

# Research Advances of Solar Corona and Interplanetary Physics in China: 2012–2014

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**Abstract** Solar transients and their related interplanetary counterparts have severe effects on the space environments of the Earth. Therefore, the research of solar corona and interplanetary physics has become the focus of study for both solar and space scientists. Considerable progress has been achieved in these aspects by the solar and space physics community of China during 2012–2014, which will be given in this report. The brief report summarizes the research advances of solar corona and interplanetary physics into the following parts: solar wind origin and turbulence, coronal waves and seismology, solar eruptions, solar energetic particle and galactic cosmic ray, magnetic reconnection, Magnetohydrodynamic (MHD) models and their applications, waves and structures in solar wind, propagation of ICMEs/shocks and their arrival time predictions. These research achievements have been achieved by Chinese solar and space scientists independently or *via* international collaborations.

**Key words** Solar wind, Coronal mass ejection, Energetic particles, Interplanetary transients, Space weather

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## 1 Solar Wind Origin and Turbulence

The origin of the heliospheric magnetic flux on the Sun, and hence the origin of the solar wind, is a topic of hot debate for both solar and space physics scientists. While the prevailing view is that the solar

wind originates from outside the coronal streamer helmets, there also exists the suggestion that the open magnetic field spans a far wider region. Without the definitive measurement of the coronal magnetic field, it is difficult to unambiguously resolve the conflict between the two scenarios. Li *et al.*<sup>[1]</sup> presented two 2-

dimensional, Alfvénic-turbulence-based models of the solar corona and solar wind, one with and the other without a closed magnetic field region in the inner corona. The purpose of the latter model was to test whether it was possible to realize a picture suggested by polarimetric measurements of the corona using the Fe XIII 10 747 Å line, where open magnetic field lines seemed to penetrate the streamer base. The boundary conditions at the coronal base were able to account for important observational constraints, especially those on the magnetic flux distribution. Interestingly, the two models provided similar polarized brightness (pB) distributions in the Field of View (FOV) of C2 and C3 of the Large Angle and Spectrometric Coronagraph (LASCO) onboard the Solar and Heliospheric Observatory (SOHO). In particular, a dome-shaped feature was present in the C2 FOV even for the model without a closed magnetic field. Moreover, both models fit the Ulysses data scaled to 1 AU equally well. They suggested that the pB observations could not be safely taken as a proxy for the magnetic field topology, as was often implicitly assumed; the Ulysses measurements, especially the one showing a nearly uniform distribution with heliocentric latitude of the radial magnetic field, did not rule out the ubiquity of open magnetic fields on the Sun.

At present it remains to address why the fast solar wind is fast and the slow wind is slow. Recently it was shown that field line curvature may substantially influence the wind speed  $v$ , thereby offering an explanation for the finding that  $v$  depends on more than just the flow tube expansion factor. Here Li *et al.*<sup>[2]</sup> showed by extensive numerical examples that the correlation between  $v$  and field line curvature was valid for rather general base boundary conditions and for rather general heating functions. Furthermore, the effect of field line curvature was even more pronounced when the proton-alpha particle speed difference was examined. They suggested that any solar wind model had to take into account the field line shape for any quantitative analysis to be made.

A new scenario for the origin of the solar wind, in which it flowed out in a magnetically open coro-

nal funnel and mass was provided to the funnel by small-scale side loops, has been suggested by Tu and his colleagues. Thus mass was supplied by means of magnetic reconnection that was driven by supergranular convection. To validate this scenario and simulate the processes involved, Yang *et al.*<sup>[3]</sup> established a 2.5 dimensional (2.5D) numerical MHD model. In their simulation a closed loop moved toward an open funnel, which had opposite polarity and was located at the edge of a super-granulation cell, and magnetic reconnection was triggered and continues while gradually opening up one half of the closed loop. Its other half connected with the root of the open funnel and formed a new closed loop which was submerged by a reconnection plasma stream flowing downward. Thus they found that the out-flowing plasma in the newly reconnected funnel originated not only from the upward reconnection flow but also from the high-pressure leg of the originally closed loop. The mass flux of the outflow released from the funnel considered in their study was calculated to be appropriate for providing the mass flux at the coronal base of the solar wind, though additional heating and acceleration mechanisms were necessary to keep the velocity at the higher location. Their numerical model demonstrated that in the funnel the mass for the solar wind might be supplied from adjacent closed loops *via* magnetic reconnection as well as directly from the footpoints of open funnels.

Observations with the space-based solar observatory Hinode show that small-scale magnetic structures in the photosphere are found to be associated with a particular class of jets of plasma in the chromosphere called anemone jets. Yang *et al.*<sup>[4]</sup> conducted a numerical experiment of such chromospheric anemone jets related to the Moving Magnetic Features (MMFs). Their numerical results reproduced many observed characteristics of chromospheric anemone jets, topologically and quantitatively. Plasmoids were generated in the reconnection process that was consistent with the observed bright moving blobs in the anemone jets. An increase in the thermal pressure at the base of the jet was also

driven by the reconnection, which induced a train of slow-mode shocks propagating upward. These shocks were a secondary effect, and only slightly modulate the outflow of the anemone jet.

To determine the wave modes prevailing in solar wind turbulence at kinetic scales, He *et al.*<sup>[5]</sup> studied the magnetic polarization of small-scale fluctuations in the plane perpendicular to the data sampling direction (namely, the solar wind flow direction) and analyzed its orientation with respect to the local background magnetic field. They found, when  $B_{0,\text{local}}$  was quasi-perpendicular to  $V_{\text{sw}}$ , the small-scale magnetic-field fluctuations showed a polarization ellipse with right-handed orientation. Moreover, for the first time they found that the major axis of the ellipse was perpendicular to  $B_{0,\text{local}}$ , a property that was characteristic of an oblique Alfvén wave rather than oblique whistler wave. For an oblique whistler wave, the major axis of the magnetic ellipse was expected to be aligned with  $B_{0,\text{local}}$ , thus indicating significant magnetic compressibility, and the polarization turns from right to left handedness as the wave propagation angle  $\theta_{\text{KB}}$  increases toward  $90^\circ$ . Therefore, they concluded that the observation of a right-handed polarization ellipse with orientation perpendicular to  $B_{0,\text{local}}$  seemed to indicate that oblique Alfvén/ion-cyclotron waves rather than oblique fast-mode/whistler waves dominated in the “dissipation” range near the break of solar wind turbulence spectra occurring around the proton inertial length.

The angular distribution of the normalized reduced magnetic helicity density ( $\sigma_{\text{m}}^{\text{r}}$ ) in solar wind turbulence reveals two components of distinct polarity in different angle ranges. This kind of two-component  $\sigma_{\text{m}}^{\text{r}}$  may indicate the possible wave modes and power spectral densities (PSDs) of the turbulent fluctuations. He *et al.*<sup>[6]</sup> modeled the measured angular distribution of  $\sigma_{\text{m}}^{\text{r}}$  by assuming a PSD distribution for Alfvén fluctuations in wave vector space, and then fit the model results to the observations by adjusting the pattern of the PSD distribution. They found that the two-component form of the PSD, which had a major and minor component close to

$k_{\perp}$  and  $k_{\parallel}$ , respectively, seems to be responsible for the observed two-component  $\sigma_{\text{m}}^{\text{r}}$ . As a conclusion, they suggested that the observed two-component  $\sigma_{\text{m}}^{\text{r}}$  in the solar wind turbulence might be due to a superposition of Alfvén waves with quasi-perpendicular (major part) and quasi-parallel (minor part) propagation. The waves seem to become gradually balanced toward shorter scales.

He *et al.*<sup>[7]</sup> presented observations of the power spectral anisotropy in the wave vector space of solar wind turbulence and studied how it evolves in interplanetary space with increasing heliocentric distance. They used magnetic field measurements from the Helios 2 spacecraft within 1 AU. They derived the spectrum  $\text{PSD}_{2\text{D}}(k_{\parallel}, k_{\perp})$  from the spatial correlation function  $\text{CF}_{2\text{D}}(r_{\parallel}, r_{\perp})$  by a transformation according to the projection-slice theorem. They found the so-constructed PSDs to be distributed in  $k$  space mainly along a ridge that was more inclined toward the  $k_{\perp}$  axis than the  $k_{\parallel}$  axis. Furthermore, this ridge of the distribution was found to gradually get closer to the  $k_{\perp}$  axis as the outer scale length of the turbulence became larger with increasing radial distance. In the vicinity of the  $k_{\parallel}$  axis, a minor spectral component appeared that probably corresponds to quasi-parallel Alfvénic fluctuations. Their relative contribution to the total spectral density tended to decrease with radial distance. These findings suggested that solar wind turbulence underwent an anisotropic cascade transporting most of its magnetic energy toward larger  $k_{\perp}$  and that the anisotropy in the inertial range was radially developing further at scales that were relatively far from the ever increasing outer scale.

The relation between the intermittency and the anisotropy of the power spectrum in the solar wind turbulence was studied by Wang *et al.*<sup>[8]</sup> They applied the wavelet technique to the magnetic field and flow velocity data measured by the WIND spacecraft. It was found that when the intermittency is removed from the turbulence, the spectral indices of the power spectra of the field and velocity turn out to be independent of the angle  $\theta_{\text{RB}}$  between the direction of the local scale-dependent background magnetic field

and the heliocentric direction. The spectral index became  $-1.63 \pm 0.02$  for magnetic field fluctuations and  $-1.56 \pm 0.02$  for velocity fluctuations. These results might suggest that the recently found spectral anisotropy of solar wind power spectra in the inertial range could result from turbulence intermittency. As a consequence, a new concept was proposed of an intermittency-associated sub-range of the inertial domain adjacent to the dissipation range. Since spectral anisotropy was previously explained as evidence for the presence of a critical balance type turbulent cascade, and also for the existence of kinetic Alfvén waves, their finding might stimulate fresh thoughts on how to analyze and interpret solar wind turbulence and the associated heating.

A puzzling observation of solar wind MHD turbulence is the often seen Kolmogorov scaling of  $k^{-5/3}$ , even though the solar wind MHD turbulence is dominated by Alfvénic fluctuations. Using a cell model of the solar wind, Li *et al.*<sup>[9]</sup> examined the effect of current sheets on the power spectrum of the solar wind magnetic field. They modeled the solar wind as multiple cells separated by current sheets. They prescribed the spectra of turbulent magnetic field in individual cells as IK-like and examined the spectra along trajectories that crossed multiple boundaries. They found that these spectra became softer and were consistent with the Kolmogorov-scaling.

Dalena *et al.*<sup>[10]</sup> presented a versatile Fortran 77 and C++ program for calculating charged test particle trajectories or field-lines for user-specified fields using the test-particle method. The user had the freedom to specify any type of field (analytical, tabulated in files, time dependent, *etc.*) and maintained complete control over initial conditions of trajectories/field-lines and boundary conditions of specified fields. The structure of streamline was redesigned from previous versions in order to know not only particle or field-lines positions and velocities at each step of the simulations, but also the instantaneous field values as seen by particles. This was made to compute the instantaneous value of the particles magnetic moment, but other applications were pos-

sible too. Accuracy tests of the code were shown for different cases, *i.e.*, particles moving in constant magnetic field, magnetic plus constant electric field and wave field.

## 2 Coronal Waves and Seimology

Cheng *et al.*<sup>[11]</sup> investigated the formation and subsequent separation of a diffuse wave from associated CME front. An important finding was that a diffuse wave front started to separate from the front of the expanding CME bubble shortly after the lateral expansion slowed down. Also a Type II burst was formed near the time of the separation. After the separation, two distinct fronts propagated with different kinematic properties. The diffuse front travelled across the entire solar disk, while the sharp front rose up, forming the CME ejecta with the diffuse front ahead of it. They suggested that the previously termed EUV wave was a composite phenomenon and driven by the CME expansion. While the CME expansion was accelerating, the wave front was cospatial with the CME front, thus the two fronts were indiscernible. Following the end of the acceleration phase, the wave moved away from the CME front with a gradually increasing distance between them.

Dai *et al.*<sup>[12]</sup> also found the two components of EUV waves through analyzing another EUV wave event. A primary front was launched with an initial speed of  $\sim 440 \text{ km}\cdot\text{s}^{-1}$ . When the primary front encountered a large coronal loop system and slowed down, a secondary, much fainter, front emanated from the primary front with a relatively higher starting speed of  $\sim 550 \text{ km}\cdot\text{s}^{-1}$ . Afterward, the two fronts propagated independently with increasing separation.

Li *et al.*<sup>[13]</sup> for the first time presented observations of secondary waves of global EUV wave on June 7, 2011. The primary global wave had a three-dimensional (3D) dome shape, with propagation speeds ranging from  $430$  to  $780 \text{ km}\cdot\text{s}^{-1}$  in different directions. The primary coronal wave ran in front of the expanding loops involved in the Coronal Mass Ejection (CME) and its propagation speeds

were approximately constant within 10–20 minutes. Upon arrival at an Active Region (AR) on its path, the primary EUV wave apparently disappeared and a secondary wave rapidly reemerged within 75 Mm of the AR boundary at a similar speed. When the EUV wave encountered a coronal bright structure, an additional wave front appeared there and propagated in front of it at a velocity nearly a factor of two faster.

Wang and Yan<sup>[14]</sup> found that the shock structure, the energy injection and energy spectrum of a CME-driven shock which occurred on December 14, 2006, could be well fitted by dynamical Monte Carlo simulation.

Waves play a crucial role in diagnosing the plasma properties of various structures in the solar corona and coronal heating. Slow Magnetoacoustic (MA) waves are one of the important types of MHD waves. In past decades, numerous slow MA waves were detected above active regions and coronal holes, but were rarely found elsewhere. Liu *et al.*<sup>[15]</sup> investigated a tornado-like structure consisting of quasi-periodic streaks within a dark cavity at about 40–110 Mm above a quiet-Sun region on September 25, 2011. Their analysis revealed that these streaks are actually slow MA wave trains. The properties of these wave trains, including phase speed, compression ratio, and kinetic energy density, are similar to those of the reported slow MA waves, except that the period of these waves is about 50 s, much shorter than the typical reported values (3–5 minutes).

Yang *et al.*<sup>[16]</sup> presented an EIS observations of an EUV wave and found that at the time of the wave transit, the original red shift increased by about  $3 \text{ km}\cdot\text{s}^{-1}$ , while the original blue shift decreased slightly. After the wave transit, these changes were reversed. When the EUV wave arrived at the boundary of a polar coronal hole, two reflected waves were successively produced and part of them propagated above the solar limb. The first reflected wave above the solar limb encountered a large-scale loop system on its path, and a secondary wave rapidly emerged 144 Mm ahead of it at a higher speed. These findings can be explained in the framework of a fast-mode

magnetosonic wave interpretation for EUV waves, in which observed EUV waves are generated by expanding coronal mass ejections.

Using Big Bear Solar Observatory (BBSO) film data recently digitized at NJIT, Liu *et al.*<sup>[17]</sup> reported a Moreton wave associated with an X9 flare on 1990 May 24, as well as its interactions with four filaments F1–F4 located close to the flaring region. The interaction yielded interesting insight into physical properties of both the wave and the filaments. The first clear Moreton wave front appeared at the flaring-region periphery at approximately the same time as the peak of a microwave burst and the first of two  $\gamma$ -ray peaks. The wave front propagated at different speeds ranging from  $1500\text{--}2600 \text{ km}\cdot\text{s}^{-1}$  in different directions, reaching as far as 600 Mm away from the flaring site. Sequential chromospheric brightenings were observed ahead of the Moreton wave front. As lower diffuse front at  $300\text{--}600 \text{ km}\cdot\text{s}^{-1}$  was observed to trail the fast Moreton wave front about one minute after the onset. The Moreton wave decelerated to  $\sim 550 \text{ km}\cdot\text{s}^{-1}$  as it swept through F1. The wave passage resulted in F1's oscillation which was featured by  $\sim 1 \text{ mHz}$  signals with coherent Fourier phases over the filament, the activation of F3 and F4 followed by gradual recovery, but no disturbance in F2. Different height and magnetic environment together might account for the distinct responses of the filaments to the wave passage. The wave front bulged at F4, whose spine was oriented perpendicular to the upcoming wave front. The deformation of the wave front was suggested to be due to both the forward inclination of the wave front and the enhancement of the local Alfvén speed within the filament channel.

