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A Brief Review of Interplanetary Physics Research Progress in Mainland China during 2020–2022*

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Abstract Through independent research by the Chinese scientists or their international collaborations, great achievements have been made in interplanetary physics research in Mainland China during the past two years (2020–2022). More than 150 papers have been published in academic journals in this field during this period. These achievements can be grouped into the following areas, at least: (i) solar corona; (ii) solar and interplanetary transient phenomena; (iii) radio bursts; (iv) Magnetohydrodynamic (MHD) numerical modeling; (v) solar energetic particles and cosmic rays. These advances have greatly enriched our understanding of interplanetary physics, *i.e.* our knowledge of solar activities and solar eruptions, their propagation in the interplanetary space, and the corresponding geoeffects on the Earth. In the sense of application, they have also improved the forecasting of space weather. In this paper we will give a very short review about these advances.

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

Classified index P353

1 Solar Corona and Solar Wind

Coronal loops are building blocks of solar corona. Li *et al*.[1] reported that magnetic reconnection between loops could be accelerated by a nearby filament eruption. Hou *et al*.[2] presented direct observational evidence for the formation of coronal loops through magnetic reconnection as new magnetic fluxes emerge into the solar atmo-

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sphere.

Coronal jets are one type of pervasive and explosive phenomena on the Sun and are often observed in EUV and X-ray passbands in Active Regions (ARs) and Coronal Holes (CHs). Chen *et al*.[3] reported some tornado-like mini-jets suspended in the corona, which were probably generated by fine-scale external or internal magnetic reconnections. In quiet-Sun regions, Hou *et al*.[4] reported many smallest coronal jets ever observed with high-resolution observations from the High Resolution Telescopes of the Extreme Ultraviolet Imager (EUI) onboard Solar Orbiter (SO).

Recent high-resolution observations of EUI/SO revealed prevalent small-scale transient brightenings, named as campfires, appearing frequently in the corona above the quiet Sun. Using a numerical three-dimensional (3D) Magnetohydrodynamics (MHD) model, Chen *et al*.[5] investigated the relation of brightenings to the magnetic field and the driven processes. They found that component reconnection between bundles of field lines at coronal heights could generate the majority of campfire events.

Significant progress has been made in the measurement of a coronal magnetic field. Using spectral observations, Yang *et al*.[6,7] have firstly mapped the plane-of-sky component of the global coronal magnetic field. The field strengths in the corona were measured to be mostly 1–5 Gs from 1.05 to 1.35 solar radii. Based on the theory of gyrosynchrotron emission, Zhu *et al*.[8] performed microwave diagnostics to measure the magnetic field strengths in solar flaring loops. Chen *et al*.[9] performed a forward modeling with a 3D radiation MHD model of a solar AR and found that the magnetic-field-induced transition technique can provide reasonably accurate measurements of the coronal magnetic field.

Coronal wave-like phenomena have been extensively studied, which are generally associated with flares and CMEs. Their formation mechanisms, propagating properties and relation to other activities have been studied by Zhou *et al*.[10], Zhou *et al*.[11,12], Duan *et al*.[13], and Hou *et al*.[14]. In addition, Zhang *et al*.[15–17] studied several events, in which oscillations of remote coronal loops could be triggered by flares or the eruption of a prominence-carrying flux rope.

Supra-arcade Downflows (SADs) appear as dark, teardrop-shaped features descending toward flaring loop top, which might be the results of magnetic reconnection during solar flares. The thermodynamic properties of SADs have been studied by Xue *et al*.[18] and Li *et al*.[19]. Using EUV images, Samanta, Tian *et al*.[20] found direct evidence of plasma heating to a temperature of 10-20 MK in flaring coronal loops collided by SADs and clear signatures of quasi-periodic enhancement in the full-Sun-integrated soft X-ray emission created by the interactions between flaring loops and SADs.

Quiescent coronal rain is generally observed to form along with both closed and open magnetic field structures. Recently, Li *et al*.[21–23] proposed a new and alternative formation mechanism for quiescent coronal rain. They found that some quiescent coronal rain events could be generated by interchange magnetic reconnection between open and closed field lines. Filament formations and quasi-steady sunspot supersonic downflows were found to be associated with magnetic reconnection between two sets of loops, and the subsequent cooling and condensation processes of plasma by Li *et al*.[24], Yang *et al*.[25], and Chen *et al*.[26].

Using Parker Solar Probe data, it is found for the solar wind turbulence that the proton-scale break frequency is controlled by the plasma β and the three-dimensional anisotropy and scaling properties exist in both the transition range and the ion-electron scales[27–29]; the outward Alfven mode dominates with a minority of outward fast mode and inward Alfven mode at MHD scale, the kinetic Alfven waves and Alfven ion cyclotron waves co-exist at kinetic scale[30,31]); the correlation between spectral index and magnetic helicity exists[32]; the energy supply mechanism by low-frequency break sweeping for the solar wind turbulence supplies enough energy for the slow solar wind heating and the energy transfer rate is consistent with that from the traditional eddy decay mechanism[33,34].

