate-speed events, and obtained key results complementing the attempt of Liu *et al*. to create a general picture of CME Sun-to-Earth propagation: (1) the Sun-to-Earth propagation of a typical slow CME can be approximately described by two phases, a gradual acceleration out to about 20–30 solar radii, followed by a nearly invariant speed around the average solar wind level; (2) comparison between different types of CMEs indicates that faster CMEs tend to accelerate and decelerate more rapidly and have shorter cessation distances for the acceleration and deceleration; (3) both intermediate-speed and slow CMEs would have speeds comparable to the average solar wind level before reaching 1 AU; (4) slow CMEs have a high potential to interact with other solar wind structures in the Sun–Earth space due to their slow motion, providing critical ingredients to enhance space weather; and (5) the slow CMEs studied here lack strong magnetic fields at the Earth but tend to preserve a flux-rope structure with an axis generally perpendicular to the radial direction from the Sun. They also suggest a “best” strategy for the application of a triangulation concept in determining CME Sun-to-Earth kinematics, which helps to clarify confusions about CME geometry assumptions in the triangulation and to improve CME analysis and observations.

Wang *et al*.[69] presented an analysis of Solar Dynamics Observatory (SDO) observations of an X1.4 class flare on 12 July 2012 (SOL2012-07-12T15: 37L082C105), which was associated with a pronounced sunspot rotation in the associated active region. Based on the magnetograms taken with the Helioseismic and Magnetic Imager (HMI) on the SDO, they measured the rotational speed of the sunspot. They also used a technique, called the differential affine velocity estimator for vector magnetograms (DAVE4VM), to determine the horizontal velocities and the magnetic helicity flux transport. The helicity flux rate due to shearing motion changed sign after the onset of the eruption. A high correlation between the sunspot rotation speed and the change in the total accumulated helicity was found. They also calculated the net fluxes of the respective magnetic polarities and the net vertical currents. The net current in the region of interest showed a synchronous change with the sunspot rotation rate. The magnetic configurations of the sigmoid filament in the active region and the associated possible interaction between different structures were further investigated by means of a nonlinear force-free field extrapolation. They identified a possible magnetic reconnection region from the three-dimensional magnetic fields and its association with EUV structures. These results suggest that the major eruption of this active region was connected with the sunspot rotation.

Hu *et al*.[70] investigated the coronal and interplanetary evolution of a Coronal Mass Ejection (CME) launched on 2010 September 4 from a source region linking two Active Regions (ARs), 11101 and 11103, using extreme ultraviolet imaging, magnetogram, white-light, and in situ observations from SDO, STEREO, SOHO, VEX, and Wind. A potential-field source-surface model is employed to examine the configuration of the coronal magnetic field surrounding the source region. The graduated cylindrical shell model and a triangulation method are applied to determine the kinematics of the CME in the corona and interplanetary space. From the remote sensing and in situ observations, they obtained some key results: (1) the CME was deflected in both the eastward and southward directions in the low corona by the magnetic pressure from the two ARs, and possibly interacted with another ejection, which caused that the CME arrived at VEX that was longitudinally distant from the source region; (2) although VEX was closer to the Sun, the observed and derived CME arrival times at VEX are not earlier than those at Wind, which suggests the importance of determining both the frontal shape and propagation direction of the CME in interplanetary space; and (3) the ICME was compressed in the radial direction while the longitudinal transverse size was extended.

Liu *et al*.[71] examined the propagation and interaction properties of three successive Coronal Mass Ejections (CMEs) from 2001 November 21–22, with a focus on their connection with the behaviors of the associated long-duration complex type II radio burst. In combination with coronagraph and multi-point in situ observations, the long-duration type II burst provides key features for resolving the propagation and interaction complexities of the three CMEs. The two CMEs from November 22 interacted first and then overtook the November 21 CME at a distance of about 0.85 AU from the Sun. The timescale for the shock originally driven by the last CME to propagate through the preceding two CMEs is estimated to be about 14 and 6 hr, respectively. They present a simple analytical model without any free parameters to characterize the whole Sun-to-Earth propagation of the shock, which shows a remarkable consistency with all the available data and MHD simulations even out to the distance of Ulysses (2.34 AU). The coordination of in situ measurements at the Earth and Ulysses, which were separated by about 71°.4 in latitude, gives important clues for the understanding of shock structure and the interpretation of in situ signatures. The results also indicate a means by which to increase geo-effectiveness with multiple CMEs, which can be considered as another manifestation of the "perfect storm" scenario proposed by Liu *et al*., although the current case is not "super" in the same sense as the 2012 July 23 event.

Liu *et al*.[72] examined the structure, propagation, and expansion of the shock associated with the 2012 July 23 extreme coronal mass ejection. Characteristics of the shock determined from multi-point imaging observations are compared to in situ measurements at different locations and a complex radio type II burst, which according to their definition has multiple branches that may not all be fundamental-harmonic related. The white-light shock signature can be modeled reasonably well by a spherical structure and was expanding backward even on the opposite side of the Sun. The expansion of the shock, which was roughly self-similar after the first ~1.5 h from launch, largely dominated over the translation of the shock center for the time period of interest. Their study also suggests a bow shock morphology around the nose at later times due to the outward motion in combination with the expansion of the ejecta. The shock decayed and failed to reach Mercury in the backward direction and the Solar Terrestrial Relations Observatory B (STEREO B) and Venus in the lateral directions, as indicated by the imaging and in situ observations. The shock in the nose direction, however, may have persisted to the far outer heliosphere, with predicted impact on Dawn around 06:00 UT on July 25 and on Jupiter around 23:30 UT on July 27 by a magnetohydrodynamic model. The type II burst shows properties generally consistent with the spatial/temporal variations of the shock deduced from imaging and in situ observations. In particular, the low-frequency bands agree well with the in situ measurements of a very low density ahead of the shock at STEREO A.

Propagation of CMEs from the Sun far into interplanetary space is not well understood, due to limited observations. Zhao *et al.*[73] examined the propagation characteristics of two geo-effective CMEs, which occurred on 2005 May 6 and 13, respectively. Significant heliospheric consequences associated with the two CMEs are observed, including ICMEs at the Earth and Ulysses, interplanetary shocks, a long-duration type II radio burst, and intense geomagnetic storms. They used coronagraph observations from SOHO/LASCO, frequency drift of the long-duration type II burst, in situ measurements at the Earth and Ulysses, and Magnetohydrodynamic propagation of the observed solar wind disturbances at 1 AU to track the CMEs from the Sun far into interplanetary space. They found that both of the CMEs underwent a major deceleration within 1 AU and thereafter a gradual deceleration when they propagated from the Earth to deep interplanetary space, due to interactions with the ambient solar wind. The results also reveal that the two CMEs interacted with each other in the distant interplanetary space even though their launch times on the Sun were well separated. The intense geomagnetic storm for each case was caused by the southward magnetic fields ahead of the CME, stressing the critical role of the sheath region in geomagnetic storm generation, although for the first case there is a corotating interaction region involved.