In the applications of solar magneto-seismology, the ratio of the period of the fundamental mode to twice the period of its first overtone,  $P_1/2P_2$ , plays an important role. Li *et al.*<sup>[18]</sup> examined how field-aligned flows affected the dispersion properties, and hence the period ratios, of standing modes supported by magnetic slabs in the solar atmosphere. They numerically solved the dispersion relations and devised a graphic means to construct standing modes. For coro-

nal slabs, they found that the flow effects were significant for the fast kink and sausage modes alike. For the kink ones, they might reduce  $P_1/2P_2$  by up to 23% compared with the static case, and the minimum allowed  $P_1/2P_2$  could fall below the lower limit analytically derived for static slabs. For the sausage modes, while introducing the flow reduces  $P_1/2P_2$  by typically  $< 5\%$  relative to the static case, it significantly increased the threshold aspect ratio only above which standing sausage modes could be supported, meaning that their detectability was restricted to even wider slabs. In the case of photospheric slabs, the flow effect was not as strong. However, standing modes were distinct from the coronal case in that standing kink modes showed a  $P_1/2P_2$  that deviated from unity even for a zero-width slab, while standing sausage modes no longer suffered from a threshold aspect ratio. They concluded that transverse structuring in plasma density and flow speed should be considered in seismological applications of multiple periodicities to solar atmospheric structures.

Fundamental standing modes and their overtones play an important role in coronal seismology. Chen *et al.*<sup>[19]</sup> examined the effects of a significant field-aligned flow on standing modes that were supported by coronal loops, which were modeled as cold magnetic slabs. Of particular interest were the period ratios of the fundamental to its  $(n - 1)$ th overtone  $P_1/nP_n$  for kink and sausage modes, and the threshold half-width-to-length ratio for sausage modes. For standing kink modes, the flow significantly reduced  $P_1/nP_n$  in general, the effect being particularly strong for higher  $n$  and weaker density contrast  $\rho_0/\rho_e$  between loops and their surroundings. That said, even when  $\rho_0/\rho_e$  approached infinity, this effect was still substantial, reducing the minimal  $P_1/nP_n$  by up to 13.7% (24.5%) for  $n = 2$  ( $n = 4$ ) relative to the static case, when the Alfvén Mach number ( $M_A$ ) reached 0.8, where  $M_A$  measured the loop flow speed in units of the internal Alfvén speed. Although it was not negligible for standing sausage modes, the flow effect in reducing  $P_1/nP_n$  was not as strong. However, the threshold half-width-to-length

ratio was considerably higher in the flowing case than in its static counterpart. For  $\rho_0/\rho_e$  in the range (9, 1024) and  $M_A$  in the range (0, 0.5), an exhaustive parameter study yielded that this threshold was well fitted by an empirical formula which involved the two parameters in a simple way. This allowed one to analytically constrain the combination  $\rho_0/\rho_e$ ,  $M_A$  for a loop with a known width-to-length ratio when a standing sausage oscillation was identified. It also allowed one to examine the idea of partial sausage modes in more detail, and the flow was found to significantly reduce the spatial extent where partial modes were allowed.

Bains *et al.*<sup>[20]</sup> investigated the small but finite amplitude solitary Kinetic Alfvén Waves (KAWs) in low  $\beta$  plasmas with superthermal electrons modeled by a kappa-type distribution. A nonlinear Korteweg-de Vries (KdV) equation describing the evolution of KAWs was derived by using the standard reductive perturbation method. Examining the dependence of the nonlinear and dispersion coefficients of the KdV equation on the superthermal parameter  $\kappa$ , plasma  $\beta$  and obliqueness of propagation, they showed that these parameters might change substantially the shape and size of solitary KAW pulses. Only sub-Alfvénic, compressive solitons were supported. They then extended the study to examine kinetic Alfvén rogue waves by deriving a nonlinear Schrödinger equation from the KdV equation. Rational solutions that formed rogue wave envelopes were obtained. They examined how the behavior of rogue waves depended on the plasma parameters in question, finding that the rogue envelopes were lowered with increasing electron superthermality whereas the opposite was true when the plasma  $\beta$  increased. The findings of this study might find applications to low  $\beta$  plasmas in astrophysical environments where particles were superthermally distributed.

### 3 Solar Eruptions

#### 3.1 Coronal Mass Ejections

Coronal Mass Ejections (CMEs) and extreme-

ultraviolet (EUV) jets, have rarely been investigated with spectroscopic observations. Tian *et al.*<sup>[21]</sup> analyzed several data sets obtained by the EUV Imaging Spectrometer on board Hinode and found various types of flows during CMEs and jet eruptions. CME-induced dimming regions were found to be characterized by significant blueshift and enhanced line width by using a single Gaussian fit, while a Red-Blue (RB) asymmetry analysis and an RB-guided double Gaussian fit of the coronal line profiles indicated that these were likely caused by the superposition of a strong background emission component and a relatively weak ( $\sim 10\%$ ), high-speed ( $\sim 100 \text{ km}\cdot\text{s}^{-1}$ ) up-flow component. This finding suggested that the out-flow velocity in the dimming region was probably of the order of  $100 \text{ km}\cdot\text{s}^{-1}$ , not  $\sim 20 \text{ km}\cdot\text{s}^{-1}$  as reported previously. The mass losses in dimming regions as estimated from different methods were roughly consistent with each other, and they were 20%–60% of the masses of the associated CMEs. In an erupted CME loop and an EUV jet, profiles of emission lines formed at coronal and transition region temperatures were found to exhibit two well-separated components, an almost stationary component accounting for the background emission and a highly blueshifted ( $\sim 200 \text{ km}\cdot\text{s}^{-1}$ ) component representing emission from the erupting material. The two components could easily be decomposed through a double Gaussian fit, and they could diagnose the electron density, temperature, and mass of the ejecta.

Shen *et al.*<sup>[22]</sup> reported a multiple spacecraft observation of the 2012 May 17 GLE event. Using the coronagraph observations by SOHO/LASCO, COR1 of the Solar Terrestrial Relations Observatory-Ahead (STEREO-A), and COR1 of the Solar Terrestrial Relations Observatory-Behind (STEREO-B), they identified two eruptions resulting in two CMEs that occurred in the same active region and close in time ( $\sim 2$  minutes) in the 2012 May 17 GLE event. Both CMEs were fast. Complicated radio emissions, with multiple Type II episodes, were observed from ground-based stations: Learmonth and BIRS, as well as the WAVES instrument on board the WIND space-

craft. High time-resolution imaging data of the Atmospheric Imaging Assembly (AIA) and the vector magnetic field data of the Helioseismic and Magnetic Imager (HMI) onboard the Solar Dynamic Observatory (SDO) were also examined. A complicated pre-eruption magnetic field configuration, consisting of twisted flux-tube structure, is reconstructed. Solar Energetic Particles (SEPs) up to several hundred MeV/nucleon were detected in this event. Although the eruption source region was near the west limb, the event led to ground-level enhancement. The existence of two fast CMEs and the observation of high-energy particles with ground-level enhancement agreed well with a recently proposed twin CME scenario.

With a survey through the Large Angle and Spectrometric Coronagraph (LASCO) data from 1996 to 2009, Song *et al.*<sup>[23]</sup> presented 11 events with plasma blobs flowing outwards sequentially along a bright coronal ray in the wake of a CME. The ray was believed to be associated with the current-sheet structure that formed as a result of solar eruption, and the blobs were products of magnetic reconnection occurring along the current sheet. The ray morphology and blob dynamics were investigated statistically. It was found that the apparent angular widths of the rays at a fixed time vary in a range of  $2.1^\circ$ – $6.6^\circ$  ( $2.0^\circ$ – $4.4^\circ$ ) with an average of  $3.5^\circ$  ( $2.9^\circ$ ) at  $3 R_s$  ( $4 R_s$ ), respectively, and the observed durations of the events varied from 12 h to a few days with an average of 27 h. It was also found, based on the analysis of blob motions, that 58% (26) of the blobs were accelerated, 20% (9) were decelerated, and 22% (10) moved with a nearly constant speed. Comparing the dynamics of their blobs and those that were observed above the tip of a helmet streamer, they found that the speeds and accelerations of the blobs in these two cases differed significantly. It was suggested that these differences of the blob dynamics stemmed from the associated magnetic reconnection involving different magnetic field configurations and triggering processes.

Through Differential Emission Measure (DEM) analysis, Cheng *et al.*<sup>[24]</sup> studied the temperature and density properties of different components of CMEs.

They found that the flux rope had the highest average temperature and density, resulting in an enhanced Emission Measure (EM) over a broad temperature range (3–20 MK). On the other hand, the CME front had a relatively cool temperature (2 MK) and a narrow temperature range (1–3 MK), similar to the pre-eruption coronal temperature; the difference is that the density in the LF increased by 2%–33% compared with the pre-eruption coronal value. For coronal dimming, the temperature varied in a broader range (1–4 MK), but the density decreased by 35%–40%. These observational results showed that the CME core regions were significantly heated, the CME fronts were a consequence of compression of the ambient plasma by the expansion of the CME core region, and the dimming were largely caused by the plasma rarefaction associated with the eruption.

In order to better understand the initiation mechanisms of the flux rope, Cheng *et al.*<sup>[25]</sup> investigated two successive flux rope (FR1 and FR2) eruptions on January 23, 2012. Through fitting their height evolution with a function consisting of linear and exponential components, they determined the onset time of the FR impulsive acceleration with high temporal accuracy for the first time. They found that at the onset of the impulsive acceleration phase, FR1 (FR2) reached the critical height of  $84.4 \pm 11.2$  Mm ( $86.2 \pm 13.0$  Mm) where the decline of the overlying field with height was fast enough to trigger the torus instability. After a very short interval ( $\sim 2$  minutes), the flare emission began to enhance. They suggested that the ideal torus instability probably played the essential role of initiating the impulsive acceleration of CMEs and the energy release of flares.

Owing to that it remains unclear how a Magnetic Flux Rope (MFR) evolves into and forms the multi-component structure of a CME, Cheng *et al.*<sup>[26]</sup> performed a comprehensive study of an MFR eruption on May 22, 2013. They found that as EUV brightenings began, the MFR started to rise slowly and showed helical threads winding around an axis. Meanwhile, cool filamentary materials descended spirally down to the chromosphere. These features provided direct ob-

servational evidence of intrinsically helical structure of the MFR. Moreover, they identified that the MFR evolved smoothly into the outer corona and appeared as a coherent structure within the white-light CME volume. The MFR in the outer corona was enveloped by bright fronts that originated from plasma pile-up in front of the expanding MFR.

Magnetic flux rope structure is a volumetric current channel. Using the data provided by the Atmospheric Imaging Assembly telescope on board SDO, Zhang *et al.*<sup>[27]</sup> for the first time found that the flux rope existed as a hot channel before and during a solar eruption. It initially appeared as a twisted and writhed sigmoidal structure with a temperature as high as 10 MK, and then transformed toward a semi-circular shape during a slow-rise phase, which was followed by fast acceleration and onset of a flare.

Through studying two well-observed CMEs that occurred on March 7, 2011 and March 8, 2011 in detail, Cheng *et al.*<sup>[28]</sup> found that the hot channel rose earlier than the first appearance of the CME Leading Front (LF) and the onset of the associated flare; the speed of the hot channel was always faster than that of the LF, at least in the field of view of AIA. These results indicated that the hot channel acted as a continuous driver of the CME formation and eruption in the early acceleration phase.

Li and Zhang<sup>[29]</sup> for the first time reported the eruption of two flux ropes occurred on January 23, 2012. They found that the first one appeared in SDO/AIA 94 Å ( $\sim 6.4$  MK) and 131 Å ( $\sim 10$  MK) images and another longer saddle-shaped flux rope appeared 25 min later. These two flux ropes initially rose rapidly, then slowly, and finally were again accelerated fast to become CMEs.

Using the materials motion of filaments, Li and Zhang<sup>[30]</sup> revealed the fine-scale structures of two flux ropes. The two flux ropes were, respectively, composed of  $85 \pm 12$  and  $102 \pm 15$  fine-scale structures, with an average width of about  $1.6''$ . They showed that two extreme ends of the flux rope were rooted in opposite polarity fields and each end was composed of multiple Foot Points (FPs) of fine-scale structures.



The FPs of the fine-scale structures were located at network magnetic fields, with magnetic fluxes from  $5.6 \times 10^{10}$  Wb to  $8.6 \times 10^{11}$  Wb. By calculating the magnetic fields of the FPs, they deduced that the two flux ropes occupied at least  $4.3 \times 10^{12}$  Wb and  $7.6 \times 10^{12}$  Wb magnetic fluxes, respectively.

Li and Zhang<sup>[31]</sup> also studied homologous flux ropes in the same Active Region (AR) 11 745 on May 20–22, 2013. The four flux ropes were all above the neutral line of the AR, with endpoints anchoring at the same region, and had a generally similar morphology. The first three flux-rope rose with a velocity of less than  $30 \text{ km}\cdot\text{s}^{-1}$  after their appearance, and subsequently their intensities at  $131 \text{ \AA}$  decreased and the flux ropes became obscure. The fourth flux rope erupted last, with a speed of about  $130 \text{ km}\cdot\text{s}^{-1}$  and formed a CME.

Guo *et al.*<sup>[32]</sup> studied Hard X-Ray (HXR) properties of a flux rope on May 27, 2005. They found that magnetic reconnection first started at the location of the pre-eruptive flux rope. Then, magnetic reconnection occurred between the pre-eruptive magnetic flux rope and the sheared magnetic arcades more than 10 minutes before the flare peak. This implied the formation of the larger flux rope, as observed with TRACE. Next, HXR sources appeared at the foot points of this larger flux rope at the peak of the flare. The associated high-energy particles might have been accelerated below the flux rope in or around a reconnection region. Still, the close spatial association between the HXR sources and the flux rope foot points favored the occurrence of acceleration within the flux rope.

To study the buildup of a magnetic flux rope, Guo *et al.*<sup>[33]</sup> computed the magnetic helicity injection, twist accumulation, and topology structure of the 3D magnetic field, which was derived by the non-linear force-free field model. They found that only about 1.8% of the injected magnetic helicity became the internal helicity of the magnetic flux rope, whose twist increasing rate was  $-0.18 \pm 0.08 \text{ r}\cdot\text{h}^{-1}$  and the flux rope was wrapped by QSLs with large  $Q$  values, where the magnetic reconnection induced by the con-

tinuously injected magnetic helicity further produced the confined flares. In the end, they suggested that the flux rope was built up and heated by the magnetic reconnection in the QSLs.

Moreover, Roussev *et al.*<sup>[34]</sup> presented a model of the dynamics of the solar atmosphere and inner solar wind region using a realistic representation of the electric field at the photosphere, calculated from flux-emergence computer simulations, as the boundary conditions. From the simulations, they showed how magnetic flux and helicity injection led to the reorganization of the solar corona and finally connected this process to the formation of the hot X-ray structure and CME.

