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Magnetospheric Physics in China: 2020–2021

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Abstract In the past two years, many progresses were made in magnetospheric physics by the data of OMNI, SuperMAG networks, Double Star Program, Cluster, THEMIS, RBSP, DMSP, DEMETER, NOAA, Van Allen Probes, GOES, Geotail, Swarm, MMS, BeiDa, Fengyun, ARTEMIS, MESSENGER, Juno, Chinese Mars ROVER, MAVEN, Tianwen-1, Venus Express, Lunar Prospector *e.g.*, or by computer simulations. This paper briefly reviews these works based on 356 papers published from January 2020 to December 2021. The subjects covered various sub-branches of Magnetospheric Physics, including solar wind-magnetosphere-ionosphere interaction, inner magnetosphere, outer magnetosphere, magnetic reconnection, planetary magnetosphere.

Key words Solar wind-magnetosphere-ionosphere interaction, Inner magnetosphere, Outer magnetosphere, Magnetic reconnection, Planetary magnetosphere

Classified index P35

1 Solar Wind-magnetosphere-ionosphere Interaction

Solar wind dynamic pressure ($P_{\rm dyn}$) is the main driving factor that determines the intensity of a great geomagnetic storm[1,2] and plays an important role in the wave evolution and particle dynamics in the inner magnetosphere[3–5]. Xiang *et al*.[6] confirmed that the solar wind speed has the greatest influence on the MeV electron flux variations, particularly at higher L, while the $P_{\rm dyn}$ has more influence at lower L. There were both electron dropout and enhancement drift echoes in some $P_{\rm dyn}$ decrease events[7]. The magnetopause shadowing process in association with a sudden $P_{\rm dyn}$ pulse or a large geomagnetic storm may be the major loss mechanism during the initial phase of the storm at $L > 4.5$[8]. Shi *et al*.[9] reviewed how changing solar wind $P_{\rm dyn}$ produces the vortices, Ultralow Frequency (ULF) waves, and aurorae. Zhao *et al*.[10] provided direct evidence of the scenario that magnetospheric flow vortices generated by a $P_{\rm dyn}$ pulse carry Field-Aligned Currents (FACs) into the ionosphere and thereby modulate auroral activity.

Zou *et al*.[11] demonstrated that persistently enhanced $P_{\rm dyn}$ can modulate the radiation belt electron dynamics before the storm main phase. For energetic energy level, the occurrence rate of the pancake (butterfly) PADs does not clearly decrease (increase) with the enhancement of $P_{\rm dyn}$ at $L \leqslant 12$[12]. About 5% time, protons with energies of 30–50 keV showed two distinct populations, having an additional field-aligned population overlapping with the original pancake population[13]. Radiation belt electron butterfly PADs are well connected to the solar wind condition, substorm activity, and magnetospheric wave distribution[14].

Xiang *et al*.[15] suggested that actual radial diffusion rates in the inner belt are lower than previous estimates in which cosmic ray albedo neutron decay contributions were not considered. Simulations showed that

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solar flares increased global daytime currents and reduced the eastward electric fields during the daytime from the equator to middle latitudes[16]. The solar wind density plays a significant role in transferring solar wind energy into the magnetosphere, besides the southward magnetic field and the solar wind speed[17].

Cai *et al.*[18] reported the characteristics of the topside ionospheric O^+ diffusive flux during both geomagnetically quiet and moderate times for solar minimum from 1970 to 2018. Statistical results show that the O^+ density and its abundance (O^+/H^+) vary with SYM-H index and P_{dyn} exponentially[19], and the H^+ and O^+ lifetimes generally increase with L shell[20]. During the main phase, Ring Current (RC) ions with lower magnetic moments can penetrate into the deep inner magnetosphere[21].

The global lightning can dominate the atmospheric noise[22] and can generate whistler waves which can travel upward into the radiation belts during higher geomagnetic activities[23]. The day-night difference of energetic electrons in the South Atlantic Anomaly (SAA) region depends not only on the electron energy but also on the geomagnetic activity levels[24]. The subauroral polarization streams induced equatorial electrojet presented a semidiurnal pattern associated with the variations of the F_2-layer virtual height[25] and flows westward and eastward in the daytime and dawn/dusk sectors, respectively[26].