For the structures in the solar wind, it is found that the solar origin of the compressive Alfvenic spikes can be the guide-field discontinuity[35]; the large-amplitude fluctuations inside the switchbacks are the magnetic-velocity alignment structure, which is one of the main components in the slow solar wind within 0.1–0.3 AU[36,37]; the ion cyclotron waves are inside small-scale flux ropes with medium Alfvenicity[38]; the discontinuity occurrence and the occurrence ratio of the rotational and tangential discontinuity decrease with the heliocentric distance[39]; the duration longer, the depth deeper and the occurrence no clear variation with the increasing heliocentric distance for linear magnetic holes[40].

For the waves and instabilities in the solar wind, Shi *et al*.[41] exhibited the observational evidence of the nonlinear interactions of the oblique ion acoustic wave or lower-hybrid wave and the electron Bernstein mode wave; Chen *et al*.[42] found the electron cyclotron maser emission mechanism of type IIIb burst and the modulation of Alfven waves to generate the fine striae structure.

Other than the Parker Solar Probe (PSP) observation, other missions keep producing new observations: the spectral indices at MHD scales vary from –5/3 in the near-Mercury solar wind to –1.3 within the Mercury magnetosheath[43]; the low-frequency break sweeping mechanism provides enough energy for the fast solar wind heating and the sign of the energy cascade rate relates to the large structures[44,45]; the solar activity level affects the magnetic field and the dynamic pressure in the solar wind upstream of Mars[46]; low-frequency whistler waves modulate electrons and generate higher-frequency whistler waves[47]. Using Wind data at 1 AU, it is found that the scaling indices are isotropic with a stationary background local field[48]; the fluctuations in the slow wind are consistent with the magnetic-field directional turnings and magnetic-velocity alignment structures[49]; the solar wind temperature depends on the radial angle, alpha-proton differential flow vector and the magnetic helicity[50,51]; the stochastic heating depends on the plasma β and cyclotron damping of kinetic Alfven waves leads to the proton perpendicular heating[52].

Based on the MMS observations in the magnetosheath, He *et al*.[53] found the positive dispersion due to the Hall effect and the dominant parallel dissipation with energy transferred to electrons; Hou *et al*.[54] found magnetic reconnection not the major contributor to energy dissipation; Luo *et al*.[55] revealed the energy exchange between the electromagnetic energy, particle bulk kinetic energy and thermal energy; Wang *et al*.[56] found that the anisotropies at sub-ion scales rose and fell as the scales decreased; Zhu *et al*.[57] found the remarkable differences of the intermittent properties between the magnetic and electric field from ion scales to sub-electron scales.

By analyzing the dispersion relation of fluctuating field components directly issued from the shock simulation, Yang *et al*.[58] obtained key findings concerning wave excitations at the shock front: (i) at the leading edge of the foot, two types of Electrostatic (ES) waves are observed. (ii) From the middle of the foot all the way to the ramp, electrons can couple with both incident and reflected ions. Results shed new insight on the mechanism for the occurrence of ES wave excitations and possible electromagnetic wave emissions at young coronal mass ejection–driven shocks in the near-Sun solar wind.

Liu *et al*.[59] reported on two small solar wind transients embedded in the corotating interaction region, characterized by surprisingly lower proton density compared with their surrounding regions. A synthesized picture for event One combining the observations by STEREO B, ACE, and Wind showed that this small solar transient has an independent magnetic field. Backmapping links the origin of the small solar transient to a small coronal hole on the surface of the Sun. They concluded that such small solar wind transients may have originated from a small coronal hole at low latitudes.

Chen *et al*.[60] performed a detailed analysis of the 2020 January 30 event and found the possible cause of the Macro Magnetic Hole (MMH) using coordinated remote sensing observations from STEREO A and PSP in situ measurements. The results indicate that an MMH represents a brief encounter with the rippled heliospheric current sheet. Out of the data from the first four orbits of PSP, they identified 17 MMHs and carried out a statistical analysis. These results suggest that MMHs are a frequent phenomenon that may shed light on the dynamics of the HCS and the origins and evolutions of the solar wind structures in the heliosphere.

Liu *et al*.[61] presented an approach to determining the solar wind angular momentum flux based on observations from PSP. A flux of about 0.15×10^{30} dyn·cm·sr^{-1} near the ecliptic plane and 0.7:1 partition of that flux between the particles and magnetic field is obtained by averaging data from the first four encounters within 0.3 AU from the Sun. The angular momentum flux and its particle component decrease with the solar wind speed, while the flux in the field is remarkably constant. A speed dependence in the Alfvén radius is also observed, which suggests a "rugged" Alfvén surface around the Sun. Substantial diving below the Alfvén surface seems plausible only for relatively slow solar wind given the orbital design of PSP. The large proton transverse velocity observed by PSP is perhaps inherent in the solar wind acceleration process, where an opposite transverse velocity is produced for the alphas with the angular momentum conserved.