Liu *et al*.[74] presented an investigation of the rotation and nonradial motion of a CME from AR 12468 on 2015 December 16 using observations from SDO, SOHO, STEREO A, and Wind. The EUV and HMI observations of the source region show that the associated Magnetic Flux Rope (MFR) axis pointed to the east before the eruption. They used a NonLinear Force-Free Field (NLFFF) extrapolation to determine the configuration of the coronal magnetic field and calculate the magnetic energy density distributions at different heights. The distribution of the magnetic energy density shows a strong gradient toward the northeast. The propagation direction of the CME from a Graduated Cylindrical Shell (GCS) modeling deviates from the radial direction of the source region by about 45° in longitude and about 30° in latitude, which is consistent with the gradient of the magnetic energy distribution around the AR. The MFR axis determined by the GCS modeling points southward, which has rotated counterclockwise by about 95° compared with the orientation of the MFR in the low corona. The MFR reconstructed by a Grad–Shafranov (GS) method at 1 AU has almost the same orientation as the MFR from the GCS modeling, which indicates that the MFR rotation occurred in the low corona. It is the rotation of the MFR that caused the intense geomagnetic storm with the minimum Dst of −155 nT. These results suggest that the coronal magnetic field surrounding the MFR plays a crucial role in the MFR rotation and propagation direction.

The prediction of the arrival time for fast Coronal Mass Ejections (CMEs) and their associated shocks is highly desirable in space weather studies. Zhao *et al.*[75] used two shock propagation models, *i.e.*, Data Guided Shock Time Of Arrival (DGSTOA) and Data Guided Shock Propagation Model (DGSPM), to predict the kinematical evolution of interplanetary shocks associated with fast CMEs. DGSTOA is based on the similarity theory of shock waves in the solar wind reference frame, and DGSPM is based on the non-similarity theory in the stationary reference frame. The inputs are the kinematics of the CME front at the maximum speed moment obtained from the geometric triangulation method applied to STEREO imaging observations together with the Harmonic Mean approximation. The outputs provide the subsequent propagation of the associated shock. They applied these models to the CMEs on 2012 January 19, January 23, and March 7. They found that the shock models predict reasonably well the shock's propagation after the impulsive acceleration. The shock's arrival time and local propagation speed at Earth predicted by these models are consistent with in situ measurements of WIND. They also employed the Drag-Based Model (DBM) as a comparison, and found that it predicts a steeper deceleration than the shock models after the rapid deceleration phase. The predictions of DBM at 1 AU agree with the following ICME or sheath structure, not the preceding shock. These results demonstrate the applicability of the shock models used here for future arrival time prediction of interplanetary shocks associated with fast CMEs.

The angular width of a CME is an important factor in determining whether the corresponding ICME and its preceding shock will reach Earth. However, there have been very few studies of the decisive factors of the CME's angular width. Zhao *et al.*[76] used the three- dimensional (3D) angular width of CMEs obtained from the Graduated Cylindrical Shell model based on observations of STEREO to study the relations between the CME's 3D width and characteristics of the CME's source region. They found that for the CMEs produced by Active Regions (ARs), the CME width has some correlations with the AR's area and flux, but these correlations are not strong. The magnetic flux contained in the CME seems to come from only part of the AR's total flux. For the CMEs produced by flare regions, the correlations between the CME angular width and the flare region's area and flux are strong. The magnetic flux within those CMEs seems to come from the whole flare region or even from a larger region than the flare. Their findings show that the CME's 3D angular width can be generally estimated based on observations of Solar Dynamics Observatory (SDO) for the CME's source region instead of the observations from coronagraphs on board the Solar and Heliospheric Observatory (SOHO) and STEREO if the two foot points of the CME stay in the same places with no expansion of the CME in the transverse direction until reaching Earth.

The in-flight performance of the Coriolis/SMEI and STEREO/HI instruments substantiates the high-technology readiness level of White-Light (WL) imaging of Coronal Mass Ejections (CMEs) in the inner heliosphere. The WL intensity of a propagating CME is jointly determined by its evolving mass distribution and the fixed Thomsonscattering geometry. From their in-ecliptic viewpoints, SMEI and HI, the only heliospheric imagers that have been flown to date, integrate the longitudinal dimension of CMEs. Using forward magnetohydrodynamic modeling, Xiong *et al.*[77] synthesized the WL radiance pattern of a typical halo CME viewed from an Out-Of-Ecliptic (OOE) vantage point. The major anatomical elements of the CME identified in WL imagery are a leading sheath and a trailing ejecta; the ejecta-driven sheath is the brightest feature of the CME. The sheath, a three-dimensional (3D) dome-like density structure, occupies a wide angular extent ahead of the ejecta itself. The 2D radiance pattern of the sheath depends critically on viewpoint. For a CME modeled under solar minimum conditions, the WL radiance pattern of the sheath is generally a quasi-straight band when viewed from an in-ecliptic viewpoint and a semicircular arc from an OOE viewpoint. The dependence of the radiance pattern of the ejecta-driven sheath on viewpoint is attributed to the bimodal nature of the 3D background solar wind flow. Their forward-modeling results suggest that OOE imaging in WL radiance can enable (1) a near-ecliptic CME to be continuously tracked from its coronal initiation, (2) the longitudinal span of the CME to be readily charted, and (3) the transporting speed of the CME to be reliably determined. Additional WL polarization measurements can significantly limit the ambiguity of localizing CMEs. They asserted that a panoramic OOE view in WL would be highly beneficial in revealing CME morphology and kinematics in the hitherto-unresolved longitudinal dimension and hence for monitoring the propagation and evolution of near-ecliptic CMEs for space weather operations.

## 11. Magnetohydrodynamic (MHD) Numerical Modeling

Wu *et al.*[78] presented a three-dimensional magnetohydrodynamic model based on an observed eruptive twisted flux rope (sigmoid) deduced from solar vector magnetograms. This model is a combination of their two very well tested MHD models: (1) data-driven 3-D Magnetohydrodynamic (MHD) active region evolution (MHD-DARE) model for the reconstruction of the observed flux rope and (2) 3-D MHD Global Coronal-Heliosphere Evolution (MHD-GCHE) model to track the propagation of the observed flux rope. The 6 September 2011, AR11283, event is used to test this model. First, the formation of the flux rope (sigmoid) from AR11283 is reproduced by the MHD-DARE model with input from the measured vector magnetograms given by Solar Dynamics Observatory/Helioseismic and Magnetic Imager. Second, these results are used as the initial boundary condition for their MHD- GCHE model for the initiation of a Coronal Mass Ejection (CME) as observed. The model output indicates that the flux rope resulting from MHD-DARE produces the physical properties of a CME, and the morphology resembles the observations made by STEREO/COR-1.

The photospheric vector magnetograms obtained by Helioseismic and Magnetic Imager on-board the Solar Dynamics Observatory are used by Jiang *et al.*[79] as boundary conditions for a CESE-MHD model to investigate some photosphere characteristics around the time of a confined flare in solar active region NOAA AR11117. They reported their attempt of characterizing a more realistic solar atmosphere by including plasma with temperature stratified from the photosphere to the corona in the CESE-MHD model. The resulted photospheric transverse flow is comparable to the apparent movements of the magnetic flux features that demonstrates shearing and rotations. They calculated the relevant parameters such as the magnetic energy flux and helicity flux, and with analysis of these parameters, they found that magnetic non-potentiality is transported across the photosphere into the corona in the simulated time interval, which might provide a favorable condition for producing the flare.