The statistical characteristics of the structures of giant undulations during geomagnetic storms were studied for the first time, based on aurora images during 2005–2019[27]. He *et al.*[28] showed direct observations of a plasmapause surface wave and its impacts during a geomagnetic storm. The electron density fluctuation events at the plasmapause mainly occur in the twilight sectors and the spatial distribution varies with MLT and geomagnetic activity[29]. Li *et al.*[30] suggested that the occurrence rate of an observed plasmaspheric plume in the inner magnetosphere is larger during stronger geomagnetic activity. The source population and the charge exchange losses along the drift paths play a very important role in the formation of the "finger" structure[31].

The result of Ren *et al.*[32] may explain previous observation that substorms frequently occur shortly after northward IMF turning. The statistical analysis shows that strong substorms (AE>1000 nT) and super substorms (AE>2000 nT) triggered by interplanetary shocks are most likely to occur under southward IMF and fast solar wind pre-conditions[33]. Duan *et al.*[34] indicated that characteristics of dipolarization with a large beginning elevation angle within the substorm onset region provide a new indicator to identify substorm onset location. Fu *et al.*[35] suggested that there is an additional current wedge during intense substorms located near the dusk. Tang *et al.*[36] reported local secondary magnetic reconnection at Earth's flank magnetopause, suggesting a new pathway for the entry of the solar wind into geospace. The magnetospheric energy deposition into the northern polar upper atmosphere has obvious longitudinal and seasonal variations[37]. The ions with larger grazing angles would meander around the magnetopause without a full escape, whereas the meandering motion for those with smaller angles could be more easily to escape[38]. Non-storm time super-substorm may also have a significant contribution to the RC[39]. The reversed energy spectra of RC protons with distinct flux can be prevalent inside the plasmasphere[40].

Wang *et al.*[41] provided the first observational evidence that solar/interplanetary energetic electrons can directly and continuously enter the planet's cusp/lobe regions and get trapped there. Guo *et al.*[42] found that during the northward IMF, high latitude magnetic reconnection both poleward and equatorward of the cusp can occur almost simultaneously. High solar wind density, low latitude magnetopause reconnection and positive dipole tilt are favorable conditions for high-density cusp events[43]. Based on topology information, a new normalized statistical methodology is developed by Xiao *et al.*[44] to organize the measurements of cusp crossings to obtain distributions of magnetic field and plasma parameters in the *xz* plane.

Xue *et al.*[45] reported a simultaneous observation of two band Electromagnetic Ion Cyclotron (EMIC) waves and toroidal Alfven waves by the Van Allen Probe mission. The original right-handed elliptically polarized Alfven waves become linearly polarized, and eventually become right-handed and circularly polarized[46]. Dipolarization Fronts (DFs) in the magnetosphere could couple the ionosphere with Alfven waves[47].

Chen *et al.*[48] demonstrated that kinetic-scale FACs are significant in magnetosphere-ionosphere coupling which can be generated by velocity shear shortly and locally[49] between fast plasma flows associated with nightside magnetic reconnection and slower background magnetotail plasma flows[50]. Ion upflow occurrence shows a dawn-dusk asymmetry distribution that matches well with the Region 1 FACs[51]. Conjunctive observations of a downward FAC and ground data were made to investigate the generation of downward FAC[52].

Yao *et al.*[53] presented a new type of Kinetic-Scale Flux Rope (KFR) in the Earth's dayside magnetosheath boundary layer, which was possibly generated by a FAC, differing from typical dayside flux ropes usually observed within the current sheet where magnetic reconnection can occur. Pitkanen *et al.*[54] statistically investigated how the rotation of the neutral sheet depends on the sign and magnitude of IMF By. Electrons can be non-adiabatic at the neutral sheet, which is able to scatter their PAD[55].

The Transpolar Arcs (TPAs) presented by Park *et al.*[56] were believed to be the result of both indirect and direct processes of solar wind energy transfer to the high-latitude ionosphere. Tang *et al.*[57] suggested that the semiannual variation observed in the TPA incidence may be related to the Russell-McPherron effect due to the projection effect of the IMF By under northward IMF conditions. The observations and simulations reveal that these multiple TPAs are generated by precipitating energetic magnetospheric electrons within FAC sheets[58].

Ma *et al.*[59] suggest that the flow of polar cap origin may play a crucial role in auroral surges by feeding low entropy plasma into surge initiation and development. Li *et al.*[60] suggested that the electron precipitation through the polar rain can be a main energy source of the polar wind during periods of high levels of solar activity. Polar cap cold patches occur more frequently during solar maximum years[61]. The spatial size of cold and hot patches decreases with solar activity (increases with geomagnetic activity). Zhang *et al.*[62] summarized the recent new progress in the formation and evolution of patches.