Qi *et al.*[62] calculated the propagation of small coronal hole winds and Alfvén waves using a simple two-dimensional solar wind model. Their results showed that the Alfvén waves are separated from the co-originated plasma during the propagation, leading to small coronal hole winds with low Alfvénicity and ordinary slow winds with high Alfvénicity. This result provides a new insight into the origin of the slow solar wind mystery.

Liu *et al.*[63] did a Superposed Epoch Analysis (SEA) to investigate the plasma characteristics in the vicinity of switchbacks and their radial evolution. SEA is a good way to get the statistical average features of certain types of events that have obvious boundaries and different durations. For 55 events ranging from 1 to 30 min, the SEA results show that a small parcel of plasma is piling up in front of the reversed field, and that the trailing plasma density enhancement is much lower. This asymmetry can be explained in part by a fast ejecta and plasma piling up around it. The evolution of events at different distances from the Sun also supports that the switchbacks are related to the faster flow near the Sun. However, these features cannot rule out the possibility that these switchbacks and the related fast flows may be caused by the interchange reconnection near the surface of the Sun.

Meng *et al.*[64] identified 242 switchbacks during the first two encounters of PSP. Statistics methods were applied to analyze the distribution and the rotation angle and direction of the magnetic field rotation of the switchbacks. Their main conclusions are as follows: (i) the rotation angles of switchbacks observed during the first encounter seem larger than those of the switchbacks observed during the second encounter in general; (ii) the tangential component of the velocity inside the switchbacks tends to be more positive (westward) than in the ambient solar wind; (iii) switchbacks are more likely to rotate clockwise than counterclockwise, and the number of switchbacks with clockwise rotation is 1.48 and 2.65 times those with counterclockwise rotation during the first and second encounters, respectively; (iv) the diameter of switchbacks is about 10^5 km on average and across five orders of magnitude (10^3–10^7 km).

2 Solar and Interplanetary Transient Phenomena

2.1 Large Scale Structures

In the study of large-scale interplanetary transients, a series of achievements have been made in the propagation of CMEs, the *in-situ* characteristics of CMEs and shocks, and the evolution of CMEs based on multi-point observations.

In terms of CME propagation, many methods for analyzing CME propagation properties based on multi-point observations have been established. Li *et al.*[65] developed a new method called CORrelation-Aided Reconstruction (CORAR) to recognize and locate CMEs based on two simultaneous STEREO-A/B HI1 images. This method does not presume any morphology of transients and can be run in an automated way. The accuracy of the reconstruction may be affected by the separation angle between the two spacecraft. Lyu *et al.*[66] further indicated that the optimal separation angle should locate between 120° and 150°. In addition, Li *et al.*[67] put forward a technique called maximum correlation-coefficient localization and cross-correlation tracking to reconstruct the radial velocity map of CMEs in 3D space based on 2D white-light images, and used it to estimate the expansion rate as well as some kinematic properties.

In terms of in-situ measurements of CME properties, some achievements have been made in the study of the southward magnetic fields in ICMEs. Shen *et al.*[68] analyzed the origins of intense B_s in different types of ICMEs, finding that the ICME interaction events are more likely to carry extreme intense B_s and cause large geomagnetic storms. In particular, they indicated that some ICME interaction events, like the completely shocked ICME (ICME-in-sheath) or ICME cannibalism, could be classified as isolated ICME events. Liu *et al.*[69] suggested that a geomagnetic storm with a minimum *Dst* of about –2000 nT could occur in principle if the ICME-in-sheath event on 2012 July 23 hit the Earth.

Besides, there has also been some work focusing on the magnetic flux rope structure of CMEs. Song *et al*.[70] conducted comparative statistics on several parameters, including the shock compression ratio, the sheath and ejecta sizes, the sheath-to-ejecta ratio, as well as the magnetic field strength in both sheath and ejecta regions of CMEs with and without magnetic flux ropes. Their analyses suggested that ICMEs without magnetic flux ropes mainly resulted from the spacecraft passing through the ICMEs from the leg flank. Zhao *et al*.[71] made a statistical study of the azimuthal flux of flux ropes embedded within MCs near 5 AU, finding that the average azimuthal flux was less than 20% of that near 1 AU and the rope structure occupied from 30% to 100% of the magnetic cloud interval with an average of 69%. The results indicate that the rope structure of MCs still can be efficiently destructed as they move out beyond 1 AU.

The compositions of the ICMEs have also been analyzed. Song *et al*.[72] conducted a statistical study on ion charge states and relative element abundances within ICMEs measured by ACE spacecraft from 1998 to 2011, and found that all the ICME compositions possess a solar cycle dependence. Huang *et al*.[73] presented a comprehensive analysis of plasma and composition characteristics inside Magnetic Clouds (MCs). The results indicated that MCs of different speeds showed differences in composition and structure. The bimodal distribution of $\langle Q_{\rm Fe}\rangle$ in both the fast and slow MCs suggests the existence of flux rope prior to the eruption. In addition, the distribution of iron charge state and some relevant element abundance ratio distribution inside fast MCs agrees with the “standard model” for CME/flares. Song *et al*.[74] demonstrated that the helium abundance ($A_{\rm He}$) in both ICMEs and slow wind exhibited a positive correlation with the sunspot numbers, indicating that the high $A_{\rm He}$ emanates from active regions as more ICMEs and slow wind originate from active regions around solar maximum. In the meantime, no high $A_{\rm He}$ data points existing in fast wind throughout a solar cycle imply that coronal holes do not emanate plasmas with enriched helium.