Solar eruptions are well-recognized as major drivers of space weather but what causes them remains an open question. Jiang *et al.*[80] show how an eruption is initiated in a non-potential magnetic flux-emerging region using magnetohydrodynamic modelling driven directly by solar magnetograms. Their model simulates the coronal magnetic field following a long-duration quasi-static evolution to its fast eruption. The field morphology resembles a set of extreme ultraviolet images for the whole process. Study of the magnetic field suggests that in this event, the key transition from the pre-eruptive to eruptive state is due to the establishment of a positive feedback between the upward expansion of internal stressed magnetic arcades of new emergence and an external magnetic reconnection which triggers the eruption. Such a nearly realistic simulation of a solar eruption from origin to onset can provide important insight into its cause, and also has the potential for improving space weather modelling.

To develop a high performance MHD numerical simulation method is an important factor in research of numerical prediction of space weather. The upwind flux splitting scheme based on finite volume method has good ability to capture discontinuities. Steger-Warming and AUSM (Advection Upstream Splitting Method) schemes are two outstanding upwind flux splitting scheme, which are classified as FVS (Flux Vector Splitting) method. These two schemes are applied by Zhang and Li[81] to solve the Extended Generalized Lagrange Multiplier Magnetohydrodynamics (EGLM-MHD) equation with Galilean invariance. Results obtained from Orszag-Tang vortex and three-dimensional blast wave problem indicate that those two schemes are both robust and accurate. Particularly, AUSM scheme is superior to Steger-Warming scheme in divergence error control and computational speed.

MHD numerical simulation is an important tool for space physics research. Liu and Li[82] employed the Lax-Friderchs scheme with TVD property to solve

GLMMHD equations. The diffusion turning coefficient is introduced for scheme optimization. Simulation result of 2D rotor test and magnetic cloud current sheet interaction test demonstrates GLM-MHD method's divergence control capability. The simulation consumes less than half of the computational time comparing with simulation utilizing Poisson correction method. While numerical stability is not damaged, numerical diffusion is reduced by the diffusion tuning coefficient.

To synthesize the WL radiance patterns of CIRs from an Out-Of-Ecliptic (OOE) vantage point, Xiong *et al*.[83] performed a forward magnetohydrodynamic modeling of the 3D inner heliosphere during Carrington Rotation CR1967 at solar maximum. The mixing effects associated with viewing 3D Corotating Interaction Regions (CIRs) are significantly minimized from an OOE viewpoint. Their forward modeling results demonstrate that Out-Of-Ecliptic (OOE) White Light (WL) imaging from a latitude greater than 60° can (1) enable the gardenhose spiral morphology of CIRs to be readily resolved, (2) enable multiple coexisting CIRs to be differentiated, and (3) enable the continuous tracing of any interplanetary CIR back toward its coronal source. In particular, an OOE view in WL can reveal where nascent CIRs are formed in the extended corona and how these CIRs develop in interplanetary space. Therefore, a panoramic view from a suite of wide-field WL imagers in a solar polar orbit would be invaluable in unambiguously resolving the large-scale longitudinal structure of CIRs in the 3D inner heliosphere.

Yang *et al*.[84] gave a high-order space–time Conservation Element and Solution Element (CESE) method with a most compact stencil for Magnetohydrodynamics (MHD) equations. This is the first study to extend the second-order CESE scheme to a high order for MHD equations. In the CESE method, the conservative variables and their spatial derivatives are regarded as the independent marching quantities, making the CESE method significantly different from the Finite Difference Method (FDM) and finite volume method (FVM). To utilize the characteristics of the CESE method to the maximum extent possible, their proposed method based on the least-squares method fundamentally keeps the magnetic field divergence-free. The results of some test examples indicate that this new method is very efficient.

A second-order path-conservative scheme with Godunov-type Finite Volume Method (FVM) has been implemented by Feng *et al*.[85] to advance the equations of single-fluid solar wind plasma Magnetohydrodynamics (MHD) in time. This code operates on the six-component composite grid system in 3D spherical coordinates with hexahedral cells of quadrilateral frustum type. The generalized Osher-Solomon Riemann solver is employed based on a numerical integration of the path-dependent dissipation matrix. For simplicity, the straight line segment path is used and the path-integral is evaluated in a fully numerical way by high-order numerical Gauss-Legendre quadrature. Besides its closest similarity to Godunov, the resulting scheme retains the attractive features of the original solver: it is nonlinear, free of entropy-fix, differentiable and complete in that each characteristic field results in a different numerical viscosity, due to the full use of the MHD eigen structure. By using a minmod limiter for spatial oscillation control, the path conservative scheme is realized for the Generalized Lagrange Multiplier (GLM) and the Extended Generalized Lagrange Multiplier (EGLM) formulation of solar wind MHD systems. This new model of second-order in space and time is written in FORTRAN language with Message Passing Interface (MPI) parallelization, and validated in modeling time-dependent large-scale structure of solar corona, driven continuously by the Global Oscillation Network Group (GONG) data. To demonstrate the suitability of their code for the simulation of solar wind, they presented selected results from October 9th, 2009 to December 29th, 2009 to show its capability of producing structured solar corona in agreement with solar coronal observations.

Using a 3D MHD model, Zhou and Feng[86] analyzed and studied the propagation characteristics of Coronal Mass Ejections (CMEs) launched at different positions in a realistic structured ambient solar wind. Here the ambient solar wind structure during the Carrington rotation 2095 is selected, which is the characteristics of activity rising phase. CMEs with a simple spherical plasmoid structure are initiated at different solar latitudes with respect to the Heliospheric Current Sheet (HCS) and the Earth in the same ambient solar wind. Then, they numerically obtained the evolution process of the CMEs from the Sun to the interplanetary space. When the Earth and the CME launch position are located on the same side of the HCS, the arrival time of the shock at the Earth is faster than that when the Earth and the CME launch position are located on the opposite side of the HCS. The disturbance amplitudes for the same side event are also larger than those for the opposite side event. This may be due to the fact that the HCS between the CME and the Earth for the opposite side event hinders its propagation and weaken it. The CMEs tend to deflect toward the HCS in the latitudinal direction near the corona and then propagate almost parallel to the HCS in the interplanetary space. This deflecting tendency may be caused by the dynamic action of near-Sun magnetic pressure gradient force.

For realistic Magnetohydrodynamics (MHD) simulation of the solar Active Region (AR), two types of capabilities are required. The first is the capability to calculate the bottom-boundary electric field vector, with which the observed magnetic field can be reconstructed through the induction equation. The second is a proper boundary treatment to limit the size of the sub-Alfvénic simulation region. Hayashi *et al.*[87] developed (1) a practical inversion method to yield the solar-surface electric field vector from the temporal evolution of the three components of magnetic field data maps, and (2) a characteristic-based free boundary treatment for the top and side sub-Alfvénic boundary surfaces. We simulate the temporal evolution of AR 11158 over 16 hr for testing, using Solar Dynamics Observatory/Helioseismic Magnetic Imager vector magnetic field observation data and their time-dependent three dimensional MHD simulation with these two features. Despite several assumptions in calculating the electric field and compromises for mitigating computational difficulties at the very low beta regime, several features of the AR were reasonably retrieved, such as twisting field structures, energy accumulation comparable to an X-class flare, and sudden changes at the time of the X-flare. The present MHD model can be a first step toward more realistic modeling of AR in the future.