It is well accepted that CMEs are natural products of coronal evolution as a consequence of magnetic helicity accumulation and that the triggering of CMEs by surface processes such as flux emergence also have their origin in magnetic helicity accumulation. The studies on magnetic helicity transport, accumulation, and its relationship between the CME are undergoing. Zhang *et al.*<sup>[35]</sup> used mathematical approach to study the magnetic helicity of axisymmetric power-law force-free fields and focused on a family whose surface flux distributions were defined by self-similar force-free fields. Their study suggested that there might be an absolute upper bound on the total magnetic helicity of all bipolar axisymmetric force-free fields. With the increase of accumulated magnetic helicity, the force-free field approached being fully opened up with Parker-spiral-like structures present around a current-sheet layer as evidence of magnetic helicity in the interplanetary space. It was also found that among the axisymmetric force-free fields having the same boundary flux distribution, the self-similar one had the maximum amount of total magnetic helicity. This gave a possible physical reason why self-similar fields are often found in astrophysical bodies, where magnetic helicity accumulation is presumably also taking place.

Zhang *et al.*<sup>[36]</sup> demonstrated that since  $v_{\perp}B$  could be deduced from a horizontal motion and vector magnetograms under a simple relation of  $v_t =$

$\mu_t + (v_n/B_n)B_t$ . And then they presented a new methodology which could determine magnetic helicity transport by the passage of helical magnetic field lines from the sub-photosphere and the shuffling motions of foot points of preexisting coronal field lines separately. Active Region (AR) NOAA 10930 was analyzed as an example. The observational results were: the helicity injection by flux emergence and shuffling motions had the same sign; during the studied period, the main contribution of helicity accumulation came from the flux emergence effect, while the dynamic transient evolution came from the shuffling motions effect. Their observational results further indicated that for this AR the apparent rotational motion in the following sunspot was the real shuffling motions on the solar surface.

An investigation on correlations between photospheric current helicity and subsurface kinetic helicity was carried out by analyzing vector magnetograms and subsurface velocities for two rapidly developing active regions by Gao *et al.*<sup>[37]</sup>. Over a span of several days, the evolution of the weighted current helicity showed a tendency similar to that of the weighted subsurface kinetic helicity, attaining a correlation coefficient above 0.60 for both active regions. Additionally, there seemed to be a phase lag between the evolutions of the un-weighted current and subsurface kinetic helicities for one of the active regions. The good correlation between these two helicities indicated that there was some intrinsic connection between the interior dynamics and photospheric magnetic twistedness inside active regions, which might help to interpret the well-known hemispheric preponderance of current-helicity distribution.

Yang *et al.*<sup>[38]</sup> used the method of Local Correlation Tracking to estimate the magnetic helicity evolution over Solar Cycle 23 from 1996 to 2009 using 795 MDI magnetic synoptic charts to investigate the characteristics of large-scale and long-term evolution of magnetic helicity with solar cycles. The main results were as follows: the hemispheric helicity rule still held in general, *i.e.*, the large-scale negative (positive) magnetic helicity dominated the

northern (southern) hemisphere. However, the large-scale magnetic helicity fluxes showed the same sign in both hemispheres around 2001 and 2005. The global, large-scale magnetic helicity flux over the solar disk changed from a negative value at the beginning of Solar Cycle 23 to a positive value at the end of the cycle, while the net accumulated magnetic helicity was negative in the period between 1996 and 2009.

Yang *et al.*<sup>[39]</sup> developed a method for calculating the vector potential of a magnetic field given in a finite volume. Their method used a fast Laplace/Poisson solver to obtain the vector potentials for a given magnetic field and for the corresponding potential (current-free) field. This allowed an efficient calculation of the relative magnetic helicity in a finite 3D volume. They tested their approach on a theoretical model and also applied the method to the magnetic field above active region NOAA 8210 obtained by a photospheric-data-driven MHD model. The results were: the amount of accumulated relative magnetic helicity coincided well with the relative helicity inflow through the boundaries in the ideal and non-ideal cases; the temporal evolution of relative magnetic helicity was consistent with that of magnetic energy. The maximum value of normalized helicity,  $H_m/\Phi^2 = 0.0298$ , was reached just before a drastic energy release by magnetic reconnection. This value was close to the corresponding value inferred from the formula that connected the magnetic flux and the accumulated magnetic helicity based on the observations of solar active regions.

Why and how do some Active Regions (ARs) frequently produce Coronal Mass Ejections (CMEs)? These are key questions for deepening our understanding of the mechanisms and processes of energy accumulation and sudden release in ARs and for improving our space weather prediction capability. Although some case studies have been performed, these questions are still far from fully answered. Wang *et al.*<sup>[40]</sup> addressed these issues through a statistically investigation of the waiting times of quasi-homologous CMEs from super ARs in Solar Cycle 23. It was found that the waiting times of quasi-homologous CMEs

had a two-component distribution with a separation at about 18 h. The first component was a Gaussian-like distribution with a peak at about 7 h, which indicated a tight physical connection between these quasi-homologous CMEs. The likelihood of two or more occurrences of CMEs faster than  $1200 \text{ km}\cdot\text{s}^{-1}$  from the same AR within 18 h was about 20%. Furthermore, the correlation analysis among CME waiting times, CME speeds, and CME occurrence rates revealed that these quantities were independent of each other, suggesting that the perturbation by preceding CMEs rather than free energy input was the direct cause of quasi-homologous CMEs. The peak waiting time of 7 h probably characterized the time scale of the growth of the instabilities triggered by preceding CMEs. This study uncovered some clues from a statistical perspective for us to understand quasi-homologous CMEs as well as CME-rich ARs.

Two major processes have been proposed to convert coronal magnetic energy into the kinetic energy of a CME: resistive magnetic reconnection and the ideal macroscopic MHD instability of a magnetic flux rope. However, it remains elusive whether both processes play a comparable role or one of them prevails during a particular eruption. To shed light on this issue, Song *et al.*<sup>[41]</sup> carefully studied energetic but flareless CMEs, *i.e.*, fast CMEs not accompanied by any flares. Through searching the Coordinated Data Analysis Workshops database of CMEs observed in Solar Cycle 23, they found 13 such events with speeds larger than  $1000 \text{ km}\cdot\text{s}^{-1}$ . Other common observational features of these events were: (1) none of them originated in active regions, they were associated with eruptions of well-developed long filaments in quiet-Sun regions; (2) no apparent enhancement of flare emissions was present in soft X-ray, EUV, and microwave data. Further studies of two events reveal that (1) the reconnection electric fields, as inferred from the product of the separation speed of post-eruption ribbons and the photospheric magnetic field measurement, were generally weak; (2) the period with a measurable reconnection electric field is considerably shorter than the total filament, CME

acceleration time. These observations indicated that for these fast CMEs, the magnetic energy was released mainly via the ideal flux-rope instability through the work done by the large-scale Lorentz force acting on the rope currents rather than via magnetic reconnections. They also suggested that reconnections played a less important role in accelerating CMEs in quiet-Sun regions of weak magnetic field than those in active regions of strong magnetic field.

The projection effect is one of the biggest obstacles in learning the real properties of CMEs and forecasting their geoeffectiveness. To evaluate the projection effect, Shen *et al.*<sup>[42]</sup> investigated 86 Full Halo CMEs (FHCMEs) listed in the Coordinated Data Analysis Workshop CME catalog from March 1, 2007 to May 31, 2012. By applying the Graduated Cylindrical Shell model, they obtained the deprojected values of the propagation velocity, direction, and angular width of these FHCMEs and compared them with the projected values measured in the plane-of-sky. Although these CMEs looked full halo in the view angle of SOHO, it was found that their propagation directions and angular widths could vary in a large range, implying projection effect was a major reason causing a CME being halo, but not the only one. Furthermore, the comparison of the deprojected and projected velocities revealed that most FHCMEs originating within  $45^\circ$  of the Sun-Earth line with a projected speed slower than  $900 \text{ km}\cdot\text{s}^{-1}$  suffered from large projection effect, while the FHCMEs originating far from the vicinity of solar disk center or moving faster than  $900 \text{ km}\cdot\text{s}^{-1}$  had small projection effect. Thus, for the latter class of FHCMEs, it was not necessary to correct the measured velocities.

Ruan *et al.*<sup>[43]</sup> presented the observation of a major solar eruption that was associated with fast sunspot rotation. The event included a sigmoidal filament eruption, a CME, and a Geostationary Operational Environmental Satellite (GOES) X2.1 flare from NOAA active region 11283. The filament and some overlying arcades were partially rooted in a sunspot. The sunspot rotated at  $\sim 10 \text{ h}^{-1}$  during a period of 6 h prior to the eruption. In this pe-

riod, the filament was found to rise gradually along with the sunspot rotation. Based on the Helioseismic and Magnetic Imager observation, for an area along the polarity inversion line underneath the filament, they found gradual pre-eruption decreases of both the mean strength of the photospheric horizontal field ( $B_h$ ) and the mean inclination angle between the vector magnetic field and the local radial (or vertical) direction. These observations were consistent with the pre-eruption gradual rising of the filament-associated magnetic structure. In addition, according to the nonlinear force-free field reconstruction of the coronal magnetic field, a pre-eruption magnetic flux rope structure was found to be in alignment with the filament, and a considerable amount of magnetic energy was transported to the corona during the period of sunspot rotation. Their study provided evidence that in that event sunspot rotation played an important role in twisting, energizing, and destabilizing the coronal filament-flux rope system, and led to the eruption. They also proposed that the pre-event evolution of  $B_h$  might be used to discern the driving mechanism of eruptions.

Song *et al.*<sup>[44]</sup> reported for the first time the detailed temperature evolution process of the magnetic flux rope in a failed solar eruption. Occurring on January 05, 2013, the flux rope was impulsively accelerated to a speed of  $\sim 400 \text{ km}\cdot\text{s}^{-1}$  in the first minute, then decelerated and came to a complete stop in two minutes. The failed eruption resulted in a large-size high-lying ( $\sim 100 \text{ Mm}$  above the surface), high-temperature “fire ball” sitting in the corona for more than two hours. The time evolution of the thermal structure of the flux rope was revealed through the differential emission measure analysis technique, which produced temperature maps using observations of the Atmospheric Imaging Assembly on board SDO. The average temperature of the flux rope steadily increased from 5 MK to 10 MK during the first nine minutes of the evolution, which was much longer than the rise time ( $\sim 3$  minutes) of the associated soft X-ray flare. They suggested that the flux rope was heated by the energy release of the continuing magnetic re-

connection, different from the heating of the low-lying flare loops, which was mainly produced by the chromospheric plasma evaporation. The loop arcade overlying the flux rope was pushed up by  $\sim 10 \text{ Mm}$  during the attempted eruption. The pattern of the velocity variation of the loop arcade strongly suggested that the failure of the eruption was caused by the strapping effect of the overlying loop arcade.

Feng *et al.*<sup>[45]</sup> developed a new 3D mask fitting reconstruction method and applied it to the CME ejected on August 7, 2010. They found that due to its interaction with the ambient solar wind, the morphology of this CME changed significantly in the early phase of evolution. Two hours after its initiation, it was expanding almost self-similarly. The CME's 3D localization was quite helpful to link remote sensing observations to in-situ measurements. They also found that the orientation of the major axis was consistent with the orientation of a filament (polarity inversion line) and the CME speed possibly had been adjusted to the speed of the ambient solar wind flow after leaving the COR2 field of view and before arriving at Venus.

Feng *et al.*<sup>[46]</sup> compared different CME reconstruction methods including geometric localization, mask fitting, forward modelling, polarization ratio, and local correlation tracking plus triangulation. They applied these five methods to the same CME event and found that the mask fitting and geometric localization methods produced consistent results; compared to the forward modelling method, the mask fitting had more flexibility; the 3D CME derived from the mask fitting lied mostly in the overlap region obtained with the polarization method using data from STEREO; the mask fitting could help resolve the front/back ambiguity inherent in the polarization ratio method.

Feng *et al.*<sup>[47]</sup> further applied the mask fitting reconstruction method to the CME on September 6, 2011. The sum of the kinetic and potential energy of the CME could go up to  $6.5 \times 10^{24} \text{ J}$  and the released free magnetic energy resulting from the NLFFF model was able to power the CME and asso-

ciated flare in AR 11283. Moreover, they uncovered that within the uncertainty, the flare and the CME might consume a similar amount of free energy.

Moreover, based on Thomson scattering theory that there exist explicit and implicit ambiguities in polarimetric analyses of CME observations, Dai *et al.*<sup>[48]</sup> suggested a classification for these ambiguities in CME reconstruction. They displayed three samples, including double explicit, mixed, and double implicit ambiguity with the polarimetric analyses of STEREO CME observations, which was helpful for improving polarimetric reconstruction.

### 3.2 Solar Flares

The observed hard X-ray and  $\gamma$ -ray continuum in solar flares is interpreted as Bremsstrahlung emission of accelerated non-thermal electrons. It has been noted for a long time that in many flares the energy spectra show hardening at energies around or above 300 keV. Kong *et al.*<sup>[49]</sup> first conducted a survey of spectral hardening events that were previously studied in literatures. They then performed a systematic examination of 185 flares from the Solar Maximum Mission. They identified 23 electron-dominated events whose energy spectra showed clear double power laws. A statistical study of these events showed that the spectral index below the break ( $\gamma_1$ ) anti-correlated with the break energy ( $\varepsilon_b$ ). Furthermore,  $\gamma_1$  also anti-correlated with  $F_r$ , the fraction of photons above the break compared to the total photons. A hardening spectrum, as well as the correlations between ( $\gamma_1$ ,  $\varepsilon_b$ ) and ( $\gamma_1$ ,  $F_r$ ), provided stringent constraints on the underlying electron acceleration mechanism. Their results supported a recent proposal that electrons were being accelerated diffusively at a flare termination shock with a width of the order of an ion inertial length scale.

It has long been noted that the spectra of observed continuum emissions in many solar flares are consistent with double power laws with a hardening at energies  $\geq 300$  keV. It is now widely believed that at least in electron dominated events, the hardening in the photon spectrum reflects an intrinsic hardening in the source electron spectrum. Li *et al.*<sup>[50]</sup> pointed

out that a power-law spectrum of electrons with a hardening at high energies could be explained by the diffusive shock acceleration of electrons at a termination shock with a finite width. Their suggestion was based on an early analytical work, where the steady-state transport equation at a shock with a tanh profile was solved for a  $p$ -independent diffusion coefficient. Numerical simulations with a  $p$ -dependent diffusion coefficient showed hardenings in the accelerated electron spectrum that were comparable with observations. One necessary condition for their proposed scenario to work was that high-energy electrons resonated with the inertial range of the MHD turbulence and low-energy electrons resonated with the dissipation range of the MHD turbulence at the acceleration site, and the spectrum of the dissipation ranged  $\sim k^{-2.7}$ . A  $\sim k^{-2.7}$  dissipation range spectrum was consistent with recent solar wind observations.

Solar flares typically have an impulsive phase that is followed by a gradual phase as best seen in soft X-ray emissions. Basing on the EUV Variability Experiment observations on board the SDO, Liu *et al.*<sup>[51]</sup> discovered that some flares exhibited a second large peak separated from the first main phase peak by tens of minutes to hours, which was coined as the flare's EUV late phase. They addressed the origin of the EUV late phase by analyzing in detail two late phase flares, an M2.9 flare on October 16, 2010 and an M1.4 flare on February 18, 2011, using multi-pass band imaging observations from the Atmospheric Imaging Assembly on board SDO. They found that the late phase emission originated from a different magnetic loop system, which was much larger and higher than the main phase loop system. The two loop systems had different thermal evolution. While the late phase loop arcade reached its peak brightness progressively at a later time spanning for more than one hour from high to low temperatures, the main phase loop arcade reached its peak brightness at almost the same time (within several minutes) in all temperatures. Nevertheless, the two loop systems seemed to be connected magnetically, forming an asymmetric magnetic quadruple configuration.