Zhang *et al.*[63] presented the first statistical study on the Auroral Kilometric Radiation (AKR) electric field amplitude in the radiation belts. The first (higher) harmonic order of AKR contributes to diffusion coefficients at small (larger) pitch angles[64].

Fujimoto and Sydora[65] showed that the electron K-H instability plays a primary role in driving intense electromagnetic turbulence, and the high-energy electrons are efficiently scattered by the turbulences, leading to the dissipation and electron heating[66]. The distribution of magnetosheath turbulence in the wavenumber space is dominantly transverse to the background magnetic field[67]. The correlation (and Taylor) length scale of the solar wind turbulence is the largest along the magnetic field, and is the smallest in the field-perpendicular directions[68]. The Taylor scale increases with the increasing sunspot number, indicating that the Taylor scale is positively correlated with the energy cascade rate[69].

2 Inner Magnetosphere

Proton sustained gaps are predominantly distributed near the prenoon sector[70], while the narrow gaps for oxygen ions are most frequently observed near the noon sector[71]. Using the time-of-flight technique based on the pitch angle dependence of electron drift velocities, the "boomerang-shaped" stripes are inferred to originate from straight stripes[72]. The particle tracing model suggests that the wedge-like structures originate from intermittent substorm injection, and it is the accessibility region of these injected ions that determines their shapes[73]. These wedge-like structures are probably attributed to fresh substorm injections from the outer region[74]. Li *et al.*[75] found a clear MLT dependence of the number of stationary "nose-like" ion spectral structures. Ren *et al.*[76] suggested that the wedge-like and nose-like spectral signatures are merely the manifestations of one single structure along different spacecraft trajectories.

The Very Low Frequency (VLF) transmitter signals have a slight influence on the loss of energetic electrons with pitch angles larger than 80°[77]. Xiang *et al.*[78] suggested that the VLF transmitter signals in the inner magnetosphere mainly propagate along the magnetic field line across the station position. Hua *et al.*[79] provided quantitative evidence that VLF transmitter emissions that leak from the Earth-ionosphere waveguide are primarily responsible for bifurcating the energetic electron belt. The bifurcation of the Earth's energetic electron belt (tens of keV) is mostly observed at 30–100 keV[80].

Electron Cyclotron Harmonic (ECH) and chorus may not grow independently but competitively or collaboratively gain energy from hot electrons[81] and nonlinear wave-wave interactions can redistribute the primary ECH wave energy over a broader frequency range[82]. Wu *et al*.[83] demonstrated that the heating of cold electrons is negligible and non-resonant, different from previous conclusions, and suggested that the saturation of the ECH wave is caused by the filling of the loss cone of hot electrons. Lou *et al*.[84] confirmed the significant role of ECH waves in driving the dayside diffuse aurora. ECH waves at Earth could exhibit frequency chirping[85].

Wave trapping caused by field-aligned density irregularities (ducts) may account for whistler-mode waves[86,87], which are found to be generated by the butterfly type PADs of electrons[88], with field-aligned electron components acting as the energy source[89]. The wave ducting effects at the plasmapause may lead to unusual and anomalous energetic pitch angle scattering[90]. Lu *et al*.[91] demonstrated that a continuous injection of energetic electrons caused by an azimuthal drift is essential for the repetitive emissions of chorus waves.

One-dimensional Particle-in-Cell (PIC) simulation can give a further understanding of the generation and propagation of rising-tone chorus waves[92,93], *e.g.*, bidirectional chirping of whistler waves in a uniform magnetic field and falling-tone-only chirping in an inhomogeneous field[92], a spectrum with a power gap around 0.5 Ω[94]. The gap is found between two peaks of whistler-mode waves, which is caused by the mode splitting of beam-like electrons[95].

Theoretical and numerical models of chorus waves were reviewed in Tao *et al*.[96], focusing on the nonlinear wave particle interactions and the frequency chirping of rising tone chorus waves. The duration of whistler mode chorus waves increases and the chirping rate (Gamma) decreases with increasing L-shell, although the dependence is weak[97]. Liu *et al*.[98] presented two unexpected chorus rising tone events within which the subelements exhibit unexpected clearly reversed, falling frequency-sweep. Statistically, lower-band chorus emissions exhibit higher wave occurrence rates and larger normalized peak wave frequencies in northern hemisphere but somehow stronger peak wave intensities in southern hemisphere[99]. Tao *et al*.[100] proposed a phenomenological model which could be applied to explain the fine structures of chorus waves, including subpackets and bandwidth.