## 12. Solar Energetic Particles and Cosmic Rays

Wang *et al*.[88] proposed that the accelerated electrons in the quiet Sun could collide with the solar atmosphere to emit Hard X-Rays (HXRs) via non-thermal bremsstrahlung, while some of these electrons would move upwards and escape into the interplanetary medium, to form a superhalo electron population measured in the solar wind. The modeled quiet-Sun HXRs related to the superhalo electrons fit well to a power-law spectrum, $f \approx \varepsilon^{-\gamma}$ in the photon energy $\varepsilon$, with an index $\gamma \approx$ 2.0–2.3 (3.3–3.7) at 10–100 keV, for the warm/cold thick-target (thin-target) emissions produced by the downward traveling (upward-traveling) accelerated electrons. These simulated spectra are significantly harder than the observed spectra of most solar HXR flares. The modeled thin-target HXRs are much weaker than quiet-Sun HXRs observation. While for thick-target model, the HXRs observation restricts the number of downward-traveling electrons to at most ~3 times the number of escaping electrons, different from solar flares situation (100 to 1000 times the number of escaping electrons).

Recently there are many perpendicular diffusion theories developed based on different analytical approximations. Qin and Shalchi[89] used test-particle simulation to check the different approximations used in diffusion theory. They show shat if the particle's gyro-radius is smaller than the turbulence perpendicular correlation length guiding center approximations work very. In addition, the mean square displacement definitions of perpendicular diffusion coefficients and Taylor–Green–Kubo formula have the same effects. However, to replace fourth-order correlation by a product of two second-order correlation functions would provide significant error. It is advance to avoid using such kind of approximation.

The influence of adiabatic focusing on particle diffusion is an important topic in astrophysics and plasma physics. In the past, several authors have explored the influence of along-field adiabatic focusing on the parallel diffusion of charged energetic particles. By using the unified nonlinear transport theory developed by Shalchi and the method of He and Schlickeiser, Wang *et al.*[90] derive a new nonlinear perpendicular diffusion coefficient for the uneven background magnetic field. This formula demonstrates that the particle perpendicular diffusion coefficient is modified by along-field adiabatic focusing. For isotropic pitch-angle scattering and the weak adiabatic focusing limit, the derived perpendicular diffusion coefficient is independent of the sign of adiabatic focusing characteristic length. For the two-component model, the perpendicular diffusion coefficient is simplified up to the second order of the power series of the adiabatic focusing characteristic quantity. They find that the first-order modifying factor is equal to zero and that the sign of the second order is determined by the energy of the particles. The new analytic formula could be applied to calculate the spatial diffusion coefficient in the interplanetary and interstellar space. Wang *et al.*[91] calculated the Mean Square Displacement (MSD) of FLRW(Field Line Random Walk) on all possible length scales for pure two-dimensional magnetic turbulence with the damping dynamical model by using the field line tracing method. For pure two-dimensional magnetic turbulence Kubo number cannot exist, but they found that a new dimensionless quantity R is needed to be introduced for describing FLRW with the damping dynamical model. The dimensionless quantity R is related to the temporal effect of magnetic turbulence, and it controls the features of FLWR for pure 2D magnetic turbulence. On different length scales, dimensionless MSD shows different relationships with the dimensionless quantity R. Although the temporal effect affects the MSD of FLRW and even changes regimes of FLRW, it does not affect the relationship between the dimensionless MSD and dimensionless quantity R on all possible length scales.

Recently, S. W. Kahler studied the Solar Energetic Particle (SEP) event timescales associated with Coronal Mass Ejections (CMEs) from spacecraft data analysis. They obtained different timescales of SEP events, such as TO, the onset time from CME launch to SEP onset, TR, the rise time from onset to half the peak intensity (0.5Ip), and TD, the duration of the SEP intensity above 0.5Ip. Qi *et al.*[92] solve SEPs transport equation considering ICME shocks as energetic particle sources in their work. With their modeling assumptions, their simulations show similar results to Kahler's spacecraft data analysis that the weighted average of TD increases with both CME speed and width. Besides, from their simulation results, they suggest TD is directly dependent on CME speed, but not dependent on CME width, which were not achieved from the observation data analysis.

Kong *et al.*[93] studied particle acceleration at highly perpendicular ($\theta_{Bn}\geqslant 75°$) shocks with modeling magnetic turbulence by solving the Newton-Lorentz equation numerically with a backward-in-time method. They identified a set of quasi-perpendicular shocks from the ACE shock database at 1 AU from 1998 to 2005, and used the observed solar wind parameters to construct kappa and Maxwellian functions as the background upstream particle distribution. By comparing the accelerated energy spectra between simulations and observations, they find that the shocks are capable of accelerating thermal particles to high energies of the order of MeV with both kappa and Maxwellian upstream particle distributions. In addition, they obtained the injection energy and timescale of particle acceleration for each shock event. Through examining the relationship between the acceleration time and the parameters such as upstream speed $U_1$ and shock-normal angle $\theta_{Bn}$, they clarified the crucial shock features that are responsible for efficient particle acceleration. Specially, the shocks showing a large $U_1$ and a $\theta_{Bn}$ approximate to 90° have relatively short acceleration time.

Solar images taken by CCDs are often contaminated with noises, and the single-pixel events are thought to be caused by Cosmic Ray (CR) hits. Shen and Qin[94] used a method, which is based on the median filtering algorithm, to identify the CR affected pixels in solar images taken by EIT instrument onboard SOHO satellite. While counting the CR affected pixels, they obtained the CR intensity from 2000 to 2014. Then the new data was used to study the transient variation of CRs, *i.e.*, Solar Proton Events (SPEs). Comparing with the SPEs observed by GOES and SOHO/ERNE, they concluded that CRs in the energy range 118–140 MeV affect the SOHO/EIT images the most. To get the Galactic Cosmic Ray (GCR) intensity, a robust automatic despiking method was used to exclude large spikes, which were caused by solar events, in the temporal profile of CR intensity data from solar images. The obtained GCR intensity showed an 11 year period, and it is similar to the SOHO/ERNE GCR flux and Newark neutron monitor count rates. In addition, the GCR data also had a 27 day period and showed good anticorrelation with the changes of solar wind velocity. They also found that the 27 day variation amplitudes of GCR intensity were dependent on the kinetic energy of energetic particles.