With the help of the recent planetary exploration missions, researches about the properties of ICMEs and shocks at other radial distances have been carried out. Based on the Venus Express (VEX) observation, Wang *et al*.[75] established a list of 143 Fast Forward (FF) shocks near Venus covering the time period from 2006 to 2014. The shock occurrence at Venus shows a correlated variation with the solar cycle. On average, fast forward shocks are stronger and less perpendicular near Venus than near Earth. Using the measurements from the Mars Atmosphere and Volatile EvolutioN (MAVEN) spacecraft, in orbit around Mars, Zhao *et al*.[76] identified 24 ICMEs and examined the statistical properties of the ICMEs at Mars. Meanwhile, Huang *et al*.[77] identified 52 fast shocks observed by MAVEN, including 39 FF shocks and 13 Fast Reverse (FR) shocks. Most (79%) of the FF shocks are driven by Stream Interaction Regions (SIRs) with only a few cases being driven by interplanetary coronal mass ejections, and all of the FR shocks are driven by SIRs.

In addition, studies of the CME evolution based on multipoint observation have been carried out. Chi *et al*.[78] presented the “ghost front” model to combine remote observations from STEREO/SECCHI and in situ observations from the Wind and VEX spacecraft, and to derive the kinematics and propagation directions of the two CMEs left the Sun on 13–14 June 2012. Xu *et al*.[79] report the formation process of the shock-ICME complex structure around 22 March 2011 based on the in-situ observations of two radial aligned spacecraft, VEX and STEREO-A. The interaction enhanced the magnetic field strength of the ICME by a factor of 2.3 and significantly shorten its duration.

2.2 Small Scale Structures

In the study of small-scale interplanetary transient structures, researches on the origin and evolution of small-scale magnetic flux ropes scientists have been carried out. In order to shed some light on the dispute of whether Small Flux Ropes (SFRs) are homologous to magnetic clouds, Xu *et al*.[80] analyzed the properties of SFRs in ICMEs and SFRs outside the ICMEs. On the assumption that SFRs in ICMEs have the same origin as magnetic clouds, they compare the SFRs from several aspects, including magnetic field strength, expansion signatures, iron charge state, and counter streaming electrons. The results suggest that most of the SFRs near Earth have different origins from magnetic clouds. In addition, Feng *et al*.[81] indicated that interchange reconnection and disconnection might be two important mechanisms changing the magnetic topology of the SFRs during their propagation in the interplanetary space.

3 Radio Bursts

Electron Cyclotron Maser Emission (ECME) is regarded as a plausible source for coherent radio radiations from solar active regions (*e.g.*, solar radio spikes). Ning *et al.*[82] presented a 2D3V fully kinetic electromagnetic particle-in-cell simulation to investigate the wave excitations and subsequent nonlinear processes induced by the energetic electrons in the loss-cone distribution. As a main result, they obtained strong emissions at the second-harmonic X mode (X2). While the fundamental X mode (X1) and the Z mode are amplified directly via the electron cyclotron maser instability, the X2 emissions can be produced by nonlinear coalescence between two Z modes and between Z and X1 modes. Ning *et al.*[83] also studied the harmonic emissions generated by ECME driven by energetic electrons with the horseshoe distribution to solve the escaping difficulty of ECME for solar spikes. It is found that the horseshoe-driven ECME can lead to an efficient excitation of X2 and X3 with a low value of ω_{pe}/Ω_{ce}, providing novel means for resolving the escaping difficulty of ECME when applied to solar radio spikes. The simultaneous growth of X2 and X3 can be used to explain some harmonic structures observed in solar spikes.

On the basis of the ECMI-plasma emission mechanism, Li *et al.*[84] examined the Double Plasma Resonance (DPR) effect and the corresponding plasma emission at both Harmonic (H) and Fundamental (F) bands using particle-in-cell simulations with various ω_{pe}/Ω_{ce}. They found that: (i) the simulations reproduce the DPR effect nicely for the upper hybrid and Z modes, as seen from their variation of intensity and linear growth rate with ω_{pe}/Ω_{ce}; (ii) the intensity of the H emission is stronger than that of the F emission by about 2 orders of magnitude and varies periodically with increasing ω_{pe}/Ω_{ce}, while the F emission is too weak to be significant; (iii) the peak-valley contrast of the total intensity of H is about 4, and the peak lies around integer values of ω_{pe}/Ω_{ce} (10 and 11) for the present parameter setup.