Further, the footpoint brightening in UV wavelengths showed a systematic delay of about one minute from the main flare region to the remote footpoint of the late phase arcade system. They argued that the EUV late phase was the result of a long-lasting cooling process in the larger magnetic arcade system.

It has recently been noted that solar eruptions can be associated with the contraction of coronal loops that are not involved in magnetic reconnection processes. Liu *et al.*<sup>[52]</sup> investigated five coronal eruptions originating from four sigmoidal active regions, using high-cadence, high-resolution narrow-band EUV images obtained by the SDO. The magnitudes of the flares associated with the eruptions ranged from GOES class B to class X. Owing to the high-sensitivity and broad temperature coverage of the Atmospheric Imaging Assembly (AIA) on board SDO, they were able to identify both the contracting and erupting components of the eruptions: the former was observed in cold AIA channels as the contracting coronal loops overlying the elbows of the sigmoid, and the latter was preferentially observed in warm/hot AIA channels as an expanding bubble originating from the center of the sigmoid. The initiation of eruption always preceded the contraction, and in the energetically mild events (Band C-flares), it also preceded the increase in GOES soft X-ray fluxes. In the more energetic events, the eruption was simultaneous with the impulsive phase of the non-thermal hard X-ray emission. These observations confirmed that loop contraction was an integrated process in eruptions with partially opened arcades. The consequence of contraction was a new equilibrium with reduced magnetic energy, as the contracting loops never regained their original positions. The contracting process was a direct consequence of flare energy release, as evidenced by the strong correlation of the maximal contracting speed, and strong anti-correlation of the time delay of contraction relative to expansion, with the peak soft X-ray flux. This was also implied by the relationship between contraction and expansion, *i.e.*, their timing and speed.

### 3.3 Prominences/Filaments

Prominences are sustained and confined by magnetic field lines above the chromospheres, and exhibit a strong coupling between magnetic forces and thermodynamics. At which height is a prominence inclined to be unstable, or where is the most probable critical height for the prominence destabilization? Liu *et al.*<sup>[53]</sup> statistically studied 362 solar limb prominences well recognized by Solar Limb Prominence Catcher and Tracker from April 2007 to the end of 2009. There were about 71% Disrupted Prominences (DPs), among which about 42% of them did not erupt successfully and about 89% of them experienced a sudden destabilization process. Most DPs became unstable at a height of  $0.06\text{--}0.14 R_s$  (solar radius) from the solar surface, and there were two most probable critical heights at which a prominence was very likely to become unstable, the first one was  $0.13 R_s$  and the second one was  $0.19 R_s$ . An upper limit for the erupting velocity of Eruptive Prominences (EPs) existed, which decreased following a power law with increasing height and mass; accordingly, the kinetic energy of EPs had an upper limit too, which decreased as the critical height increased. Stable prominences were generally longer and heavier than DPs, and not higher than  $0.4 R_s$ . About 62% of the EPs were associated with CMEs; but there was no difference in apparent properties between EPs associated with CMEs and those that were not.

Liu *et al.*<sup>[54]</sup> reported an active-region dextral filament that was composed of two branches separated in height by about 13 Mm, as inferred from 3D reconstruction by combining SDO and STEREO-B observations. This double-decker configuration sustained for days before the upper branch erupted with a GOES-class M1.0 flare on August 7, 2010. During the hours before the eruption, filament threads within the lower branch were observed to intermittently brighten up, lift upward, and then merged with the upper branch. The merging process contributed magnetic flux and current to the upper branch, resulting in its quasi-static ascent. This transfer might

serve as the key mechanism for the upper branch to lose equilibrium by reaching the limiting flux that could be stably held down by the overlying field or by reaching the threshold of the torus instability. The erupting branch first straightened from a reverse S shape that followed the polarity inversion line and then writhed into a forward S shape. This showed a transfer of left-handed helicity in a sequence of writhe-twist-writhe. The fact that the initial writhe was converted into the twist of the flux rope excluded the helical kink instability as the trigger process of the eruption, but supported the occurrence of the instability in the main phase, which was indeed indicated by the very strong writhing motion. A hard X-ray sigmoid, likely of coronal origin, formed in the gap between the two original filament branches in the impulsive phase of the associated flare. This supported a model of transient sigmoids forming in the vertical flare current sheet. Left-handed magnetic helicity was inferred for both branches of the dextral filament. Two types of force-free magnetic configurations were compatible with the data, a double flux rope equilibrium and a single flux rope situated above a loop arcade.

Liu *et al.*<sup>[55]</sup> investigated a prominence-like jet observed by SDO/AIA and STEREO-A/EUVI and found that the continuous relaxation of the post-reconnection magnetic field structure was an important process for a jet to climb up higher than it could through only reconnection. The kinetic energy of the jet gained through the relaxation was 1.6 times of that gained from the reconnection. The resultant energy flux was hundreds of times larger than the flux required for the local coronal heating, suggesting that such jets were a possible source to keep corona hot. Furthermore, rotational motions appeared all the time during the jet. They suggested that torsional Alfvén waves induced during reconnection could not be the only mechanism to release magnetic energy and drive jets.

Xia *et al.*<sup>[56]</sup> simulated the formation and sustained growth of a quiescent prominence. Contrary to previous works, their model captured all phases of

the prominence formation, including the loss of thermal equilibrium, its successive growth in height and width to macroscopic dimensions, and the gradual bending of the arched loops into dipped loops, as a result of the mass accumulation. They contributed the formation to concentrated heating in the chromosphere, followed by plasma evaporation and later rapid condensation in the corona due to thermal instability, as verified by linear instability criteria.

Zhang *et al.*<sup>[57]</sup> found that the prominence, seen as a concave-inward shape in lower-resolution Extreme Ultraviolet (EUV) images, consisting of many concave-outward threads, which was a strong indication of magnetic dips. After being injected into the dip region, a bulk of prominence material started to oscillate for more than 3.5 h, with the period of 52 min. The oscillation decayed with time, on the decay timescale 133 min. Zhang *et al.*<sup>[58]</sup> further investigated the underlying physics for coherent longitudinal oscillations of the entire filament body. Through radiative hydrodynamic numerical simulations of the longitudinal prominence oscillations with the help of the MPI-AMRVAC code, they figured out that microflare-sized impulsive heating at one leg of the loop and a suddenly imposed velocity perturbation could propel the prominence to oscillate along the magnetic dip. Their extensive parameter survey resulted in a scaling law that shows that the period of the oscillation scales with  $\sqrt{R/g_s}$ , where  $R$  represented the curvature radius of the dip, and  $g_s$  was the gravitational acceleration of the Sun.

Li and Zhang<sup>[59]</sup> showed observations of the Large-Amplitude Longitudinal (LAL) oscillations of two parts of a prominence on April 7, 2012. They found that the period varies with filamentary threads, ranging from 44 to 67 minutes. The oscillations of different threads were out of phase, and their velocity amplitudes varied from 30 to 60 km·s<sup>-1</sup>, with a maximum displacement of about 25 Mm. The oscillations of the south part repeated for about four cycles without any significant damping and then a nearby C2.4 flare caused the transition from the LAL oscillations of the filament to its later eruption. However, the

oscillations of the NP damp with time and died out at last. Their observations showed that the activated part of the south part repeatedly showed a helical motion. This indicated that the magnetic structure of the filament was possibly modified during this process.

Jiang *et al.*<sup>[60]</sup> studied the sunspot evolution associated with the first X-class flare of the present Solar Cycle 24 and found that the preceding spot of a bipole underwent the fastest movement. This led to the formation of a  $\delta$  configuration with an S-shaped neutral line. Along with the development of a Clockwise (CW) spiral penumbra-filament pattern, the merged spot started rapid CW rotation around its umbral center 20 h before the flare. When the shearing and rotational motions were main contributors to the energy buildup and helicity injection for the flare, the cancellation and collision might act as a trigger. Their observations supported the idea that the rotation could be attributed to the emergence of twisted magnetic fields, as proposed in recent theories.

Yan *et al.*<sup>[61–62]</sup> also found that the sunspot rotation played an important role in the formation and eruption of the sigmoidal active-region filament through transporting the twist into the filament from the lower atmosphere to the higher atmosphere.

Bi *et al.*<sup>[63]</sup> displayed an eruption of the solar filament consisting of two threads. They found that the elongating thread was driven to contact and interact with the second one, and it then erupted with its southern leg being wrapped by a newly formed thread produced by the magnetic reconnection between fields carried by the two threads. They suggested that the eruption was triggered by the reconnection of the turbulent filament thread and the surrounding magnetic field, and that it was mainly driven by the kink instability of the southern leg of the eruptive filament that possessed a more twisted field introduced by the reconnection-produced thread.

Bi *et al.*<sup>[64]</sup> studied an eruptive filament showing both rotation and non-radial motion. The consequence of the 3D reconstruction of the filament axis indicated that a significant rotation was simultane-

ous with the severe deflection in the latitude during the eruption. In combination with the results of a derived coronal magnetic configuration, their observations suggested that the non-radial motion resulted from the interaction between the eruption and an overlying pseudo-streamer. Moreover, they found that the deflection of the eruption was asymmetric, with its eastern segment being dragged more significantly than its western one, indicating that the action of the asymmetric deflection was possibly an alternative mechanism for the rotation of the eruptive filament.

Jiang *et al.*<sup>[65]</sup> presented a rare observation of an interaction between two filaments. They found that a small filament (F12) underwent a failed eruption that brought it into contact with a nearby larger, thicker filament (F34). Accompanied by the appearance of complicated internal structures below the erupting F12, its two legs separated away from each other and then connected into F34. This process led the filaments to change their connectivity to form two newly linked filaments. These observations could be interpreted as a partial slingshot reconnection between two filaments that had unequal axial magnetic flux. Kong *et al.*<sup>[66]</sup> also investigated two successive filament eruptions and concluded that the interaction of two filaments and the opening of the large-scale overlying coronal loops caused by the first filament eruption were the most important reason that led to the second filament eruption.

Wang *et al.*<sup>[67]</sup> reconstructed the 3D coronal magnetic field for the NOAA active region 11158 on February 14, 2011 for the first time, and compared the reconstructed magnetic field lines in all 3 aspects with the projected EUV loop structures as observed in the front-view (SDO/AIA) and the side-view (STEREO-A/B) images. They found that the reconstructed highly sheared magnetic field lines agreed very well with the low-lying sigmoidal filament along the polarity inversion line and demonstrated the importance of stereoscopic information in the coronal magnetic field reconstruction. It was pointed out that this central low-lying magnetic field loop system must have played



a key role in powering the flare.

Yan *et al.*<sup>[68]</sup> presented an observation of overlying coronal loop contraction and rotating motion of the sigmoid filament during its eruption on May 22, 2012 observed by SDO. Their results showed that the twist could be transported into the filament from the lower atmosphere to the higher atmosphere. The successive contraction of the coronal loops was due to a suddenly reduced magnetic pressure underneath the filament, which was caused by the rising of the filament. Before the sigmoid filament eruption, there was a counterclockwise flow in the photosphere at the right feet of the filament and the contraction loops and a convergence flow at the left foot of the filament. The hot and cool materials had inverse motion along the filament before the filament eruption. Moreover, two coronal loops overlying the filament first experienced brightening, expansion, and contraction successively. At the beginning of the rising and rotation of the left part of the filament, the second coronal loop exhibited rapid contraction. The top of the second coronal loop also showed counterclockwise rotation during the contraction process. After the contraction of the second loop, the left part of the filament rotated counterclockwise and expanded toward the right of NOAA AR 11485. During the filament expansion, the right part of the filament also exhibited counterclockwise rotation like a tornado.

Yan *et al.*<sup>[69]</sup> also studied the kink instability of a filament. They found that during the eruption of filament, its leg exhibited a significant rotation motion with the rotation angle up to about  $510^\circ$  (about  $2.83\pi$ ) around the axis of the filament within 23 minutes. The maximal rotation speed reached  $100^\circ\cdot\text{min}^{-1}$  (about  $379.9\text{km}\cdot\text{s}^{-1}$  at radius  $18''$ ), which was the fastest rotation speed reported. In the end, they suggested that the kink instability could be the trigger mechanism for the solar filament eruption.

Zhang *et al.*<sup>[70]</sup> investigated how magnetic flux emergence affected the formation and evolution of solar quiescent prominences following the two-stage catastrophic flux rope model presented by them. The

magnetic properties of the flux rope were described with its toroidal magnetic flux per radian  $\Phi_\varphi$  and poloidal flux  $\Phi_p$ , and  $\Phi_p$  was defined as the Emerging Strength (ES) of the magnetic flux. After the first catastrophe, the quiescent prominences were supported by the vertical current sheet and located in cavities below the curved transverse current sheet in the inner corona, for which both ES and  $\Phi_\varphi$  were in the certain ranges. They calculated the strength range as  $0.25 < \text{ES} < 0.50$  for the quadrupolar field, and obtained the equation  $\Phi_p \Phi_\varphi = \text{const.}$ , that was, the relationship between  $\Phi_p$  and  $\Phi_\varphi$  of the emerging flux for which the quiescent prominences were formed in the inner corona. After the second catastrophe, the quiescent prominences would either fall down onto the solar surface or erupt as an important part of CMEs. During the eruption of the quiescent prominences, most of the magnetic energy in the flux rope was lost, and less than half of the energy loss of the rope was released in the form of Alfvén waves. They argued that there would be two important conditions required for the formation and eruption of solar quiescent prominences, a complicated source region and emerging toroidal magnetic flux that exceeded a critical strength.

Chen *et al.*<sup>[71]</sup> studied the dynamics of a filament channel on January 29, 2011. The Extreme Ultraviolet (EUV) spectral observations revealed that there were no EUV counterparts of the  $H_\alpha$  counterstreamings in the filament channel, implying that the ubiquitous  $H_\alpha$  counter-streaming found by previous research were mainly due to longitudinal oscillations of filament threads. However, there existed larger-scale patchy counter-streaming in EUV along the filament channel from one polarity to the other, implying that there was another component of unidirectional flow inside each filament thread in addition to the implied longitudinal oscillation. Their results implied that the flow direction of the larger-scale patchy counter-streaming plasma in the EUV was related to the intensity of the plage or active network, with the upflows being located at brighter areas of the plage and downflows at the weaker areas. Finally, they pro-

posed a new method to determine the chirality of an erupting filament based on the skewness of the conjugate filament drainage sites and suggested that the right-skewed drainage corresponded to sinistral chirality, whereas the left-skewed drainage corresponded to dextral chirality.

### 3.4 Radio Bursts and Non-thermal Processes

It has been suggested that Type II radio bursts are due to energetic electrons accelerated at coronal shocks. Radio observations, however, have poor or no spatial resolutions to pinpoint the exact acceleration locations of these electrons. Feng *et al.*<sup>[72]</sup> discussed a promising approach to infer the electron acceleration location by combining radio and white light observations. The key assumption was to relate specific morphological features (*e.g.*, spectral bumps) of the dynamic spectra of Type II radio bursts to imaging features (*e.g.*, CME going into a streamer) along the CME (and its driven shock) propagation. They examined the CME-streamer interaction for the solar eruption dated on November 1, 2003. The presence of spectral bump in the relevant Type II radio burst was identified, which was interpreted as a natural result of the shock-radio-emitting region entering the dense streamer structure. The study was useful for further determinations of the location of Type II radio burst and the associated electron acceleration by CME-driven shock.

Kong *et al.*<sup>[73]</sup> discussed an intriguing Type II radio burst that occurred on March 27, 2011. The dynamic spectrum was featured by a sudden break at about 43 MHz on the well-observed harmonic branch. Before the break, the spectrum drifted gradually with a mean rate of about  $-0.05 \text{ MHz}\cdot\text{s}^{-1}$ . Following the break, the spectrum jumped to lower frequencies. The post-break emission lasted for about 3 minutes. It consisted of an overall slow drift which appeared to have a few fast-drift sub-bands. Simultaneous observations from the STEREO and SDO were also available and were examined for this event. They suggested that the slow-drift period before the break was generated inside a streamer by a coronal eruption driven shock, and the spectral break as well as the

relatively wide spectrum after the break was a consequence of the shock crossing the streamer boundary where density dropped abruptly. It was suggested that this type of radio bursts could be taken as a unique diagnostic tool for inferring the coronal density structure, as well as the radio-emitting source region.