The energy spectrum of Ground Level Enhancement (GLE) events of Solar Energetic Particles (SEPs) is well fitted by the double power law, which has four spectral parameters. Wu and Qin[95] investigated the spectral parameters of GLEs that occurred during solar cycle 23. According to their analysis, 13 GLEs were selected for study by excluding 3 complicated GLEs. They found that these 13 GLEs could be divided into two categories, of which the events underwent strong or weak Inter-Planetary (IP) shock acceleration with softer or harder spectra in high-energy part. In particular, all of the events with shock nose being not toward the Earth are accelerated weakly by the IP shock, while the events could be any category if the shock nose is toward the Earth. Therefore, they found that three methods could be used to distinguish between the events originated near central meridian according to solar event conditions. The methods are the brightness of CME image, the starting and ending frequencies of Decameter-Hectometric (DH) type II radio bursts, and 12–45 MeV/nucleon Fe/O ratio of SEPs. Based on the classification, they presented the statistical analysis of the four spectral parameters of the selected GLEs, with which they established an empirical model of the double power law GLE spectra, showing how the spectra can be modeled largely by using the previous day 10.7 cm solar radio flux and the event corresponding solar flare condition. What's more, they obtained modeling results for 7 selected GLEs occurred in solar cycles 22 and 24 to check the validity of the model partially. Therefore, the model shows potential for application in space weather forecasting.

Qin and Shen[96] developed a numerical model to study the time-dependent modulation of galactic cosmic rays in the inner heliosphere. Based on the numerical solutions of Parker's transport equations, the model incorporated a modified Parker heliospheric magnetic field, a locally static time delayed heliosphere and a new diffusion coefficient model NLGCE-F. The NLGCE-F model needs turbulence quantities as input parameters. They established an analytical expression to describe the radial and latitudinal variations of the magnetic turbulence magnitude, and the radial dependence was related to the heliospheric current sheet tilt angle. They showed that the analytical expression agreed well with the Ulysses, Voyager 1, and Voyager 2 observations. In addition, they also considered the latitude-dependence of the solar wind velocity during solar minimum. By numerically calculating the modulation code, they got the proton energy spectra as a function of time during the past solar minimum. The modulation results were consistent with the PAMELA measurements.

Cosmic Ray (CR) transport near the HelioPause (HP) is studied using a hybrid transport model, with the parameters constrained by observations from the Voyager 1 spacecraft. Luo *et al.*[97] simulated the CR radial flux along different directions in the heliosphere. There is no well-defined thin layer between the solar wind region and the interstellar region along the tail and polar directions of the heliosphere. By analyzing the radial flux curve along the direction of Voyager 2, together with its trajectory information, the crossing time of the HP by Voyager 2 is predicted to be in 2017.14. They simulated the CR radial flux for different energy values along the direction of Voyager 1. They found that there was only a modest modulation region of about 10 AU wide beyond the HP, so that Voyager 1 observing the Local Interstellar Spectra is justified in numerical modeling. They analyzed the heliospheric exit information of pseudo-particles in their stochastic numerical (time-backward) method, conjecturing that they represent the behavior of CR particles, and they found that pseudo-particles that have been traced from the nose region exit in the tail region. This implies that many CR particles diffuse directly from the heliospheric tail region to the nose region near the HP. In addition, when pseudo- particles were traced from the Local InterStellar Medium (LISM), it is found that their exit location (entrance for real particles) from the simulation domain is along the prescribed Interstellar Magnetic Field direction. This indicates that parallel diffusion dominates CR particle transport in the LISM.

Based on the reduced diffusion mechanism for producing Forbush decreases ($F_{ds}$) in the heliosphere, Luo *et al.*[98] constructed a 3D diffusion barrier, and by incorporating it into a Stochastic Differential Equation (SDE) based time-dependent, cosmic-ray transport model, a 3D numerical model for simulating $F_{ds}$ is built and applied to a period of relatively quiet solar activity. This SDE model generally corroborates previous $F_d$ simulations concerning the effects of the solar magnetic polarity, the tilt angle of the Heliospheric Current Sheet (HCS), and cosmic-ray particle energy. Because the modulation processes in this 3D model are multi-directional, the barrier's geometrical features affect the intensity profiles of $F_{ds}$ differently. They found that both the latitudinal and longitudinal extent of the barrier have relatively fewer effects on these profiles than its radial extent and the level of decreased diffusion inside the disturbance. They found, with the 3D approach, that the HCS rotational motion causes the relative location from the observation point to the HCS to vary, so that a periodic pattern appears in the cosmic ray intensity at the observing location. Correspondingly, the magnitude and recovery time of an $F_d$ change, and the recovering intensity profile contains oscillation as well. Investigating the $F_d$ magnitude variation with heliocentric radial distance, they found that the magnitude decreases overall and, additionally, that the $F_d$ magnitude exhibits an oscillating pattern as the radial distance increases, which coincides well with the wavy profile of the HCS under quiet solar modulation conditions.

## References


[1] Ruan W Z, He J S, Zhang L, Vocks C, Marsch E, Tu C Y, Peter H, Wang L H. Kinetic Simulation of Slow Magnetosonic Waves and Quasi-periodic Upflows in the Solar Corona[J]. *Astrophys. J.*, 2016, 825: 58(9)

[2] Yang L P, Feng X S, He J S, Zhang L, Zhang M. A self-consistent numerical study of the global solar wind driven by the unified nonlinear Alfven wave. *Sol. Phys.*, 2016, 291(3): 953-963

[3] Pei Z, He J, Wang X, Tu C, Marsch E, Wang L, Yan L. Influence of intermittency on the anisotropy of magnetic structure functions of solar wind turbulence[J]. *J. Geophys. Res. Space Physics*, 2016, 121(2): 911-924

[4] Yang L, He J, Tu C, *et al*. Multiscale Pressure-Balanced Structures in Three-dimensional Magnetohydrodynamic Turbulence. *Astrophys. J.*, 2017, 836: 69(8pp)

[5] Yang L, He J, Tu C, Li S, Zhang L, Wang X, Wang L. Influence of intermittency on the quasi-perpendicular scaling in three-dimensional magnetohydrodynamic turbulence. *Astrophys. J.*, 2017, 846: 49(10pp)

[6] Yang L, Zhang L, He J, Tu C, Li S, Wang X, Wang L. Formation and properties of tangential discontinuities in three-dimensional compressive MHD turbulence[J]. *Astrophys. J.*, 2017, 851(2): 121(9pp)

[7] Wang X, Tu C Y, He J S, Marsch E, Wang L H. Reexamination of data analysis for -2 spectral index at small theta-VB angle[R]. *Proceedings of the 14th Solar Wind Conference*, 2016, 1720: 040020

[8] Wang X, Tu C Y, He J S, Marsch E, Wang L H. On the weakly anisotropic nature of the time-stationary turbulence in the solar wind[R]. *Proceedings of the 14th Solar Wind Conference*, 2016, 1720: 040019

[9] Tu C Y, Wang X, He J S, Marsch E, Wang L H. The nature of the slow solar wind turbulence[R]. *Proceedings of the 14th Solar Wind Conference*, 2016, 1720: 040017

[10] Wang X, Tu C Y, He J S, Wang L H. Ion-scale spectral break in the normal plasma beta range in the solar wind turbulence[J]. *J. Geophys. Res.: Space Phys.*, 2018, 123: 68

[11] Wang X, Tu C Y, He J S, Wang L H. Possible noise nature of Elsässer variable z− in highly Alfvénic solar wind fluctuations[J]. *J. Geophys. Res.: Space Phys.*, 2018, 123: 57