The radial structures of seed electron Phase Space Density (PSD) should be considered when studying the dynamics of the outer radiation belt[101]. Chen *et al*.[102] showed that electron PSD presents a peaked radial profile and power law energy spectrum, confirming that local acceleration plays an important role in the electron dynamics. Liu *et al*.[103] reported that whistler waves can effectively trap/bunch thermal electrons and modulate electron phase space trajectories. Using a test particle simulation code, Cai *et al*.[104] investigated effects of nonlinear resonance broadening on scattering of electrons and compare the results with a previous nonlinear theory. Wu *et al*.[105] suggested that the loss and recovery processes developed first at higher L-shells. The “S-shaped” inner boundary is abruptly transformed from “V-shaped” in storm main phase but reoccurs in several days in the late recovery phase[106].

Various frequency chorus waves have different effects on electron dynamics[107]. ELF chorus can result in unusual loss of relativistic electrons while regular chorus contributes to the acceleration[108]. By studying the Landau resonance between whistler mode waves and electrons, Kong *et al*.[109] provided a better understanding of the formation of beam-like electron distribution in the Earth’s magnetosphere. However, bounce resonance diffusion rates have slight energy dependence for >100 keV electrons while Landau-resonant scattering rates decrease significantly in the MeV energy range[110]. Statistical electron PADs features observed in the whistler- and non-whistler waves are associated with the Landau resonance of whistler-mode waves and drift-shell splitting effect[111]. Chen *et al*.[112] demonstrated that the particle energy change might be underestimated in the conventional theories, as the Betatron acceleration induced by the curl of the wave electric field was often omitted.

The statistical studies of He *et al*.[113] showed that incoherent hiss is widely distributed in dayside plasmasphere, with peak frequencies below 500 Hz; and intense coherent hiss occurs in outer plasmasphere of $L > 4$. Liu *et al*.[114] presented the first comprehensive observations of hiss waves growing from the substorm-injected electron instability. Both hiss and exohiss waves have higher occurrence rates on the dayside (08:00–20:00 MLT) and are positively correlated[115].

Hiss and chorus can simultaneously occur at the same electron drifting shells due to the irregular plasmasphere[116]. Chorus wave is incoherent when the spatial extent is greater than 433 km or the time lag lasts about 10 s[117]. Using high-quality Van Allen Probes measurements, Gu *et al*.[118] verified that chorus waves act as a critical candidate for relativistic electron acceleration and plasmaspheric hiss as a viable cause for relativistic electron loss. Fu *et al*.[119] suggested that the hiss waves have different sources: low-frequency (<0.18 f_{ce}) hiss waves transmitted from chorus outside the plasmasphere and high-frequency (>0.18 f_{ce}) hiss waves locally amplified. Li *et al*.[120] suggested that the enhanced electric field can significantly change the energetic electron distributions, which provide free energy for hiss wave amplification.

The gradual formation of "reversed energy spectrum" at L≈3.5 indicates that hiss scattering inside the plasmapause contributed to the fast decay of sub-MeV remnant belt[121]. The collaborated effect of a low-frequency band and high-frequency band hiss can cause significant precipitation losses of energetic electrons of tens to several hundreds keV within 2 days[122] and Locally generated High-Frequency Plasmaspheric Hiss (LHFPH) could be a potential mechanism for the precipitation loss of suprathermal electrons of 0.1 keV to tens of keV[123].

The competitive influences of different plasma waves on the PAD of energetic electrons depend on density of ambient plasmas and relative intensity of waves[124]. Man-made VLF waves and naturally generated hiss or Lightning-Generated Whistlers (LGWs) play complementary and catalytic roles in the loss of radiation belt electrons[125], and weaken the top hat Pitch Angle (PA) distribution[126]. Mei *et al*.[127] developed an empirical model of the energy-dependent boundaries of Earth's electron radiation belt slot region. Slot region electron loss timescales vary significantly from <1 day to several years[128].