In recent studies, Feng *et al.*<sup>[74]</sup> proposed that source properties of Type II radio bursts could be inferred through a causal relationship between the special shape of the Type II dynamic spectrum (*e.g.*, bump or break) and simultaneous Extreme Ultraviolet (EUV)/white light imaging observations (*e.g.*, CME-shock crossing streamer structures). As a further extension of these studies, they examined the CME event on December 31, 2007 associated with a multiple Type II radio burst. They identified the presence of two spectral bump features on the observed dynamic spectrum. By combining observational analyses of the radio spectral observations and the EUV-white light imaging data, they concluded that the two spectral bumps resulted from a CME-shock propagating across dense streamers on the southern and northern sides of the CME. It was inferred that the corresponding two Type II emissions originating separately from the two CME-shock flanks where the shock geometries were likely quasi-perpendicular or oblique. Since the emission lanes were bumped as a whole within a relatively short time, it suggested that the Type II radio bursts with bumps of this study were emitted from spatially confined sources (with a projected lateral dimension smaller than  $0.05\text{--}0.1 R_s$  at a fundamental frequency level of 20–30 MHz).

Liu *et al.*<sup>[75]</sup> reported a solar eruptive event, in which a Vertical Current Sheet (VCS) was observed in the wake of an erupting flux rope in the SDO/AIA 131 Å pass band. The VCS was first detected following the impulsive acceleration of the erupting flux rope but prior to the onset of a non-thermal Hard X-Ray (HXR)/microwave burst, with plasma blobs moving upwards at speeds up to  $1400 \text{ km}\cdot\text{s}^{-1}$  along the sheet. The timing suggested that the VCS with plasma blobs might not be the primary accelerator for

non-thermal electrons emitting HXR/microwaves. The initial, slow acceleration of the erupting structure was associated with the slow elevation of a thermal loop top HXR source and the subsequent, impulsive acceleration was associated with the downward motion of the loop top source. They found that the plasma blobs moving downwards within the VCS into the cusp region and the flare loops retracting from the cusp region made a continuous process, with the former apparently initiating the latter, which provided a 3D perspective on reconnections at the VCS. They also identified a dark void moving within the VCS towards the flare arcade, which suggested that dark voids in supra-arcade down flows were of the same origin as plasma blobs within the VCS.

Decameter-Hectometric (D-H) Type II radio bursts are widely thought to be caused by CMEs. However, it is still unclear where the exact source of the Type II on the shock surface is. Shen *et al.*<sup>[76]</sup> identified the source regions of the D-H Type II based on imaging observations from SOHO/LASCO and the radio dynamic spectrum from WIND/Waves. The analysis of two well-observed events suggested that the sources of these two events were located in the interaction regions between shocks and streamers, and that the shocks were enhanced significantly in these regions.

Chen *et al.*<sup>[77]</sup> presented a comprehensive review of recent studies on coronal dynamics, including research progresses of the physics of coronal streamers that are the largest structure in the corona, physics of CMEs that might cause a global disturbance to the corona, as well as physics of CME-streamer interactions. The following topics were discussed in depth: acceleration of the slow wind flowing around the streamer considering the effect of magnetic flux tube curvature, physical mechanism accounting for persistent releases of streamer blobs and diagnostic results on the temporal variability of the slow wind speed with such events, force balance analysis and energy release mechanism of CMEs with a flux rope MHD model, statistical studies on magnetic islands along the coronal-ray structure behind a CME and

the first observation of magnetic island coalescence with associated electron acceleration, and white light and radio manifestations of CME-streamer interactions. These studies shed new light on the physics of coronal streamers, the acceleration of the slow wind, the physics of solar eruptions, the physics of magnetic reconnection and associated electron acceleration, the large-scale coronal wave phenomenon, as well as the physics accounting for CME shock-induced Type II radio bursts.

Based on observations of the Chinese Solar Broadband Radio Spectrometer at Huairou with super high cadence and frequency resolution, the non-thermal processes of solar eruptions in the form of microwave fine structures, such as quasi-periodic pulsation, zebra pattern, dot, spike, and narrowband Type III bursts, are studied in more detail in recently years. Huang *et al.*<sup>[78]</sup> studied the microwave bursts with Fine Structures (FSs) at 1.10–1.34 GHz in the decay phase of a solar flare, which showed a peak-to-peak correlation with 25–50 keV Hard X-Ray (HXR) bursts observed by Reuven Ramaty High Energy Solar Spectroscopic Imaging (RHESSI). The similarity between 25 and 50 keV HXR light curve and microwave time profiles at 1.10–1.34 GHz suggested that these microwave FSs were related to the properties of electron acceleration. The electron velocity inferred from the frequency drift rates in short narrowband bursts was in the range of  $0.13c$ – $0.53c$  and the corresponding energy was about 10–85 keV, which was close to the energy of HXR-emitting electrons. From the Alfvén soliton model of fiber structures, the double plasma resonance model of ZPs, and the Bernstein model of the lace bursts, a similar magnetic field strength in the range of 60–70 G was deduced.

Tan *et al.*<sup>[79]</sup> studied a peculiar microwave Quasi-Periodic Pulsation (QPP) of millisecond timescale superfine structures accompanying a Hard X-ray (HXR) QPP of about 20 s duration occurring just before the maximum of a solar flare. Each microwave QPP pulse was made up of clusters of millisecond spike bursts or narrowband Type III bursts. The physical analysis indicated that the energetic electrons accelerated from

a large-scale highly dynamic magnetic reconnecting current sheet above the flaring loop propagated downward, impacted the flaring plasma loop, and produced HXR bursts. The Tearing-Mode (TM) oscillations in the current sheet modulated HXR emission and generated HXR QPP; the energetic electrons propagating downward produced Langmuir turbulence and plasma waves, resulting in plasma emission. The modulation of TM oscillation on the plasma emission in the current-carrying plasma loop might generate microwave QPP. The TM instability produced magnetic islands in the loop. Each X-point would be a small reconnection site and would accelerate the ambient electrons. These accelerated electrons impacted the ambient plasma and triggered the millisecond spike clusters or the group of Type III bursts. Possibly, each millisecond spike burst or Type III burst was one of the Elementary Bursts (EBs). A large number of such EB clustered formed an intense flaring microwave burst.

Tan *et al.*<sup>[80]</sup> studied an unusual high-frequency Zebra Pattern (ZP) structure at a frequency of 6.40–7.00 GHz (ZP1) and at a frequency of 2.60–2.75 GHz (ZP2) and a frequency of 1.04–1.13 GHz (ZP3), which occurred in the early rising phase of the flare (ZP1) and the decay phase of the flare (ZP2, ZP3). Their observational results suggested that the double plasma resonance model was the most probable one for explaining the formation of microwave ZPs, which might derive the magnetic field strengths at about 230–345 G, 126–147 G, and 23–26 G in the source regions of ZP1, ZP2, and ZP3, respectively.

By analyzing the parameter of Zebra Pattern (ZP), Yu *et al.*<sup>[81]</sup> found that the ratio between the plasma density scale height and the magnetic field scale height in emission sources displayed a tendency to decrease during the flaring processes.

Yu *et al.*<sup>[82]</sup> found a quasi-periodic wiggles of microwave Zebra Pattern (ZP) structures with periods ranging from about 0.5 s to 1.5 s. The wiggles had two to three significant periodicities and were almost in phase between stripes at different frequencies. The

Alfvén speed estimated from the ZP structures was about  $700 \text{ km}\cdot\text{s}^{-1}$ . They found the spatial size of the wave-guiding plasma structure to be about 1 Mm with a detected period of about 1 s. This suggested that the ZP wiggles could be associated with the fast magnetoacoustic oscillations in the flaring active region. The lack of a significant phase shift between wiggles of different stripes suggested that the ZP wiggles were caused by a standing sausage oscillation.

Based on the synthetic investigations of RHESSI hard X-ray, GOES soft X-ray observations, and magnetic field extrapolation, Wang *et al.*<sup>[83]</sup> presented a reversed drifting quasi-periodic pulsating structure (R-DPS), and suggested that the R-DPS possibly reflected flaring dynamic processes of the emission source regions.

Solar small-scale Microwave Bursts (SMBs), including microwave dot, spike, and narrow-band Type III bursts, in several flares that occurred in active region NOAA 10720 during January 14–21, 2005 were investigated by Tan *et al.*<sup>[84]</sup>. They found that the SMBs occurred not only in the early rising and impulsive phase, but also in the flare decay phase and even after the end of the flare. These SMBs were strong bursts with inferred brightness temperatures of at least  $8.18 \times 10^{11}$ – $1.92 \times 10^{13}$  K, very short lifetimes of 5–18 ms, relative frequency bandwidths of 0.7%–3.5%, and super high frequency drifting rates. Together with their obviously different polarizations from background emission (the quiet Sun, and the underlying flaring broad band continuum), such SMBs should be individual, independent strong coherent bursts related to some non-thermal energy release and the production of energetic particles in a small-scale source region. These facts showed the existence of small-scale strong non-thermal energy releasing activities after the flare maxima, which was meaningful for predicting space weather. Physical analysis indicated that a plasma mechanism might be the most favorable candidate for the formation of SMBs. From the plasma mechanism, the velocities and kinetic energy of fast electrons could be deduced and the region of electron acceleration could also be tracked.

## 4 Solar Energetic Particle and Galactic Cosmic Ray

Wang *et al.*<sup>[85]</sup> presented a statistical survey of 2–20 keV superhalo electrons in the solar wind measured by the two STEREO spacecraft during quiet-time periods from 2007 March through 2009 March at solar minimum. The observed superhalo electrons had a nearly isotropic angular distribution and a power-law spectrum. The integrated density of quiet-time superhalo electrons at 2–20 keV and the power-law spectrum showed no correlation with solar wind proton density, velocity, or temperature. The density of superhalo electrons appeared to show a solar-cycle variation at solar minimum, while the power-law spectral index had no solar-cycle variation. The results suggested that these superhalo electrons may be accelerated by processes such as resonant wave-particle interactions in the interplanetary medium, or possibly by nonthermal processes related to the acceleration of the solar wind such as nanoflares, or by acceleration at the CIR forward shocks.

Wang *et al.*<sup>[86]</sup> surveyed the statistical properties of solar electron events observed by the WIND 3DP instrument for a solar cycle. After taking into account times of high background, the corrected occurrence frequency of solar electron events versus peak flux exhibited a power-law distribution, and the corrected occurrence rate over the whole Sun was  $\sim 104 \text{ a}^{-1}$  near solar maximum. The observed solar electron events have a  $\sim 35\%$  association with GOES SXR flares, but a  $\sim 60\%$  association with a west-limb CME. These electrons are often detected down to below 1 keV, indicating a source high in the corona.

Wang *et al.*<sup>[87]</sup> studied effects of perpendicular diffusion on energetic particles accelerated by the interplanetary coronal mass ejection shock. Based on a numerical solution of the focused transport equation, they obtained the intensity and anisotropy time profiles of Solar Energetic Particles (SEPs) accelerated by an interplanetary shock in the 3D Parker magnetic field. The shock was treated as a moving source of energetic particles with an assumed particle distribution function.

They computed the time profiles of particle flux and anisotropy as measured by an observer at 1 AU, equatorial plane, and various longitudes with respect to the shock propagation direction. Their simulations showed that the particle onset time, peak time, peak intensity, decay rate, and duration of SEP event could be significantly influenced by the effect of perpendicular diffusion. The anisotropy with perpendicular diffusion was almost the same as that without perpendicular diffusion, but there was an obvious difference at the moment when the observer's field line began to be connected to the shock.

Qin and Shalchi<sup>[88]</sup> used computer simulations to investigate numerically cross field transport and particle propagation along the mean magnetic field for different turbulence models at large scales. Their results were compared with quasilinear theory and nonlinear diffusion theories. They showed that for different forms of the turbulence spectrum at large scales, the perpendicular mean free paths obtained numerically were in agreement with recent predictions made by analytical theory.

Qin *et al.*<sup>[89]</sup> reproduced the reservoir phenomenon in which it was frequently observed during the decay phase of gradual SEP events that particle fluxes were nearly the same at very different locations in the inner heliosphere up to 5 AU. The reservoir phenomenon was reproduced in their simulation under a variety of conditions of particle perpendicular diffusion estimated from the Non-Linear Guiding Center theory (NLGC). As the perpendicular diffusion coefficient increased, the nonuniformity of particle fluxes became smaller, making the reservoir phenomenon more prominent.

Qin and Shalchi<sup>[90]</sup> explored the random walk of magnetic field lines in two-component turbulence by using computer simulations. They showed that there were two transport regimes. One was the well-known quasilinear regime in which the diffusion coefficient was proportional to the Kubo number squared, and the second one was a nonlinear regime in which the diffusion coefficient was directly proportional to the Kubo number. The so-called percolative trans-

port regime which was often discussed in the literature could not be found. The numerical results obtained by them confirmed analytical theories for random walking field lines developed in the past.

Qin and Shalchi<sup>[91]</sup> revisited a well-known problem in diffusion theory, namely the  $90^\circ$  scattering problem. They used a test-particle code to compute the pitch-angle Fokker-Planck coefficient at  $90^\circ$  for different values of the turbulent magnetic field strength and the magnetic rigidity. They considered a slab model and compared their numerical findings with the analytical result provided by second-order quasilinear theory. They showed that the latter theory accurately describes  $90^\circ$  scattering.

Qin and Shalchi<sup>[92]</sup> employed a test-particle code to explore diffusion of energetic particles interacting with the solar wind plasma. The first time they investigated the pitch-angle dependence of perpendicular diffusion for different parameter regimes. These results were important for numerical solutions of the pitch-angle dependent Cosmic Ray Fokker-Planck equation.

Qin and Zhang<sup>[93]</sup> modified the NLGC theory for perpendicular diffusion by replacing the spectral amplitude of the two-component model of magnetic turbulence with that of the two-dimensional (2D) model, and replacing the constant  $a^2$ , which indicated the degree particles following the magnetic field line, with the variable  $a'^2$  as a function of the magnetic turbulence. They combined the modified model with the Non-Linear Parallel diffusion theory to solve perpendicular and parallel diffusion coefficients simultaneously. It was shown that the new model agreed better with simulations.

Wu *et al.*<sup>[94]</sup> reported observations of the acceleration and trapping of energetic ions and electrons between a pair of Corotating Interaction Regions (CIRs). The event occurred in Carrington Rotation 2060. Observed by the STEREO-B spacecraft, the two CIRs were separated by less than 5 days. In contrast to other CIR events, the fluxes of the energetic ions and electrons in this event reached their maxima between the trailing edge of the first CIR

and the leading edge of the second CIR. The radial magnetic field ( $B_r$ ) reversed its sense and the anisotropy of the flux also changed from Sunward to anti-Sunward between the two CIRs. Furthermore, there was an extended period of counter-streaming-suprathermal electrons between the two CIRs. Similar observations for this event were also obtained with the Advanced Composition Explorer and STEREO-A. They conjectured that these observations were due to a U-shaped, large-scale magnetic field topology connecting the reverse shock of the first CIR and the forward shock of the second CIR. Such a disconnected U-shaped magnetic field topology may have formed due to magnetic reconnection in the upper corona.