Ni *et al.*[85] performed a fully kinetic, electromagnetic particle-in-cell simulation to investigate the proposed radiation process. They found that the electrostatic UH mode is the fastest-growing mode. Around the time when its energy starts to decline, the W mode grows to be dominant. During this stage, they observe significant F and H plasma emissions. They suggested that the F emission is caused by coalescence of almost counter propagating Z and W modes, while the H emission arises from a coalescence of an almost counter propagating UH mode at a relatively large wave number. Thus the plasma emission investigated here is induced by a combination of wave growth due to ECMI and further nonlinear wave-coupling processes.

Li *et al.*[86] performed 2.5-dimensional Particle-In-Cell (PIC) simulations to investigate the plasma emission excited by a relativistic electron beam using different pitch angles in the magnetized plasma. Langmuir waves at the fundamental and harmonic frequencies were excited *via* the energy dissipation of the electron beam. The backward Langmuir waves up to the third harmonic frequencies were reproduced in the cases of large pitch angles, likely arising from the reflecting and scattering of density fluctuations to the Langmuir waves during electron beam-plasma interaction.

Feng and Lü[87] and Feng and Zhao[88] presented recent progresses on observational studies of the fine structures of type II and type III radio bursts and outlined outstanding issues for future studies. These fine structures can be used to diagnose the coronal parameters, such as electron densities, atmospheric turbulences, energetic electron velocities, and magnetic field strength. It is of great importance to use data with high angular resolution available from newly-built radio heliographs in China for research.

Gao *et al.*[89] investigated the reverse-drifting (RS) type-III bursts, intermittent sequence of type-U bursts, Drifting Pulsation Structure (DPS), and fine structures observed by the Yunnan Observatories Solar Radio Spectrometer (YNSRS). Their observations are consistent with previous numerical simulation results, support numerical simulations during the flare-impulsive phase, and are generally consistent with the results of numerical simulations.

Wan *et al.*[90] performed a detailed statistical study of fiber bursts observed by the Chinese Solar Broadband Radio Spectrometers in Huairou (SBRS/Huairou) with high spectral-temporal resolutions in the frequency ranges of 1.10–2.06 GHz and 2.60–3.80 GHz during 2000–2006. The results indicate that most fiber bursts have a close temporal relation with energetic electrons. Tang *et al*.[91] identified more than 600-millisecond microwave spikes which were also recorded by the SBRS/Huairou during an X3.4 solar flare on 2006 December 13 and presented a statistical analysis about their parametric evolution characteristic. They found that the spikes have nearly the same probability of positive and negative frequency drifting rates not only in the flare rising phase, but also in the peak and decay phase.

Zhang *et al*.[92] presented the main observational results identified by MUSER from 2014 to 2019, including the quiet Sun and 94 solar radio burst events. They found that there are 81 events accompanied with Geostationary Operational Environmental Satellites (GOES) Soft X-ray (SXR) flares, among which the smallest flare class is B1.0. There are 13 events without accompanying any recorded flares, among which the smallest SXR intensity during the radio burst period is equivalent to level-A. The main characteristics of all radio burst events are presented, which shows the powerful ability of MUSER to capture the valuable information of the solar non-thermal processes and the importance for space weather.

Lu *et al*.[93] reported Quasi-Periodic Pulsations (QPPs) with double periods during three solar flares. QPPs with double periods of about two minutes and one minute was first found in the Ly-α emission. They suggested that the two-minute QPP results from the periodic acceleration of nonthermal electrons during magnetic reconnections. Hong *et al*.[94] also reported the analysis of multi-wavelength observations of QPPs during the impulsive phase of the C6.7 flare on 9 May 2019. Their observations suggest that the flare QPPs are possibly related to nonthermal electrons accelerated by the intermittent magnetic reconnection during the flare's impulsive phase.

Lü *et al*.[95] presented an analysis on 34 stationary type IV Solar radio bursts (IVSs) using two-dimensional imaging data provided by Nançay Radioheliograh (NRH) at 10 frequencies from 150 to 445 MHz. The main findings are as follows. (i) In the majority of events (23/34) regular and systematic source dispersion with frequency can be clearly recognized. (ii) In most (31/34) events the maximum brightness temperature ($T^{\mathrm{E}}_{\mathrm{BM}}$) exceeds 10^8 K, and exceeds 10^9 K in 23 events. (iii) In most events (30/34) the sense of polarization remains unchanged and the numbers of events with right and left-handed polarization are comparable.

Zhang *et al*.[96] performed ray-tracing simulations on radio wave transport in the corona and interplanetary region with anisotropic electron density fluctuations. It is found that position offsets due to wave scattering and refraction can produce the co-spatial of the fundamental and harmonic waves in the observation of some type III radio bursts. The visual speed due to the wave propagation effect can reach 1.5c for $\eta = 2.4 \times 10^{-4}$ km^{-1} and $\alpha = 0.2$ for the fundamental emission in the sky plane, accompanied with a large expansion rate of the source size. The direction of the visual speed is mostly identical to the direction of the offset, thus, for the observation aimed at obtaining the source position, the source centroid at the starting time is closer to the wave excitation site.