[12] Yang Z C, Shen F, Zhang J, Yang Y, Feng X S, Richardson I G. Correlation between the magnetic field and plasma parameters at 1 AU[J]. Solar Phys., 2018, 293: 24, https://doi.org/10.1007/s11207-017-1238-5

[13] Yang L P, Zhang L, He J S, Tu C Y, Li S T, Wang X, Wang L H. Disappearance of anisotropic intermittency in large-amplitude MHD turbulence and its comparison with small-amplitude MHD turbulence[J]. *Astrophys. J.*, 2018, 855: 69(9pp)

[14] Zhang Q H, Wang Y M, Liu R, Shen C L, Zhang M, Gou T Y, Liu J J, Liu K, Zhou Z J, Wang S. Damped large amplitude oscillations in a solar prominence and a bundle of coronal loops[J]. *Res. Astron. Astrophys.*, 2016, 16: 167(10pp)

[15] Wang W S, Liu R, Wang Y M. Tornado-Like Evolution of A Kink-Unstable Solar Prominence[J]. *Astrophys. J.*, 2017, 834: 38(11pp)

[16] Liu J J, Wang Y M, Erdelyi R, Liu R, McIntosh S W, Gou T Y, Chen J, Liu K, Liu L J, Pan Z H. On the Magnetic and Energy Characteristics of Recurrent Homologous Jets from An Emerging Flux[J]. *Astrophys. J.*, 2016, 833: 150(11pp)

[17] Liu J J, Fang F, Wang Y M, McIntosh S W, Fan Y H, Zhang Q H. On the Observation and Simulation of Solar Coronal Twin Jets[J]. *Astrophys. J.*, 2016, 817: 126(8pp)

[18] Wang B, Chen Y, Fu J, Li B, Li X, Liu W. Dynamics of a Prominence-Horn Structure During Its Evaporation in the Solar Corona[J]. *Astrophys J.*, 2016, 827(2): L33

[19] Zheng R, Zhang Q, Chen Y, *et al.* Interaction of two filaments in a long filament channel associated with twin coronal mass ejections [J]. *Astrophys J.*, 2017, 836(2): 160

[20] Song H Q, Chen Y, Li B, *et al*. The Origin of Solar Filament Plasma Inferred from In Situ Observations of Elemental Abundances[J]. *Astrophys. J. Lett.*, 2017, 836(1): L11

[21] Zheng R, Chen Y, Wang B, Li G, Xiang Y. Interchange Reconnection Associated with a Confined Filament Eruption: Implications for the Source of Transient Cold-dense Plasma in Solar Winds[J]. *Astrophys J.*, 2017, 840(1): 3

[22] Wang Y M, Zhou Z J, Zhang J, Liu L, Liu R, Shen C L, Chamberlin P C. Thermodynamic Spectrum of Solar Flares Based on SDO/EVE Observations: Techniques and First Results[J]. *Astrophys. J. Supp.*, 2016, 223: 4(22pp)

[23] Gou T Y, Liu R, Wang Y M, Liu K, Zhuang B, Chen J, Zhang Q H, and Liu J J. Stereoscopic Observation of Slipping Reconnection in A Double Candle-Flame-Shaped Flare[J]. *Astrophys. J. Lett.*, 2016, 821: L28(7pp)

[24] Liu R, Chen J, Wang Y M, Liu K. Investigating Energetic X-Shaped Flares on the Outskirts of A Solar Active Region[J]. *Sci. Rep.*, 2016, 6, 34021

[25] Wu Z, Chen Y, Huang G, *et al*. Microwave Imaging of a Hot Flux Rope Structure During the Pre-Impulsive Stage of an Eruptive M7.7 Solar Flare[J]. *Astrophy.s J.*, 2016, 820(2): L29

[26] Zheng R, Chen Y, Wang B. Slipping magnetic reconnections with multiple flare ribbons during an X-class solar flare[J]. *Astrophys. J.*, 2016, 823(2): 136

[27] Chen Y, Wu Z, Liu W, *et al*. Double-coronal X-Ray and Microwave Sources Associated with a Magnetic Breakout Solar Eruption [J]. *Astrophys. J.*, 2017, 843(1): 8

[28] Song Q, Wang J S, Feng X S, Zhang X X. Dark post-flare loops observed by the solar dynamics observatory[J]. *Astrophys. J.*, 2016, 821: 83(11pp)

[29] Jiang C W, Wu S T, Yurchyshyn V, Wang H M, Feng X S, Hu Q. How did a major confined flare occur in super solar active region 12192[J]. *Astrophys. J.*, 2016, 828: 62(12pp)

[30] Feng SW, Chen Y, Song HQ, Wang B, Kong XL. An Imaging Study of a Complex Solar Coronal Radio Eruption[J]. *Astrophys. J.*, 2016, 827(1): L9

[31] Koval A, Stanislavsky A, Chen Y, Feng S, Konovalenko A, Volvach Y. A Decameter Stationary Type IV Burst in Imaging Observations on 2014 September 6[J]. *Astrophys J.*, 2016, 826(2): 125