Galactic Cosmic Ray (GCR) is usually assumed as a stable background, with solar influence considered as a modulation. The violent Solar Energetic Particle (SEP) events associated with solar activities change particle fluxes by several orders of magnitude in a few minutes. Qin *et al.*<sup>[95]</sup> used a robust automatic despiking algorithm based on the Poincare map thresholding method provided by Goring and Nikora for purification of the time-series GCR flux observations. They could show that the algorithm was good at cleaning up the heavily contaminated GCR intensity rates measured by both spacecraft and NMs without artificial parameters. In addition, using the algorithm to despiking the spacecraft observations of relatively lower energetic proton flux, they got both 11 year and 27 day period cycles comparable to the much higher energy GCR flux data measured by the ground-based NMs.

Zhao and Qin<sup>[96]</sup> presented an observation-based elemental GCR heavy nuclei spectra model, based on ACE/CRIS measurements. Then they extrapolated the spectra model to the lower energy range of ACE/SIS instrument. In addition, they compared the modeling results with both the CRIS and SIS measurements. The flux of lower energetic particles measured by SIS was despiked since there were SEP events. The good agreement between the modeling and the observation results, especially for the solar minimum, indicated the validity of their model in

the energy range 30–500 MeV/nuc. Compared with two GCR radiation environment models, their model could provide an improved fit to the GCRs spectra measured by ACE. Furthermore, their model is a phenomenological one, without consideration of the physical process during GCRs propagating through the heliosphere. Therefore, it is more straightforward and applicable in practice.

During the recent solar minimum between Cycle 23 and 24 (solar minimum  $P_{23/24}$ ), the intensity of GCR measured at the Earth was the highest ever recorded since space age. Zhao *et al.*<sup>[97]</sup> resolved the most plausible mechanism for this unusually high intensity. A GCR transport model in 3D heliosphere based on a simulation of Markov stochastic process was used. They calculated GCR proton energy spectra at the Earth for the last three solar minima  $P_{21/22}$ ,  $P_{22/23}$ , and  $P_{23/24}$ , with the transport parameters obtained from observations. Besides weak IMF magnitude and slow SW speed, they found that a possible low magnetic turbulence, which increased the parallel diffusion and reduced the perpendicular diffusion in the polar direction, might be an additional possible mechanism for the high GCR intensity in the solar minimum  $P_{23/24}$ .

## 5 Magnetic Reconnection

Magnetic reconnection is a fundamental plasma process. Recent theoretical studies and numerical simulations have suggested that electrons can be efficiently accelerated in contracting magnetic islands and when magnetic islands coalesce. Using data from the STEREO spacecraft, Song *et al.*<sup>[98]</sup> reported the first observation of macroscopic magnetic-island coalescence and a possible splitting, and the associated electron acceleration. On May 24, 2010, two magnetic islands were observed by both the STEREO-A and STEREO-B spacecraft to propagate out along the current sheet behind a CME and merge. Electron acceleration to above 10 keV was inferred through the observation of a Type-III-like radio burst. The acceleration process occurred at a macroscopic scale,

likely during the merging of the two magnetic islands. Their observation of the magnetic-island coalescence was supported by a 2.5D axisymmetric MHD simulation of CME in which the merging of post-CME magnetic islands was clearly identified.

Xu, Wei and Feng<sup>[99]</sup> reported that a Petschek-like reconnection exhaust of extremely low plasma density was detected by ACE and WIND on January 6, 2007 near 1 AU in the solar wind. The exhaust was characterized by an apparent Hall bipolar magnetic field, ion and electron density depletion layers and pitch angle distribution of low energy electrons anti-parallel to the direction of Hall current. Such features indicated a possible reconnection ion diffusion region in the solar wind. To the best of their knowledge, this was the first time to report direct detections of ion diffusion region associated with solar wind reconnection exhaust. Observations showed that the associated reconnection was quasi-steady, almost anti-parallel merging (no guide field) and fast with a dimensionless reconnection rate of about 2%. Meanwhile, the diffusion region was bounded by a pair of slow-mode waves and the spatial width was up to 80 ion inertial lengths, revealing large-scale characteristics of reconnection for large systems.

Magnetic reconnection is one of the hot topics in space physics. The magnetic Lundquist number can influence the magnetic reconnection process drastically. Magnetic Lundquist number is always very large in many real physical environments, for example, higher than  $10^4$  in interplanetary space and solar corona. Magnetic reconnection with enormously large Lundquist number behaves many new characteristics, while magnetic reconnection simulation needs very high grid resolution, or it can't resolve the thin current sheets formed in the magnetic reconnection. With the help of the Adaptive Mesh Refinement (AMR) package named PARAMESH, Zhang, Feng and Yang<sup>[100]</sup> introduced AMR technique into magnetic reconnection simulations and developed a 2.5D AMR magnetic reconnection model. The dynamic reconnection process with different magnetic Lundquist numbers was studied. Their results showed that this

model could automatically capture the near-singular current sheets with the development of the magnetic reconnection and the slow-mode shock structures formed in the magnetic reconnection process with high magnetic Lundquist number, providing a possible way for fast magnetic energy conversion.

The magnetic cloud Boundary Layer (BL) is a dynamic region formed by the interaction of the Magnetic Cloud (MC) and the ambient solar wind. Wang *et al.*<sup>[101]</sup> comparatively investigated the proton and electron mean flux variations in the BL, in the interplanetary Reconnection Exhaust (RE), and across the MC-driven shock by using the WIND data from 1995 to 2006. In general, the proton flux had higher increments at lower energy bands compared with the ambient solar wind. Inside the BL, the core electron flux increased quasi-isotropically and the increments decreased monotonously with energy from  $\sim 30\%$  (at 18 eV) to  $\sim 10\%$  (at 70 eV); the suprathermal electron flux usually increased in either parallel or antiparallel direction; the correlation coefficient of electron flux variations in parallel and antiparallel directions changed sharply from  $\sim 0.8$  below 70 eV to  $\sim 0$  above 70 eV. Similar results were also found for RE. However, different phenomena were found across the shock where the electron flux variations first increased and then decreased with a peak increment ( $> 200\%$ ) near 100 eV. The correlation coefficient of electron flux variations in parallel and antiparallel directions was always around 0.8. The similar behavior of flux variations in BL and RE suggested that reconnection might commonly occur in BL. Their work also implied that the strong energy dependence and direction selectivity of electron flux variations, which were previously thought to have not enough relevance to magnetic reconnection, could be considered as an important signature of solar wind reconnection from the statistical point of view.

Electron acceleration in a drastically evolved current sheet under solar coronal conditions was investigated by Zhang *et al.*<sup>[102]</sup> via the combined 2.5D resistive MHD and test-particle approaches. Having a high magnetic Reynolds number ( $10^5$ ), the long, thin

current sheet was torn into a chain of magnetic islands, which grew in size and coalesce with each other. The acceleration of electrons was explored in three typical evolution phases: when several large magnetic islands were formed (Phase 1), two of these islands were approaching each other (Phase 2), and almost merging into a “monster” magnetic island (Phase 3). The results showed that for all three phases electrons with an initial Maxwell distribution evolved into a heavy-tailed distribution and more than 20% of the electrons could be accelerated higher than 200 keV within 0.1 second and some of them could even be energized up to MeV ranges. The lower-energy electrons were located away from the magnetic separatrices and the higher-energy electrons were inside the magnetic islands. The most energetic electrons had a tendency to be around the outer regions of the magnetic islands or to appear in the small secondary magnetic islands. It was the trapping effect of the magnetic islands and the distributions of  $E_p$  that determined the acceleration and spatial distributions of the energetic electrons.

## 6 Physics-based MHD Models and Their Applications

Feng and his colleagues at the Solar-Interplanetary-Geomagnetic (SIGMA) Weather Group of the State Key Laboratory of Space Weather in China have developed a 3D MHD model to investigate solar-interplanetary phenomena based on the space time Conservation Element and Solution Element (CESE) method (abbreviated as SIP-CESE MHD model).

Feng *et al.*<sup>[103–104]</sup> carried out the AMR implementation of their SIP-CESE MHD model using a six-component grid system. By transforming the governing MHD equations from the physical space  $(x, y, z)$  to the computational space  $(\xi, \eta, \zeta)$  while retaining the form of conservation, the SIP-AMR-CESE MHD model was implemented in the reference coordinates with the aid of the parallel Adaptive Mesh Refinement (AMR). Meanwhile, the volumetric heating source terms derived from the topol-



ogy of the magnetic-field expansion factor and the minimum angular separation (at the photosphere) between an open-field foot point and its nearest coronal-hole boundary were also included. They showed the preliminary results of applying the SIP-AMR-CESE MHD model for simulating the solar-wind background of different solar-activity phases by comparison with SOHO observations and other spacecraft data from OMNI. Their numerical results showed overall good agreements in the solar corona and in interplanetary space with these multiple-spacecraft observations.

Feng *et al.*<sup>[105]</sup> constructed a data-driven model for the study of the dynamic evolution of the global corona that could respond continuously to the changing of the photospheric magnetic field. The data-driven model consisted of a Surface Flux Transport (SFT) model and a global 3D MHD coronal model. The SFT model was employed to produce the global time-varying and self-consistent synchronic snapshots of the photospheric magnetic field as the input to drive their 3D numerical global coronal AMR-CESE-MHD model on an overset grid of Yin-Yang overlapping structure. The SFT model and the 3D global coronal model were coupled through the boundary condition of the projected characteristic method. Numerical results of the coronal evolution from September 4 to October 29, 1996 provided a good comparison with multiply observed coronal images.

With the help of the 3D SIP-AMR-CESE MHD model, Yang *et al.*<sup>[106]</sup> developed a time-dependent MHD model driven by the daily-updated synoptic magnetograms (MHD-DUSM) to study the dynamic evolution of the global corona. To accommodate the observations, the tangential component of the electric field at the lower boundary was specified to allow the flux evolution to match the observed changes of magnetic field. Meanwhile, the time-dependent solar surface boundary conditions derived from the method of characteristics and the mass flux limit were incorporated to couple the observation and the 3D MHD model. The simulated evolution of the global coronal structure during 2007 was compared with so-

lar observations and solar wind measurements from both Ulysses and spacecrafts near the Earth. The MHD-DUSM model was also validated by comparisons with the standard potential field source surface (PFSS) model, the newly improved Wang-Sheeley-Arge (WSA) empirical formula, and the MHD simulation with a monthly synoptic magnetogram (MHD-MSM). Comparisons showed that the MHD-DUSM results had good overall agreements with coronal and interplanetary structures, including the sizes and distributions of coronal holes, the positions and shapes of the streamer belts, and the transitions of the solar wind speeds and magnetic field polarities. The MHD-DUSM results also displayed many features different from those of the PFSS, the WSA, and the MHD-MSM models.

High-performance computational models are required to make the real-time or faster than real-time numerical prediction of adverse space weather events and their influence on the geospace environment. In order to reduce the computation hours efficiently, Feng *et al.*<sup>[107–108]</sup> explored the application of the heterogeneous clusters of multi-core Center Processing Units (CPU) and programmable Graphic Processing Units (GPU) to the numerical space weather modeling for the study of solar wind background that is a crucial part in the numerical space weather modeling. GPU programming was realized for their SIP-CESE MHD model by numerically studying the solar corona/interplanetary solar wind. The global solar wind structures were obtained by the established GPU model with the magnetic field synoptic data as input. Meanwhile, the time-dependent solar surface boundary conditions derived from the method of characteristics and the mass flux limit were incorporated to couple the observation and the 3D MHD model. The simulated evolution of the global structures for two Carrington rotations 2058 and 2062 was compared with solar observations and solar wind measurements from spacecraft near the Earth. The MHD model was also validated by comparison with the standard Potential Field Source Surface (PFSS) model. Comparisons showed that the MHD results

were in good overall agreements with coronal and interplanetary structures, including the size and distribution of coronal holes, the position and shape of the streamer belts, and the transition of the solar wind speeds and magnetic field polarities.

Reliable measurements of the solar magnetic field are still limited to the photosphere, and our present knowledge of the 3D coronal magnetic field is largely based on extrapolations from photospheric magnetograms using physical models, *e.g.*, the NLFFF model that is usually adopted. Most of the currently available NLFFF codes have been developed with computational volume such as a Cartesian box or a spherical wedge, while a global full-sphere extrapolation is still under development. A high-performance global extrapolation code is in particular urgently needed considering that SDO can provide a full-disk magnetogram with resolution up to  $4096 \times 4096$ . Jiang, Feng and Xiang<sup>[109]</sup> applied AMR-CESE MHD Model for global NLFFF extrapolation with the photosphere magnetogram as input. The code was validated by two full-sphere force-free solutions from Low and Lou's semi-analytic force-free field model. The code showed high accuracy and fast convergence, and could be ready for future practical application if combined with an adaptive mesh refinement technique.

Different from the routine finite volume methods and finite difference schemes, the SIP-CESE MHD model employs a unified treatment of flow evolution in space and time by keeping the local and global space-time flux conservation in a coherent and efficient manner. With low-storage realized by integrating two half time steps into one full time step in the time iteration treatment, the CESE MHD solver enables the scheme suitable for building blocks for adaptive mesh refinement calculations. Besides, the SIP-CESE MHD model developed by Feng and his colleagues has the following features. (1) The spherical surface boundary can be fitted with an easy implementation of the inner boundary conditions due to the adoption of six-component grid for the computational domain from the Sun to Earth or beyond.

Both coordinate singularities and polar grid convergence have been avoided at the same time. The observation at the lower boundary can be easily utilized as input. (2) The same CESE solver is applicable to any coordinate system, such as Cartesian, spherical, cylindrical coordinates and curvilinear coordinate. The only difference is the coordinate transformation. Therefore, the solver is highly independent of the grid system. (3) High-speed and low-speed solar wind can be efficiently distinguished by the adoption of the new empirical volumetric heating source term taking the topological effect of magnetic field with the expansion factor  $f_s$  and the minimum angular distance  $\theta_b$  into consideration. Reasonable distributions of the plasma density, temperature and velocity on the solar surface are obtained in the model by the combination of the projected normal characteristic method with the mass flux limit. Incorporation of the time-dependent magnetograms into the model has been preliminary established, with emphasis focused on how to preprocess the observational data, how to solve projected normal characteristics equations, and how to update the bottom boundary by using the time-dependent magnetic field from observations or the surface flux transport model. (4) Based on the CESE MHD model, the new implementation of the MHD relaxation method for reconstruction of coronal magnetic field from a photospheric vector magnetogram opens a new way for the study of solar active region with the help of SDO/HMI or SOHO/MDI observations.

The SIP-CESE MHD model consists of a series of model suites by integratively including observational data process module, characteristic boundary condition module, active region module, solar wind module, which have been successfully applied to the solar-interplanetary process study of coronal mass ejections, solar active regions, and data-driven modeling for active regions and solar wind ambient with continuously observed data as input. In what follows some examples are given.

The magnetic field in the solar corona is usually extrapolated from a photospheric vector magne-

togram using a NLFFF model. Due to the absence of direct measurement, the magnetic field in the solar corona is usually extrapolated from the photosphere in a numerical way. At the moment, the NLFFF model dominates the physical models for field extrapolation in the low corona. Jiang and Feng<sup>[110]</sup> presented a new implementation of the MHD relaxation method for NLFFF extrapolation by the CESE-MHD scheme. The bottom boundary condition was prescribed by incrementally changing the transverse field to match the magnetogram, and all other artificial boundaries of the computational box were simply fixed. They also computed a suite of metrics to quantitatively analyze the results and demonstrated that the performance of their code in extrapolation accuracy basically reached the same level of the present best-performing code, *i.e.*, that developed by Wiegmann.