4 Magnetohydrodynamic (MHD) Numerical Modeling

MHD modeling of solar-interplanetary physics, such as solar eruptions, solar wind, and their interactions, has been witnessed with important progresses in recent two years. With an ultra-high accuracy MHD simulation, Jiang *et al*.[97] established a fundamental mechanism of both simplicity and efficacy for solar eruptions initiated in a single bipolar configuration with no additional special topology. They found that through photospheric shearing motion alone, an electric CS forms in the highly sheared core field of the magnetic arcade during its quasi-static evolution. Once magnetic reconnection sets in at this internal CS, the whole arcade is expelled impulsively, forming a fast-expanding twisted MFR with a highly turbulent reconnecting region underneath. Bian *et al*.[98] further demonstrated the robustness of this mechanism by carrying out a range of simulations with different magnetic flux distributions on the photosphere. In particular, it is found that the sheared bipolar fields with a stronger PIL can achieve more non-potentiality and their internal CS can form at a lower height and with a higher current density, by which the reconnection can be more efficient and thus produce larger eruptions. In addition, Bian *et al*.[99] show that by the continuous shearing of the same PIL, the fundamental mechanism can effectively produce homologous CMEs by recurring formation and disruption of the internal CS.

The high-accuracy simulation of eruption has also been used to interpret the relevant phenomena in observations. For example, by quantifying the toroidal flux evolution of the MFR as formed during the simulated eruption, Jiang *et al*.[100] reproduced an evolution pattern of increase-to-decrease of the toroidal flux as revealed in observations of variations in flare ribbons and transient coronal dimming[101]. The increase of toroidal flux is owing to the flare reconnection in the early phase that transforms the sheared arcade to twisted field lines, while its decrease is a result of reconnection between field lines in the interior of the MFR in the later phase. Wang *et al*.[102] analyzed the behavior of the peripheral magnetic field lines of the simulated eruption and concluded that the often-observed peripheral coronal loop contraction and disappearance are caused by the reduction in magnetic pressure in the flaring core site (consistent with implosion conjecture[103]) and the peripheral magnetic reconnection and the central eruption. Zhou *et al*.[104] found that the evolution of the MFR formed during the simulated eruption compares favorably with a typical filament eruption (*e.g.*, the direction of filament rotation during eruption and its relationship with the filament chirality) and realized that the writhe of the MFR's axis decreases while the twist of its surrounding field lines increases, which challenges the conventional explanation of filament rotation based on ideal kink instability of MFR.

Some studies are focused on the development of turbulence as induced by reconnection during eruptions, using very high-resolution 2.5D MHD simulations, such as Ye *et al*.[105]. Ye *et al*.[106] found that the region immediately above the flare loop top is made more turbulent and hotter by multiple termination shocks and plasmoid collisions, and this turbulence region could be the source of the Quasi-Periodic Pulsations (QPPs) above the looptop. They[107] further studied the turbulence region at the bottom of the CME, and found that the interaction between the CS and the turbulence region can make a significant contribution to CME heating, and this region might also generate periodically coronal wave trains around the CME. Xie *et al*.[108] found that the Rayleigh-Taylor instability inside the turbulence region below the CME can cause this region to oscillate locally, which also propagates downwards through the CS and leads to the CS oscillation. Mei *et al*.[109–111] focused on the EUV disturbances during solar eruption by performing 3D MHD numerical simulations initialized with an analytic unstable MFR. They noticed a complex triple-layered leading edge of CME consisting of a fast shock in the front, a Helical Current ribbon/Boundary (HCB) behind, and a bright MFR within the HCB. Within these layers they also found a 3D Velocity Separatrix (VS) associated with slow shocks at the flanks of the CME bubble, and two types of 3D vortices near the VS, one with plasma converging toward the vortex center, and the other with plasma spreading out.

Important progresses have also been made in data-constrained and data-driven MHD simulations of solar eruptions. Jiang *et al*.[112] developed a new model of coronal magnetic field evolution with the bottom boundary self-consistently driven by a photospheric velocity field. Their model can efficiently reproduce the magnetic energy injection process from the photosphere into the corona. They have also tested the data-driven model using ground-truth data from a flux emergence simulation[113,114], and found that the coronal field can be reliably reproduced if the input boundary data is sufficiently close to force-free. Using this model, He *et al*.[115] simulated the formation and initiation of a large-scale preflare MFR in AR 12371, and suggested that tether-cutting reconnection plays a key role in building up the MFR until its initiation by torus instability. Using a data-driven zero-β MHD model, Zhong *et al*.[116] reproduced a failed eruption of an MFR in a complex magnetic topology. They revealed that a particular Lorentz force component, which is related to the non-axisymmetry of the MFR's cross section, essentially constrains the erupting MFR. This component has been ignored in the theory of torus instability in which the confining force is thought to be coming only from the external strapping field. Guo *et al*.[117] studied a long-duration flare with filament eruption using their zero-β MHD model with the initial condition of magnetic field determined by an advanced flux-rope insertion method that is based on regularized Biot-Savart laws. The data-driven model has also been extended to the very small scale dynamics, for example, recently a high-resolution (reaching spatial scale of 45 km) simulation[118] reproduced the successive formation of mini flux ropes (*i.e.*, plasmoids in 2D) in the reconnection of a confined flare that matches the high resolution from New Vacuum Solar Telescope (NVST) and SDO.