[32] Kong X, Chen Y, Feng S, *et al*. Observation of a Metric Type N

Solar Radio Burst[J]. *Astrophys. J.*, 2016, 830(1): 37
[33] Vasanth V, Chen Y, Feng S, *et al*. An Eruptive Hot-Channel Structure Observed At Metric Wavelength As a Moving Type-IV Solar Radio Burst[J]. *Astrophys. J.*, 2016, 830(1): L2
[34] Li C Y, Chen Y, Wang B, *et al*. EUV and Magnetic Activities Associated with Type-I Solar Radio Bursts[J]. *Solar Phys*., 2017, 292(6): 82
[35] Koval A, Chen Y, Stanislavsky A, Zhang Q-H. Traveling Ionospheric Disturbances as Huge Natural Lenses: Solar Radio Emission Focusing Effect[J]. *J. Geophys. Res. Sp. Phys*., 2017, 122: 9092-9101
[36] Lv M S, Chen Y, Li CY, *et al.* Sources of the Multi-Lane Type II Solar Radio Burst on 5 November 2014[J]. *Solar Phys*., 2017, 292(12): 194
[37] Kong X, Chen Y, Guo F. The acceleration of electrons at a spherical coronal shock in a streamer-like coronal field[R]. *AIP Conference Proceedings,* 2016, 1720, 070003
[38] Kong X, Chen Y, Guo F, Feng S, Du G, Li G. Electron Acceleration At a Coronal Shock Propagating Through a Large-Scale Streamer-Like Magnetic Field[J]. *Astrophys J*., 2016, 821(1): 32
[39] Kong X, Guo F, Giacalone J, Li H, Chen Y. The Acceleration of High-energy Protons at Coronal Shocks: The Effect of Large-scale Streamer-like Magnetic Field Structures[J]. *Astrophys. J*., 2017, 851(1): 38
[40] Wang W S, Liu R, Wang Y M, Hu Q, Shen C L, Jiang C W, Zhu C M. Buildup of a Highly Twisted Magnetic Flux Rope during a Solar Eruption[J]. *Nat. Comm.*, 2017, 8, 1330
[41] Wang Y M, Zhuang B, Hu Q, Liu R, Shen C L, Chi Y T. On the twists of interplanetary magnetic flux ropes observed at 1 AU[J]. *J. Geophys. Res.*, 2016,121: 9316-9339
[42] Liu R, Kliem B, Titov V S, Chen J, Wang Y M, Wang H M, Liu C, Xu Y, Wiegelmann T. Structure, stability, and evolution of magnetic flux ropes from the perspective of magnetic twist[J]. *Astrophys. J.*, 2016, 818: 148(12pp)
[43] Zhang Q H, Wang Y M, Hu Y Q, Liu R, Liu J J. Influence of photospheric magnetic conditions on the catastrophic behaviors of flux ropes in active regions[J]. *Astrophys. J.*, 2017, 835: 211(10pp)
[44] Zhang Q H, Wang Y M, Hu Y Q, Liu R. Downward catastrophe of solar magnetic flux ropes[J]. *Astrophys. J.*, 2016, 825: 109(8pp)
[45] Liu C X, Feng X S, Nakamura R, Guo J P, Wang R S. Double-peaked core field of flux ropes during magnetic reconnection [J]. *J. Geophys. Res. Space Physics*, 2017, 122: 6374-6384
[46] Yang L P, Peter H, He J S, Tu C Y, Wang L H, Zhang L, Yan L M. Formation of cool and warm jets by magnetic flux emerging from the solar chromosphere to transition region[J]. *Astrophys. J.*, 2018, 852: 16(15pp)
[47] Tian C, Chen Y. Numerical simulations of Kelvin-Helmholtz instability: a two-dimensional parametric study[J]. *Astrophys J*., 2016, 824: 60
[48] Du Q F, Chen L, Zhao Y-C, *et al.* A solar radio dynamic spectrograph with flexible temporal-spectral resolution[J]. *Res Astron Astrophys*., 2017, 17: 98
[49] Fan S T, He J S, Yan L M, Tomczyk S, Tian H, Song H Q, Wang L H, Zhang L. Turbulence and Heating in the Flank and Wake Regions of a Coronal Mass Ejection[J]. *Solar Phys.*, 2018, 293(1): 6(16pp)
[50] Mao S, He J, Zhang L, Yang L, Wang L. Numerical Study of Erosion, Heating, and Acceleration of the Magnetic Cloud as Impacted by Fast Shock[J]. *Astrophys. J.*, 2017, 842: 109(11pp)
[51] Liu L J, Wang Y M, Wang J X, Shen C L, Ye P Z, Liu R, Chen J, Zhang Q H, Wang S. Why is a flare-rich active region CME-poor [J]. *Astrophys. J.*, 2016, 826: 119(10pp)
[52] Liu L J, Wang Y M, Liu R, Zhou Z J, Temmer M, Thalmann J K, Liu J J, Liu K, Shen C L, Zhang Q H, Veronig A M. The causes of quasi-homologous CMEs[J]. *Astrophys. J.*, 2017, 844: 141(19pp)
[53] Shen F, Wang Y M, Shen C L, Feng X S. Turn on the super-elastic collision nature of coronal mass ejections through low approaching speed[J]. *Sci. Rep.*, 2016, 6, 19576
[54] Shen F, Wang Y M, Shen C L, Feng X S. On the Collision Nature of Two Coronal Mass Ejections: A Review [J]. *Solar Phys.*, 2017, 292: 104(20pp)
[55] Guo J P, Wei F S, Feng X S, Forbes J M, Wang Y M, Liu H X, Wan W X, Yang Z L, Liu C X. Prolonged multiple excitation of large-scale traveling atmospheric disturbances (TADs) by successive and interacting coronal mass ejections[J]. *J. Geophys. Res.*, 2016, 121: 2662-2668
[56] Wang Y M, Zhang Q H, Liu J J, Shen C L, Shen F, Yang Z C, Zic T, Vrsnak B, Webb D F, Liu R, Wang S, Zhang J, Hu Q, Zhuang B. On the Propagation of a Geoeffective Coronal Mass Ejection during March 15–17, 2015[J]. *J. Geophys. Res.*, 2016, 121: 7423-7434
[57] Zhao A K*, Wang Y M*, Chi Y T, Liu J J, Shen C L, Liu R. Main cause of the poloidal plasma motion inside a magnetic cloud inferred from multiple-spacecraft observations[J]. *Solar Phys.*, 2017, 292: 58, DOI 10.1007/s11207-017-1077-4
[58] Zhao A K, Wang Y M, Liu J J, Zhou Z J, Shen C L, Liu R, Zhuang B, Zhang Q H. The role of viscosity in causing the plasma poloidal motion in magnetic clouds[J]. *Astrophys. J.*, 2017, 845: 109(6pp)
[59] Zhang B, Wang Y M, Shen C L, Liu S Q, Wang J J, Pan Z H, Li H M, Liu R. The significance of the influence of the CME deflection in interplanetary space on the CME arrival at the Earth[J]. *Astrophys. J.*, 2017, 845: 117(12pp)
[60] Chi Y T, Shen C L, Wang Y M, Xu M J, Ye P Z, Wang S. Statistical study of the interplanetary coronal mass ejections from 1996 to 2015[J]. *Solar Phys.*, 2016, 291: 2419-2439
[61] Chen Y, Du G, Zhao D, *et al.* Imaging a Magnetic-Breakout Solar Eruption[J]. *Astrophys J*., 2016, 820(2): L37
[62] Zheng R, Chen Y, Du G, Li C. Solar Jet–Coronal Hole Collision and a Closely Related Coronal Mass Ejection[J]. *Astrophys J*., 2016, 819(2): L18
[63] Song H Q, Zhong Z, Chen Y, *et al.* A Statistical Study of the Average Iron Charge State Distributions Inside Magnetic Clouds for Solar Cycle 23[J]. *Astrophys. J. Suppl. Ser*., 2016, 224(2): 27
[64] Song H Q, Cheng X, Chen Y, *et al.* The Three-part Structure of a Filament-unrelated Solar Coronal Mass Ejection[J]. *Astrophys J*., 2017, 848(1): 21
[65] Hu H D, Liu Y D, Wang R, Möstl C, Yang Z W. Sun-to-Earth characteristics of the 2012 July 12 coronal mass ejection and associated geo-effectiveness[J]. *Astrophys. J*., 2016, 829: 97(9pp)
[66] Zhu B, Liu Y D, Luhmann J G, Hu H D, Wang R, Yang Z W. Solar energetic particle event associated the 2012 July extreme solar storm[J]. *Astrophys J*., 2016, 827: 146(8pp)
[67] Wang R, Liu Y D, Zimovets I, Hu H D, Dai X H, Yang Z W. Sympathetic solar filament eruptions[J]. *Astrophys. J*., 2016, 827: L12(7pp)

[68] Liu Y D, Hu H D, Wang C, Luhmann J G, Richardson J D, Yang Z W, Wang R. On Sun-to-Earth propagation of coronal mass ejecctions: II slow events and comparison with others[J]. *Astrophys. J.* Supp., 2016, 222: 23(17pp)