Jiang and Feng<sup>[111]</sup> presented a fast solver for computing potential and Linear Force-Free Fields (LFFF) above the full solar disk with a synoptic magnetic map as input. The global potential field and the LFFF were dealt with in a unified way by solving a 3D Helmholtz equation in a spherical shell and a 2D Poisson equation on the solar surface. The solver was based on a combination of the spectral method and the finite difference scheme. In the longitudinal direction the equation was transformed into the Fourier spectral space, and the resulting 2D equations in the  $r$ - $\theta$  plane for the Fourier coefficients were solved by finite differencing. The solver showed an extremely fast computing speed, *e.g.*, the computation for a magnetogram with a resolution of  $180(\theta) \times 360(\varphi)$  was completed in less than 2 s. Even on a high-resolution  $600 \times 1200$  grid, the solution could be obtained within only about one minute on a single CPU. The solver could potentially be applied directly to the original resolution of observed magnetograms from SDO/HMI for routinely analyzing daily full-disk data.

Jiang *et al.*<sup>[112]</sup> applied a data-driven MHD model to investigate the 3D magnetic field of NOAA Active Region (AR) 11117 around the time of a C-class confined flare that occurred on October 25, 2010.

They used the CESE-MHD model to focus on the magnetic field evolution and to consider a simplified solar atmosphere with finite plasma  $\beta$ . Magnetic vector-field data derived from the observations at the photosphere was input directly to constrain the model. Assuming that the dynamic evolution of the coronal magnetic field could be approximated by successive equilibria, they solved a time sequence of MHD equilibria based on a set of vector magnetograms for AR 11117 taken by SDO/HMI around the time of the flare. The model qualitatively reproduced the basic structures of the 3D magnetic field, as supported by the visual similarity between the field lines and the coronal loops observed by the Atmospheric Imaging Assembly, which showed that the coronal field could indeed be well characterized by the MHD equilibrium in most cases. The magnetic configuration changed very little during the studied time interval of 2 h. A topological analysis revealed that the small flare was correlated with a Bald Patch (BP, where the magnetic field was tangent to the photosphere), suggesting that the energy release of the flare could be understood by magnetic reconnection associated with the BP separatrices. The total magnetic flux and energy kept increasing slightly in spite of the flare, while the computed magnetic free energy dropped during the flare by  $\sim 10^{30}$  erg, which seemed to be adequate in providing the energy budget of a minor C-class confined flare.

Jiang and Feng<sup>[113]</sup> reported the application of the CESE-MHD-NLFFF code to SDO/HMI data with magnetograms sampled for two Active Regions (ARs), NOAA AR 11158 and 11283, both of which were very non-potential, producing X-class flares and eruptions. The raw magnetograms were preprocessed to remove the force and then input into the extrapolation code. Qualitative comparison of the results with the SDO/AIA images showed that their code could reconstruct magnetic field lines resembling the EUV-observed coronal loops. Most important structures of the ARs were reproduced excellently, like the highly sheared field lines that suspend filaments in AR 11158 and twisted flux rope which corresponded

to a sigmoid in AR 11283. Quantitative assessment of the results showed that the force-free constraint was fulfilled very well in the strong-field regions but apparently not that well in the weak-field regions because of data noise and numerical errors in the small currents.

Current MHD simulations of the initiation of solar eruptions are still commonly carried out with idealized magnetic field models, whereas the realistic coronal field prior to eruptions can possibly be reconstructed from the observed photospheric field. Based on the observed photospheric vector magnetogram as the initial condition in the CESE-MHD model, Jiang *et al.*<sup>[114–116]</sup> carried out a comprehensive study of the formation and eruption of an Active Region (AR) sigmoid in AR 11283, and successfully simulated the realistic initiation process of the eruption event, as was confirmed by a remarkable resemblance to the SDO/AIA observations. Analysis of the pre-eruption field revealed that the envelope flux of the sigmoidal core contained a coronal null and furthermore the flux rope was prone to a torus instability. Observations suggested that reconnection at the null cuts overlying tethered and likely triggered the torus instability of the flux rope, which resulted in the eruption. A detailed analysis of the fields compared with observations suggested the following scenario for the evolution of the region. Initially, a new bipole emerged into the negative polarity of a preexisting bipolar AR, forming a null-point topology between the two flux systems. A weakly twisted Flux Rope (FR) was then built up slowly in the embedded core region, largely through flux cancellation, forming a Bald Patch Separatrix Surface (BPSS). The FR grew gradually until its axis runs into a Torus Instability (TI) domain, and the BPSS also developed a full S-shape. The combined effects of the TI-driven expansion of the FR and the line tying at the BP teared the FR into two parts with the upper portion freely expelled and the lower portion remaining behind the postflare arcades. This process dynamically perturbed the BPSS and resulted in the enhanced heating of the sigmoid and the rope. The accelerated expansion of the upper-portion

rope strongly pushed its envelope flux near the null point and triggered breakout reconnection at the null, which further drove the eruption. They discussed the important implications of these results for the formation and disruption of the sigmoid region with an FR. This kind of simulation demonstrated the capability of modeling the realistic solar eruptions to provide the initiation process.

Numerical reconstruction/extrapolation of the coronal NLFFF usually takes the photospheric vector magnetogram as input at the bottom boundary. The magnetic field observed at the photosphere, however, contains a force that is in conflict with the fundamental assumption of the force-free model. It also contains measurement noise, which hinders the practical computation. Jiang and Feng<sup>[117]</sup> developed a new code of magnetogram pre-processing that was consistent with their extrapolation method CESE-MHD-NLFFF. Based on the magnetic-splitting rule that a magnetic field could be split into a potential-field part and a non-potential part, they split the magnetogram and dealt with the two parts separately. The pre-processing of the magnetogram's potential part was based on a numerical potential-field model, and the non-potential part was preprocessed using the similar optimization method of Wiegmann, Inhester, and Sakurai. The code was applied to the SDO/HMI data, and results show that the method could remove the force and noise efficiently and improve the extrapolation quality.

Zhou *et al.*<sup>[118]</sup> presented the time-dependent propagation of a Sun-Earth connection event that occurred on November 4, 1997 using the SIP-CESE MHD model. A global steady state solar wind for this event was obtained by the 3D SIP-CESE MHD model with Parker's 1D solar wind solution and measured photospheric magnetic fields as the initial values. Then, superposed on the quiet background solar wind, a spherical plasmoid was used to mimic the November 4, 1997 CME event. The CME was assumed to arise from the evolution of a spheromak magnetic structure with high-speed, high-pressure, and high-plasma-density plasmoid near the

Sun. Moreover, the axis of the initial simulated CME was put at S14W34 to conform to the observed location of this flare/CME event. The result provided a relatively satisfactory comparison with the WIND spacecraft observations, such as southward interplanetary magnetic field and large-scale smooth rotation of the magnetic field associated with the CME.

Zhou and Feng<sup>[119]</sup> analyzed and quantitatively studied the deflection of CME in the latitudinal direction during its propagation from the Corona to Interplanetary (IP) space using the 3D CESE-MHD model. To this end, 12 May 1997 CME event during the Carrington rotation 1922 was selected. First, they tried to reproduce the physical properties for this halo CME event observed by the WIND spacecraft. Then, they studied the deflection of CME, and quantified the effect of the background magnetic field and the initiation parameters (such as the initial magnetic polarity and the parameters of the CME model) on the latitudinal deflection of CMEs. The simulations showed that the initial magnetic polarity substantially affected the evolution of CMEs. The “parallel” CMEs (with the CME’s initial magnetic field parallel to that of the ambient field) originating from high latitude showed a clear equatorward deflection at the beginning and then propagated almost parallel to heliospheric current sheet and the “antiparallel” CMEs (with the CME’s initial magnetic field opposite to that of the ambient field) deflected toward the pole. Their results demonstrated that the latitudinal deflection extent of the “parallel” CMEs was mainly controlled not only by the background magnetic field strength but also by the initial magnetic field strength of the CMEs. There was an anticorrelation between the latitudinal deflection extent and the CME average transit speed and the energy ratio  $E_{\text{cme}}/E_{\text{sw}}$ .

Zhou and Feng<sup>[120]</sup> presented an improved CESE by applying a non-staggered space-time mesh system and simply improving the calculation of flow variables in MHD equations. The improved CESE method could improve the solution quality even with a large disparity in the Courant number (CFL) when using a fixed global marching time. Moreover, for

a small CFL ( $< 0.1$ ), the method could significantly reduce the numerical dissipation and retain the solution quality, which were verified by two benchmark problems. And meanwhile, comparison with the original CESE scheme showed better resolution of the improved scheme results. Finally, they demonstrated its validation through the application of this method in 3D coronal dynamical structure with dipole magnetic fields and measured solar surface magnetic fields as the initial input.

Zhou and Feng<sup>[121]</sup> presented a new hybrid numerical scheme for 2D ideal MHD equations. The flow variables are calculated by the CESE method, while their first-order spatial derivatives involved in the CESE method were computed with a finite volume scheme that used the solution of the derivative Riemann problem with limited reconstruction to evaluate the numerical flux at cell interface position. Numerical results of several benchmark problems verified that the hybrid scheme could retain the solution quality even if the Courant number ranged from close to 1 to less than 0.01.

Jiang, Cui and Feng<sup>[122]</sup> presented the application of the AMR-CESE method for solving the Euler and Navier-Stokes equations. The method is a combination of the CESE method and the AMR technique. Its implementation is based on modification of the original CESE method and utilization of the framework of a parallel-AMR package PARAMESH to manage the block-AMR grid system. Furthermore, a variable time step algorithm is introduced to realize adaptivity of the method in both space and time. A test suite of standard problems for Euler and Navier-Stokes flows are calculated and the results show high resolution, high efficiency and versatility of the method for both shock capture and resolving boundary layer.

The Arbitrary accuracy Derivatives Riemann problem method (ADER) scheme is a new high order numerical scheme based on the concept of finite volume integration, and it is very easy to be extended up to any order of space and time accuracy by using a Taylor time expansion at the cell interface position.

So far the approach has been applied successfully to flow mechanics problems. Zhang *et al.*<sup>[123]</sup> carried out the extension of multidimensional ADER schemes to multidimensional MHD systems of conservation laws by calculating several MHD problems in one and two dimensions: (i) Brio-Wu shock tube problem, (ii) Dai-Woodward shock tube problem, (iii) Orszag-Tang MHD vortex problem. The numerical results proved that the ADER scheme possessed the ability to solve MHD problem, remained high order accuracy both in space and time, kept precise in capturing the shock. Meanwhile, the compared tests showed that the ADER scheme could restrain the oscillation and obtain the high order non-oscillatory result.

Feng, Shen and their colleagues established the Coronal and Interplanetary (COIN) model, a 3D MHD model extending from the Sun to Earth beyond. The model divided the computational domain into two regions as follows: one from 1 to  $22 R_s$  and the other from  $18 R_s$  to 1 AU. In the transonic and trans-Alfvénic inner region, they used the 3D ideal MHD equations with volumetric heating terms in order to describe the dynamic behavior of the coronal and solar wind plasma and produce the bimodal solar wind structure seen by Ulysses. In the supersonic and super-Alfvénic outer region, the nonconservative inertial frame form of the steady state 3D MHD equations in spherical coordinates was used in the COIN model. In the inner region, the time-dependent 3D MHD equations were solved by a modified Total Variation Diminishing/Lax-Friedrichs (TVD/LF) scheme with the electric field modification method. Shen *et al.*<sup>[124]</sup> employed their previous study of a 3D MHD simulation for the evolution of two interacting CMEs in a realistic ambient solar wind during the period 28–31 March 2001 event to illustrate these acceleration and deceleration processes. The forces which caused the acceleration and deceleration were analyzed in detail. The forces which caused the acceleration were the magnetic pressure term of Lorentz force and pressure gradient. On the other hand, the forces which caused the deceleration were aerodynamic drag, the Sun's gravity and the tension of magnetic field. In

addition the momentum exchange between the solar wind and the moving CMEs could cause acceleration and deceleration of the CME which were analyzed. In this specific CME event during 28–31 March 2001, they had analyzed those forces which caused acceleration and deceleration of CME with and without interaction with another CME. It showed that there were significant momentum changes between these two interacting CMEs to cause the acceleration and deceleration.

Shen *et al.*<sup>[125]</sup> developed an improved model to build a self-consistent global structure on the source surface of  $2.5 R_s$  covering four different phases of solar activity. This model involved the topological effect of the magnetic field expansion factor  $f_s$  and the minimum angular distance  $\theta_b$  (at the photosphere) between an open field foot point and its nearest coronal hole boundary. The purpose of this effect was to separate the open field area and the close field area more effectively. The model used as input for 136 Carrington Rotations (CRs) covering four different phases of solar activity: an empirical model of the magnetic field topology on the source surface using line-of-sight (los) photospheric field ( $B_{los}$ ) measurements by Wilcox Solar Observatory (WSO), and an empirically derived global coronal density distribution using K coronal polarized brightness (pB) by MKIII in High Altitude Observatory (HAO). The solar wind speed on the source surface was specified by the function of both  $f_s$  and  $\theta_b$ , which were obtained by the magnetic field data. Then the coronal mass outputs were analyzed and the self-consistent global distribution on the source surface was numerically studied for the four different phases. Finally, the model estimated the solar wind speed at 1 AU as a simple function of the speed on the source surface. Their numerical results indicated reasonable semi-quantitative agreement with observations at different phases of solar activity.

Shen *et al.*<sup>[126]</sup> modelled the distribution of plasma and magnetic field on the source surface of  $2.5 R_s$  covering four different phases of solar activity. They used the expansion factor  $f_s$  and the angular

distance  $\theta_b$  in specifying the solar wind speed on the source surface, which could separate the open field region and the close field region effectively. They selected 136 Carrington Rotations (CRs) covering four different phases of solar activity, and used an empirical model of the magnetic field topology by Wilcox Solar Observatory (WSO) and an empirically derived global coronal density distribution by MKIII in High Altitude Observatory (HAO) as input. The solar wind speed at 1 AU derived from the new distribution on the source surface worked much better than one derived from the previous method, as compared with observational data.

## 7 Waves and Structures in Solar Wind

Wang *et al.*<sup>[127]</sup> presented measurements of arc-polarized velocity variations together with magnetic field variations associated with a large-amplitude Alfvén wave as observed by the WIND satellite. When converting to the deHoffman-Teller frame, they found that the magnetic field and velocity vector components, in the plane perpendicular to the minimum-variance direction of the magnetic field, are arc-polarized, and their tips almost lie on the same circle. The normalized cross helicity and Alfvén ratio of the wave are both nearly equal to unity, a new result not yet reported in previous studies at 1 AU. It is worthy to stress here that pure Alfvén waves can also exist in the solar wind even near the Earth at 1 AU, but not only near 0.3 AU.

Wang *et al.*<sup>[128]</sup> used measurements from the WIND spacecraft to study the intermittent structures in solar wind turbulence. They identified the intermittent structures as being mostly Rotational Discontinuities (RDs) and rarely Tangential Discontinuities (TDs) based on the technique described by Smith. Statistical results showed that the TD-associated Current Sheets (TCSs) had a distinct tendency to be associated with local enhancements of the proton temperature, density, and plasma beta, and a local decrease of magnetic field magnitude. Con-

versely, for RDs, statistical results did not reveal convincing heating effects. These results confirmed the notion that dissipation of solar wind turbulence could take place in intermittent or locally isolated small-scale regions which corresponded to TCSs.

Recently, small-scale Pressure-Balanced Structures (PBSs) were identified in the solar wind, but their formation mechanism remains unclear. Yao *et al.*<sup>[129]</sup> analyzed the plasma and magnetic field data obtained by WIND in the quiet solar wind at 1 AU. Suspecting that the isolated small PBSs were formed by compressive waves in situ, they tested the wave modes forming a small-scale PBS with local mean magnetic field vector quasi-parallel to GSE- $x$ . As a result, they identified that the cross-helicity and the compressibility attained values for a slow mode from theoretical calculations. Besides, the proton was thermal anisotropic with  $T_{\perp} < T_{\parallel}$  derived from the velocity distribution functions, excluding a mirror mode, which was the other candidate for the formation of PBSs in situ. Thus, a small-scale PBS was shown to be driven by oblique, slow-mode waves in the solar wind.