Several studies have been devoted to developing advanced numerical techniques on corona and interplanetary MHD models to improve their robustness and accuracy in simulating ambient solar wind and CME. Feng *et al*.[119] applied an effective implicit strategy, which resorts to the implicit lower-upper symmetric Gauss-Seidel method and keeps the sparse Jacobian matrix diagonally dominant, and show that this technique can robustly deal with the extremely low plasma β (about 10^{-7}) conditions with promising computational efficiency. Based on the MHD system of extended generalized Lagrange multiplier (EGLM) formulation with Galilean invariance, Li *et al*.[120] developed a modified path-conservative HLLEM scheme that is shock-stable and can adaptively adjust diffusion according to the smoothness of the physical flow. Furthermore, an auxiliary equation of entropy has been added to the EGLM formulation, along with a specially-designed spatial reconstruction to preserve the positiveness of pressure and solenoidality of a magnetic field, forming the EC-GLM MHD model[121], which can cope with the high Mach number or low plasma β environment more handily and robustly. Meanwhile, other work that focuses on the comparison of the solenoidality-preserving methods is also carried out[122].

The data of the solar surface, for example, the synoptic map of a photospheric radial magnetic field, is a key input for MHD models of solar wind. Basd on the PFSS model, Li *et al*.[123] compared that results of 2018 obtained from HMI, ADAPT and GONG maps with observation, and found those obtained from zero-point uncorrected GONG maps give significant deviation from others, which stresses cautions are needed when using these data in MHD modeling. Yang and Shen[124] developed a new way to prescribe boundary conditions for interplanetary solar wind by utilizing multiple sets of observations and the machine learning technique. The modeling results of a few Carrington Rotations show improvements on their previous boundary conditions using only photospheric magnetic field observations.

As a critical step in the transition from research to application, an assessment suite for solar wind prediction results is established using multipoint observation in the interplanetary space. Assessment of CESE-HLLD model's results for 2008 reveal the two-stream structure observed near the ecliptic plane and the overall latitudinal variance observed by Ulysses are reproduced, but the differences among observations at L1 and the twin STEREO spacecraft are not caught by the model[125]. Li *et al*.[126] analyzed systematically the evolution of the north-south component B_z of the interplanetary magnetic field (IMF) in the GSM coordinate system and indicates that the Russell-McPherron effect is the dominant mechanism that controls the large-scale evolution of B_z. Given proper boundary conditions at 0.1 AU, the MHD model can well reproduce the evolution of ambient B_z.

For the modeling of CME evolution, Shen *et al*.[127,128] studied how the different CME initial parameters affect the results as seen by observers near different planets (*i.e.*, Earth and Mars) and the process of CME propagation in the interplanetary space. They found that with the initial mass of CME unchanged, the initial geometric thickness will have a different influence in the latitudinal and longitudinal directions. These two works confirm the importance of the initial geometric and physical parameters on the CME simulations. Zhang *et al*.[129] compared simulation results for CME with and without radial compression for the 15 November 2007 event. It is found that CME without radial compression propagates in interplanetary space with a lower velocity and arrives at 1 AU later and tends to overestimate the radial extension and underestimate the magnetic field strength at 1 AU. Yang *et al*.[130] simulated the 10 September 2017 CME focus on the morphology and kinematics of the large shock and found several characteristics of the shock, especially the asymmetry of some shock properties.

5 Solar Energetic Particles and Cosmic Rays

Liu *et al*.[131] proposed a pan-spectrum formula to examine energy spectrum of different suprathermal particle phenomena typically with a single energy break. Using this method, Wang *et al.*[132] suggested that the upward-traveling electrons from an acceleration source high in the corona would form the Solar Energetic Electron (SEE) events, while their downward-traveling counterparts may undergo a secondary acceleration before producing HXRs via thick-target bremsstrahlung processes. Wang *et al.*[133] also study SEE events observed in the Earth's cusp/lobe regions by the BeiDa Image Electron Spectrometer on board a BeiDou satellite in an inclined geosynchronous orbit, to show that interplanetary energetic electrons can enter the planet's cusp/lobe regions and get trapped.

Using test-particle simulations, Kong *et al.*[134] study the acceleration of suprathermal electrons at an ICME-driven shock event. In each energy channel the ratio of downstream to upstream intensities peaks at about 90° pitch angle, and the downstream electron energy spectral index is much larger than the theoretical index of diffusive shock acceleration, to show the importance of SDA in the acceleration of electrons by quasi-perpendicular shocks.

In reservoir phenomenon, solar energetic particle intensities of the decay phase observed by widely separated spacecraft present comparable intensities evolving similarly. Wang *et al.*[135,136] find that the reservoir events could be observed in almost all longitudes in the ecliptic at 1 AU; thus, the perpendicular diffusion in interplanetary space is the most important mechanism to explain the uniform distribution of SEPs. Furthermore, they suggest that the effects of the magnetic boundary and/or the small diffusion coefficients in the sheath region of ICME could also help to form the reservoir phenomenon.