[69] Wang R, Liu Y D, Wiegelmann T, Cheng X, Hu H D, Yang Z W. Relationship Between Sunspot Rotation and a Major Solar Eruption on 12 July 2012[J]. *Solar Phys*., 2016, 291: 1159–1171

[70] Hu H D, Liu Y D, Wang R, Zhao X W, Zhu B, Yang Z W. Multi-spacecraft observations of the coronal and interplanetary evolution of a solar eruption associated with two active regions[J]. *Astrophys. J*., 2016, 840: 76(10pp)

[71] Liu Y D, Zhao X W, Zhu B. Propagation and interaction properties of successive coronal mass ejections in relation to a complex type ii radio burst[J]. *Astrophys J*., 2017, 849: 112(8pp)

[72] Liu Y D, Hu H D, Zhu B, Luhmann J G, Vourlidas A. Structure, propagation, and expansion of a CME-driven shock in the heliosphere: A review of the 2012 July 23 extreme storm[J]. *Astrophys J*., 2017, 834: 158(9pp)

[73] Zhao X W, Liu Y D, Hu H D, Wang R. Propagation Characteristics of Two Coronal Mass Ejections from the Sun Far into Interplanetary Space[J]. *Astrophys. J*., 2017, 837: 4(10pp)

[74] Liu Y A, Liu Y D, Hu H D, Wang R, Zhao X W. Multi-spacecraft Observations of the Rotation and Nonradial Motion of a CME Flux Rope Causing an Intense Geomagnetic Storm[J]. *Astrophys. J*., 2018, 854: 126(8pp)

[75] Zhao X H, Liu Y D, Inhester B, Feng X S, Wiegelmann T, Lu L. Comparison of CME/shock propagation models with heliospheric imaging and in situ observations[J]. *Astrophys J*., 2016, 830: 48(11pp)

[76] Zhao X H, Feng X S, Feng H Q, Li Z. Correlation between angular widths of CMEs and characteristics of their source regions[J]. *Astrophys. J*., 2017, 849: 79(7pp)

[77] Xiong M, Davies J A, Harrison R A, Zhou Y F, Feng X S, Xia L D, Li B, Liu Y D, Hayashi K J, Li H C, Yang L P. Prospective out-of-ecliptic white-light imaging of coronal mass ejections traveling through the corona and heliosphere[J]. *Astrophys. J*., 2018, 852: 111(20pp)

[78] Wu S T, Zhou Y F, Jiang C W, Feng X S, Wu C C, Hu Q. A data-constrained three-dimensional magnetohydrodynamic simulation model for a coronal mass ejection initiation[J]. *J. Geophys. Res.: Space Phys*., 2016, 121, doi:10.1002/2015JA021615.

[79] Jiang C W, Feng X S, Wu S T. Analyses of the photospheric magnetic dynamics in solar active region 11117 using an advanced CESE-MHD model [J]. *Front. Astron.. Space Sci.*, 2016, 3, 16(8pp)

[80] Jiang C W, Wu S T, Feng X S, Hu Q. Data-driven magnetohydrodynamic modelling of a flux-emerging active region leading to solar eruption[J]. *Nature Commun*., 2016, 7: 11522, DOI: 10.1038/ncomms11522

[81] Zhang J K, Li H C.Two upstream splitting schemes for generalized Lagrange multiplier magnetohydrodynamics. *Chin. J. Space Sci.*, 2017, 37(1): 8-18

[82] Liu Q, Li H C. Improvement and application of Lax-Friderichs scheme in MHD numerical simulation (in Chinese). *Chin. J. Space Sci.*, 2016, 36(6): 857-865

[83] Xiong M, Davies J A, Li B, Yang L P, Liu Y D, Xia L D, Harrison R A, Keiji H, Li H C. Prospective Out-of-ecliptic White-light Imaging of Interplanetary Corotating Interaction Regions at Solar Maximum[J]. *Astrophys. J*., 2017, 844: 76(15pp)

[84] Yang Y, Feng X S, Jiang C W. A high-order CESE scheme with a new divergence-free method for MHD numerical simulation [J]. *J. Comput. Phys*., 2017, 349: 561-581

[85] Feng X S, Li C X, Xiang C Q, Zhang M, Li H C, Wei F S. Data-driven modeling of the solar corona by a new three-dimensional path-conservative Osher-Solomon MHD model[J]. *Astrophys. J Supp. Ser.*, 2017, 233: 10(33pp)

[86] Zhou Y F, Feng X S. Numerical study of the propagation characteristics of coronal mass ejections in a structured ambient solar wind[J]. *J. Geophys. Res.: Space Phys*., 2017, 122: 1451-1462

[87] Hayashi K, Feng X S, Xiong M, Jiang C W. An MHD simulation of solar active region 11158 driven with a time-dependent electric field determined from HMI Vector magnetic field measurement data[J]. *Astrophys. J*., 2018, 855: 11(16pp)

[88] Wang W, Wang L, Krucker S, Hannah I. Simulation of Quiet-Sun Hard X-Rays Related to Solar Wind Superhalo Electrons[J]. *Solar Phys.*, 2016, 291(5): 1357-1367

[89] Qin G, Shalchi A. Numerical test of different approximation used in the transport theory of energetic particles[J]. *Astrophys. J*., 2016, 823, 23

[90] Wang J F, Qin G, Ma Q M, *et al*. Perpendicular Diffusion Coefficient of Comic Rays: The Presence of Weak Adiabatic Focusing[J]. *Astrophys. J*., 2017, 845: 112

[91] Wang J F, Qin G, Ma Q M, *et al*. Magnetic field line random walk in two-dimensional dynamical turbulence[J]. *Phys. Plasmas,* 2017, 24, 082901

[92] Qi S Y, Qin G, Wang Y. Numerical simulations of solar energetic particle event timescales associated with ICMES[J]. *Res. Astron. Astrophys*., 2017, 809(4): 11-22

[93] Kong F J, Qin G, Zhang L H. Numerical simulations of particle acceleration at interplanetary quasi-perpendicular shocks[J]. *Astrophys. J*., 2017, 845: 43

[94] Shen Z N, Qin G. A study of cosmic ray flux based on the noise in raw CCD data from solar images[J]. *J. Geophys. Res.: Space Phys*., 2016, 121: 10712-10727

[95] Wu S S, Qin G. Model of energy spectrum parameters of ground level enhancement events in solar cycle 23[J]. *J. Geophys. Res.: Space Phys*., 2018, 123. DOI:10.1002/2017JA024638.

[96] Qin G, Shen Z N. Modulation of Galactic Cosmic Rays in the Inner Heliosphere, Comparing with PAMELA Measurements[J]. *Astrophys. J*., 2017, 846: 56

[97] Luo X, Potgieter M S, Zhang M, Pogorelov N V, Feng X S, Strauss R T. A numerical simulation of cosmic ray modulation near the heliopause. II Some physical insights[J]. *Astrophys. J*., 2016, 826: 182(10pp)

[98] Luo X, Potgieter M S, Zhang M, Feng X S. A numerical study of forbush decreases with a 3D cosmic-ray modulation model based on an SDE approach[J]. *Astrophys. J*., 2017, 839: 53(10pp)