Wang *et al.*<sup>[130]</sup> studied the physical process for the pick-up of minor ions by obliquely propagating low-frequency Alfvén waves. It was demonstrated that minor ions could be picked up by the intrinsic low-frequency Alfvén waves observed in the solar wind. When the wave amplitude exceeded the threshold condition for stochasticity, a minor ion could gain a high magnetic moment through the stochastic heating process. Then, the ion with a large magnetic moment could be trapped in the magnetic mirror-like field structures formed by the large-amplitude low-frequency Alfvén waves in the wave frame. As a result, the ion was picked up by the Alfvén waves.

A particle-in-cell code was used by Yang *et al.*<sup>[131]</sup> to examine contributions of the Pickup Ions (PIs) and the Solar Wind ions (SWs) to the cross shock electric field at the supercritical, perpendicular shocks. The code treated the pickup ions self-consistently as a third component. Two different runs with relative pickup ion density of 25% and 55% were

presented. Their preliminary results showed following results. (1) In the low percentage (25%) pickup ion case, the shock front was nonstationary. During the evolution of this perpendicular shock, a nonstationary foot resulting from the reflected solar wind ions was formed in front of the old ramp, and its amplitude became larger and larger. At last, the nonstationary foot grew up into a new ramp and exceeded the old one. Such a nonstationary process could be formed periodically. When the new ramp began to be formed in front of the old ramp, the Hall term mainly contributed by the solar wind ions became more and more important. The electric field  $E_x$  was dominated by the Hall term when the new ramp exceeded the old one. Furthermore, an extended and stationary foot in pickup ion gyro-scale was located upstream of the nonstationary/self-reforming region within the shock front, and was always dominated by the Lorentz term contributed by the pickup ions. (2) in the high percentage (55%) pickup ion case, the amplitude of the stationary foot increased as expected. One striking point was that the nonstationary region of the shock front evidenced by the self-reformation disappeared. Instead, a stationary extended foot dominated by Lorentz term contributed by the pickup ions, and a stationary ramp dominated by Hall term contributed by the solar wind ions were clearly evidenced. The significance of the cross electric field on ion dynamics was also discussed.

Both hybrid/full particle simulations and recent experimental results have clearly evidenced that the front of a supercritical quasi-perpendicular shock can be rippled. Recent two-dimensional simulations have focused on two different types of shock front rippling: one characterized by a small spatial scale along the front is supported by lower hybrid wave activity; the other characterized by a large spatial scale along the front is supported by the emission of large amplitude nonlinear whistler waves. These two rippled shock fronts are self-consistently observed when the static magnetic field is perpendicular to (so called  $B_0$ -OUT case) or within (so called  $B_0$ -IN case) the simulation

plane, respectively. On the other hand, several studies have been made on the reflection and energization of incoming ions with a shock but most have been restricted to a one dimensional shock profile only (no rippling effects). Two-dimensional test particle simulations based on strictly perpendicular shock profiles chosen at a fixed time in two dimensional Particle-In-Cell (PIC) simulations, were performed by Yang *et al.*<sup>[132]</sup> in order to investigate the impact of the shock front ripples on incident ion ( $H^+$ ) dynamics. The acceleration mechanisms and energy spectra of the test-ions (described by shell distributions with different initial kinetic energy) interacting with a rippled shock front were analyzed in detail. Both  $B_0$ -OUT and  $B_0$ -IN cases were considered separately; in each case,  $y$ -averaged (front rippling excluded) and non-averaged (front rippling included) profiles would be analyzed. Their results showed following. (1) The incident ions suffered both Shock Drift Acceleration (SDA) and Shock Surfing Acceleration (SSA) mechanisms. Moreover, a striking feature was that SSA ions not only were identified at the ramp but also within the foot which confirmed previous 1D simulation results. (2) The percentage of SSA ions increased with initial kinetic energy, a feature which persisted well with a rippled shock front. (3) Furthermore, the ripples increased the porosity of the shock front, and more Directly Transmitted (DT) ions were produced; these strongly affected the relative percentage of the different identified classes of ions (SSA, SDA and DT ions), their average kinetic energy and their relative contribution to the resulting downstream energy spectra. (4) One key impact of the ripples was a strong diffusion of ions (in particular through the frontiers of their injection angle domains and in phase space which were blurred out) which led to a mixing of the differentiation classes. This diffusion increased with the size of the spatial scale of the front ripples. (5) Through this diffusion, an ion belonging to a given category (SSA, SDA, or DT) in  $y$ -averaged case changed class in non-averaged case without one-to-one correspondence.



## 8 Propagation of ICMEs/Shocks and Their Arrival Time Predictions

The successive CMEs from 2010 July 30 to August 1 present us the first opportunity to study CME-CME interactions with unprecedented heliospheric imaging and in-situ observations from multiple vantage points. Liu *et al.*<sup>[133]</sup> described two cases of CME interactions: merging of two CMEs launched close in time and overtaking of a preceding CME by a shock wave. The first two CMEs on August 1 interacted close to the Sun and formed a merged front, which then overtook the July 30 CME near 1 AU, as revealed by wide-angle imaging observations. Connections between imaging observations and in-situ signatures at 1 AU suggested that the merged front was a shock wave, followed by two ejecta observed at Wind which seemed to have already merged. In-situ measurements showed that the CME from July 30 was overtaken by the shock at 1 AU and was significantly compressed, accelerated, and heated. The interaction between the preceding ejecta and shock also resulted in variations in the shock strength and structure on a global scale, as shown by widely separated in-situ measurements from WIND and STEREO-B. These results indicated important implications of CME-CME interactions for shock propagation, particle acceleration, and space weather forecasting.

A super-elastic collision is an unusual process in which some mechanism causes the kinetic energy of the system to increase. Most studies have focused on solid-like objects, and have rarely considered gases or liquids, as the collision of these is primarily a mixing process. However, magnetized plasmoids are different from ordinary gases: as cross-field diffusion is effectively prohibited, but it remains unclear how they behave during a collision. Shen *et al.*<sup>[134]</sup> presented a comprehensive picture of a unique collision between two CMEs in the heliosphere, which are the largest magnetized plasmoids erupting from the Sun. Their analysis revealed that these two magnetized plasmoids collided as if they were solid-like objects,

with a likelihood of 73% that the collision was super-elastic. The total kinetic energy of the plasmoid system was increased by about 6.6% through the collision, significantly influencing its dynamics.

To verify the superelastic collision between CMEs in the heliosphere, Shen *et al.*<sup>[135]</sup> numerically studied the event through 3D MHD simulations. The nature of CMEs' collision was examined by comparing two cases. In one case, the two CMEs collided as observed, but in the other, they did not. Results showed that the collision led to extra kinetic energy gain by 3%–4% of the initial kinetic energy of the two CMEs. It firmly proved that the collision of CMEs could be superelastic.

Shen *et al.*<sup>[136]</sup> applied the 3D time-dependent, MHD model to model the propagation and interaction of two CMEs. With help of the observation data of magnetic field and density, the background solar wind was constructed based on the self-consistent source surface. By means of the magnetized plasma blob model, two successive CMEs occurring on 2001 March 28 and forming a multiple Magnetic Cloud (multi-MC) in interplanetary space was simulated. The dynamical propagation and interaction of the two CMEs were investigated. They found that, the second CME could overtake the first one, and cause compound interactions and an obvious acceleration of the shock. At L1 point near the Earth, the two resultant magnetic clouds in their simulation were consistent with the observations by ACE

Liu *et al.*<sup>[137]</sup> investigated how CMEs propagated through, and interacted with, the inner heliosphere between the Sun and Earth, a key question in CME research and space weather forecasting. CME Sun-to-Earth kinematics were constrained by combining wide-angle heliospheric imaging observations, interplanetary radio Type II bursts, and in-situ measurements from multiple vantage points. They selected three events for the study, January 19, 23, and March 7, 2012 CMEs. Different from previous event studies, their work attempted to create a general picture for CME Sun-to-Earth propagation and compared different techniques for determining CME interplane-

tary kinematics. Key results were obtained concerning CME Sun-to-Earth propagation. (1) The Sun-to-Earth propagation of fast CMEs could be approximately formulated into three phases: an impulsive acceleration, then a rapid deceleration, and finally a nearly constant speed propagation (or gradual deceleration). (2) For the CMEs studied there were still accelerating even after the flare maximum, so energy must be continuously fed into the CME even after the time of the maximum heating and radiation had elapsed in the corona. (3) The rapid deceleration, presumably due to interactions with the ambient medium, mainly occurred over a relatively short timescale following the acceleration phase. (4) CME-CME interactions seemed a common phenomenon close to solar maximum. Their comparison between different techniques (and data sets) had important implications for CME observations and their interpretations: (i) for the current cases, triangulation assuming a compact CME geometry was more reliable than triangulation assuming a spherical front attached to the Sun for distances below 50–70 solar radii from the Sun, but beyond about 100 solar radii we would trust the latter more; (ii) a proper treatment of CME geometry must be performed in determining CME Sun-to-Earth kinematics, especially when the CME propagation direction was far away from the observer; (iii) their approach to comparing wide-angle heliospheric imaging observations with interplanetary radio Type II bursts provided a novel tool in investigating CME propagation characteristics. Future CME observations and space weather forecasting were discussed based on these results.

CMEs can be continuously tracked through a large portion of the inner heliosphere by direct imaging in visible and radio wavebands. White Light (WL) signatures of solar wind transients, such as CMEs, result from Thomson scattering of sunlight by free electrons and therefore depend on both viewing geometry and electron density. The Faraday Rotation (FR) of radio waves from extragalactic pulsars and quasars, which arises due to the presence of such solar wind features, depends on the line-of-sight mag-

netic field component  $B_{\parallel}$  and the electron density. To understand coordinated WL and FR observations of CMEs, Xiong *et al.*<sup>[138]</sup> performed forward MHD modeling of an Earth-directed shock and synthesized the signatures that would be remotely sensed at a number of widely distributed vantage points in the inner heliosphere. Removal of the background solar wind contribution revealed the shock-associated enhancements in WL and FR. While the efficiency of Thomson scattering depended on scattering angle, WL radiance  $I$  decreased with heliocentric distance  $r$  roughly according to the expression  $I \propto r^{-3}$ . The sheath region downstream of the Earth-directed shock was well viewed from the L4 and L5 Lagrangian points, demonstrating the benefits of these points in terms of space weather forecasting. The spatial position of the main scattering site  $\mathbf{r}_{\text{sheath}}$  and the mass of plasma at that position  $M_{\text{sheath}}$  could be inferred from the polarization of the shock-associated enhancement in WL radiance. From the FR measurements, the local  $B_{\parallel\text{sheath}}$  at  $\mathbf{r}_{\text{sheath}}$  could then be estimated. Simultaneous observations in polarized WL and FR could not only be used to detect CMEs, but also to diagnose their plasma and magnetic field properties.

Stereoscopic white-light imaging of a large portion of the inner heliosphere has been used to track interplanetary coronal mass ejections. At large elongations from the Sun, the white-light brightness depends on both the local electron density and the efficiency of the Thomson-scattering process. To quantify the effects of the Thomson-scattering geometry, Xiong *et al.*<sup>[139]</sup> studied an interplanetary shock using forward MHD simulation and synthetic white-light imaging. Identifiable as an inclined streak of enhanced brightness in a time-elongation map, the travelling shock could be readily imaged by an observer located within a wide range of longitudes in the ecliptic. Different parts of the shock front contributed to the imaged brightness pattern viewed by observers at different longitudes. Moreover, even for an observer located at a fixed longitude, a different part of the shock front would contribute to the imaged brightness

at any given time. The observed brightness within each imaging pixel resulted from a weighted integral along its corresponding ray-path. It was possible to infer the longitudinal location of the shock from the brightness pattern in an optical sky map, based on the east-west asymmetry in its brightness and degree of polarization. Therefore, measurement of the interplanetary polarized brightness could significantly reduce the ambiguity in performing 3D reconstruction of local electron density from white-light imaging.

Images observed by the twin spacecraft STEREO-A and B appear as complex structures for two CMEs on August 1, 2010. Therefore, a series of sky maps of Thomson-scattered white light by Interplanetary Coronal Mass Ejections (ICMEs) on August 1, 2010 were simulated by Zhang *et al.*<sup>[140]</sup> using the Hakamada-Akasofu-Fry (HAF) 3D solar wind model. A comparison between the simulated images and observations of STEREO-A and B clarified the structure and evolution of ICMEs (including shocks) in the observed images. The results demonstrated that the simulated images from the HAF model were very useful in the interpretation of the observed images when the ICMEs overlapped within the fields of view of the instruments onboard STEREO-A and B.

Liu and Qin<sup>[141]</sup> used the energy of soft X-ray during solar flare events to help predict the Shock Arrival Times (SATs) at Earth. They combined the soft X-ray energy and SAT prediction models previously developed by researchers to obtain two new methods. PODn (Probability of Detection: no) represented a methods ability in forecasting the solar flare events without shocks arriving at the Earth. By testing the methods with the total of 585 solar flare events following the generation of a metric Type II radio burst during the Solar Cycle 23 from September 1997 to December 2006, they found that the predictions of SATs at Earth could be improved by significantly increasing PODn, the proportion of events without shock detection that were correctly forecast.

The Shock Propagation Model (SPM) based on an analytic solution of blast waves had been proposed to predict shock arrival times at Earth. In order to re-

duce the limitations of the SPM theoretical model in real applications and optimize its input parameters, a new version (called SPM2) was presented by Zhao *et al.*<sup>[142]</sup> in order to enhance prediction performance. First, an empirical relationship was established to adjust the initial shock speed, which, as computed from the Type II burst drift rate, often contained observational uncertainties. Second, an additional acceleration/deceleration relation was added to the model to eliminate inherent prediction bias. Third, the propagation direction was derived in order to mitigate the isotropy limitation of blast wave theory in real predictions. Finally, an equivalent shock strength index at the Earth's location to judge whether or not an interplanetary shock would encounter the Earth was implemented in SPM2. The prediction results of SPM2 for 551 solar disturbance events of Solar Cycle 23 demonstrated that the success rate of SPM2 for both shock (W-shock) and nonshock (W/O-shock) events at Earth was  $\sim 60\%$ . The prediction error for the W-shock events was less than 12 h (root-mean-square) and 10h (mean-absolute). Comparisons between the predicted results of SPM2 and those of Shock Time of Arrival (STOA), Interplanetary Shock Propagation (ISPM), and Hakamada-Akasofu-Fry version 2 (HAFv.2) based on similar data samples revealed that the SPM2 model offered generally equivalent prediction accuracy and reliability compared to the existing Fearless Forecast models (STOA, ISPM, and HAFv.2).

Space weather refers to dynamic conditions on the Sun and in the space environment of the Earth, which are often driven by solar eruptions and their subsequent interplanetary disturbances. It has been unclear how an extreme space weather storm forms and how severe it can be. Liu *et al.*<sup>[143]</sup> reported and investigated an extreme event with multi-point remote-sensing and in-situ observations. The formation of the extreme storm showed striking novel features. They suggested that the in-transit interaction between two closely launched coronal mass ejections resulted in the extreme enhancement of the ejecta magnetic field observed near 1 AU at STEREO-A.

The fast transit to STEREO-A (in only 18.6 h), or the unusually weak deceleration of the event, was caused by the preconditioning of the upstream solar wind by an earlier solar eruption. These results provided a new view crucial to solar physics and space weather as to how an extreme space weather event could arise from a combination of solar eruptions.

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