Ground-Level Enhancements (GLE) generally accompany fast ICMEs, and ICME driven shocks are sources of SEPs. Wu and Qin[137] use numerical simulations to show that the sheath-MC structure reduced the proton intensities for about 2 days after the shock passed through the Earth, and the sheath contributed most of the decrease while the MC facilitated the formation of the second step decrease. In addition, Qin and Wu[138] use simulations to study the effects of the Forbush Decrease with the magnetic cloud and sheath during the GLE events. It is suggested that the sheath plays an important role in the amplitude of the Fd while the MC contributes to the formation of the second step decrease and prolonged recovery time.

Diffusion is important for transport and acceleration of cosmic rays. There are different definitions for the spatial parallel diffusion coefficient. Wang and Qin[139] proved that the Displacement Variance Definition (DVD) is invariant for the iterative transformation of the cosmic rays transport equation for focusing field. Therefore, for a spatially varying field, DVD is more appropriate than other definitions. In addition, Wang and Qin[140] obtain the modified momentum diffusion due to the varying magnetic field.

The intensity of Galactic Cosmic Rays (GCRs) is modulated by solar activity on various timescales. Luo *et al.*[141] have performed comprehensive numerical modeling of the solar rotational recurrent variation in GCRs caused by a Corotation Interaction Region (CIR). A newly developed MHD numerical model is adapted to simulate the background solar wind plasma with a CIR structure present in the inner heliosphere. The simulated MHD inner heliosphere is extrapolated to the outer heliosphere by using the Parker interplanetary magnetic field model. The output of these plasma and magnetic field models is incorporated into a comprehensive Parker-type transport model for GCRs. The obtained solutions of this hybrid model, for studying the CIR effect, are as follows. (i) The onset of the decrease in the GCR intensity inside the CIR coincides with the increase of the solar wind speed with the intensity depression accompanied by a magnetic field and plasma density enhancement. Additionally, the CIR effect weakens with increasing heliocentric radial distance. (ii) This decrease in GCR intensity also appears at different heliolatitudes and varies with changing latitude; the amplitude of the GCR depression exhibits a maximum in the low-latitude region. (iii) The CIR affects GCR transport at different energy levels as well. Careful analysis has revealed a specific energy dependence of the amplitude of the recurrent GCR variation in the range of 30–2000 MeV.

With continuous measurements from space-borne cosmic-ray detectors such as AMS-02 and PAMELA, precise spectra of galactic cosmic rays over the 11 yr solar cycle have become available. Song *et al.*[142] utilize proton and helium spectra below 10 GV from these missions from 2006 to 2017 to construct a cosmic-ray transport mode for a quantitative study of the processes of solar modulation. The Markov Chain Monte Carlo method is utilized to search the relevant parameter space related to the drift and the diffusion coefficients by reproducing and fitting the mentioned observed spectra. It is found that: (i) when reproducing these observations the parameters required for the drift and diffusion coefficients exhibit a clear time dependence, with the magnitude of the diffusion coefficients anticorrelated with solar activity; (ii) the rigidity dependence of the resulting mean free paths varies with time, and their rigidity dependence at lower rigidity can even have a larger slope than at higher rigidity; (iii) using a single set of modulation parameters for each pair of observed proton and helium spectra, most spectra are reproduced within observational uncertainty; and (iv) the simulated proton-to-helium flux ratio agrees with the observed values in terms of its long-term time dependence, although some discrepancy exists, and the difference is mostly coming from the underestimation of proton flux.

Shen *et al*.[143] developed a hybrid method to remove SEPs to obtain GCR background with the solar cycle variation characteristics of the 27-day GCR modulation. Shen *et al*.[144] numerically study the latitudinal dependent GCR modulation to find that the latitudinal-dependent magnetic turbulence is crucial during the negative-polarity solar cycle, while the latitudinal diffusion coefficient and the reduced drift velocity in the polar region are more important during the positive-polarity solar cycle. In addition, Shen *et al*.[145] established a predictive and empirical GCR model with a force field approach, to reproduce the 11 and 22 years cyclic variations of GCRs.

The solar eruption on 10 September 2017 was accompanied by a fast coronal mass ejection (about 3000 km$\cdot$s^{-1}) and produced a Ground-Level Enhancement (GLE) event at Earth. Zhu *et al*.[146] determined the shock parameters by combining the 3D shock kinematics and the solar wind properties obtained from a global MHD simulation, in order to compare them with the characteristics of the Solar Energetic Particles (SEPs). They extracted the magnetic connectivities of the observers from the MHD simulation and found that L1 was magnetically connected to the shock flank (rather than the nose). The weak magnetic field and relatively dense plasma around the HCS result in a large Mach number of the shock, which leads to efficient particle acceleration even at the shock flank. They conclude that the interaction between the shock and HCS provides a potential mechanism for the production of the GLE event.

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