Hot plasma effects will modify the hiss dispersion relation[129]. The cold plasma theory can become less reliable for plasmaspheric hiss waves under disturbed geomagnetic circumstances and the realistic wave dispersion is essential to better quantify the electron scattering effect of hiss waves[130]. Wang *et al*.[131] presented the first quantitative study on the evolution of suprathermal electrons under the competition between Landau heating by whistler mode hiss waves and Coulomb collisional cooling by background plasma inside a plasmaspheric plume. Fu *et al*.[132] demonstrated that the cyclotron resonance is mainly responsible for the pitch angle scattering of electrons <80°, while both Landau and bounce resonances can affect the scattering of near-equatorially mirroring electrons. Li *et al*.[133] found similarities and differences between sub-MeV and ultra-relativistic electrons three-belt events, providing a new perspective in three-belt structure study.

Strong storms and moderate storms can share in common a lot of features on the azimuthal mode structure and power spectrum of ULF waves[134]. The generation of Pc4-5 ULF waves after interplanetary shock-induced electric fields is studied by Zhang *et al*.[135]. Li *et al*.[136] proposed that the shoulder-like pulsations which had been observed in many ULF wave events can be caused by monochromatic oscillations of the magnetic flux tubes in a ballooning-mirror mode structure, which are likely facilitated by the magnetic reconnection altering the state of plasma in the downstream plasma sheet[137].

These toroidal ULF waves, like their poloidal counterparts, play an important role in magnetospheric particle dynamics[138]. The seed (hundreds of keV) and core (⩾ 1 MeV) electrons can resonate with ULF wave modes with distinctive values simultaneously[139]. Resonant electrons can remain phase trapped by the low-m ULF waves under strong convection electric fields, whereas for high-m ULF waves, the electrons trajectories can be significantly modified[140]. Zhao *et al*.[141] suggested that localized ULF waves trapped in the plume may result in the preference of localized ULF wave-electron interactions in noon-to-dusk region. Liu *et al*.[142] found the phase shift of ion flux oscillation across resonant pitch angles varies with time, when ULF wave growth and damping cannot be neglected. Li *et al*.[143] suggested 180° phase shifts across pitch angle can also result from pitch angle-dependent bump-on-tail distributions.

During large *AE*, EMIC waves are mainly generated in the dusk sector and near the magnetic equator[144]. Liu *et al*.[145] highlighted the importance of solar wind conditions for the evolution of inner magnetospheric EMIC waves from a new perspective. Xiong *et al*.[146] suggested that the inward extension of EMIC waves may be driven by the inward injection of anisotropic energetic protons from the dense plasma sheet.

However, H^+ and He^+ band EMIC waves can be simultaneously excited in the midnight sector under appropriate conditions[147]. The maximum growth rate of H-band of EMIC waves appears in the dusk-to-midnight sector near the plasmapause, while O-band is excited at a slightly outer region[148]. The frequency of the H^+ band EMIC wave triggered by anisotropic hot H^+ drops quickly in the initial stage, and then, a narrow He^+ band EMIC wave is excited [149]. He^+ band EMIC waves appeared to split into O^{2+} and He^+ band emissions, providing insight into the generation of O^{2+} band EMIC waves[150].

Wang *et al*.[151] demonstrated for the first time the existence of the intense unguided L-mode EMIC waves in the radiation belt according to the polarization characteristics. The effects of super-thermal plasmas on EMIC wave instability growth have a strong dependence on the emission band, temperature anisotropy A_{hp}, and parallel beta β_{hp} of hot protons[152]. Hot protons alter the refractive index of EMIC waves at a given wave frequency along latitude and thus modify resonance latitude[153]. Polarization reversal of EMIC waves contributes significantly to the pitch angle diffusion coefficients at low pitch angles extending to the loss cone angle for various parameter sets[154] or of H^+ band-induced particles[155].

Wang *et al*.[156] revealed the important mechanism for the loss of RC protons, that is being scattered by EMIC waves[157], and more important than the one due to field line curvature[158,159], which mostly contributes to ion precipitation in outer regions ($L > 4$–5). When the intensity of EMIC waves is large, the cold protons (ions) having low-energies can be energized by the EMIC waves[160].

Intense EMIC and Magnetosonic (MS) waves were simultaneously observed in the high-density regions and disappeared in low-density regions[161]. The linear growth rates estimated for both these two waves are in good agreement with the observed wave frequency spectra[162]. Huang *et al*.[163] suggested that the complex unstable distribution in the velocity phase space of RC protons during the magnetic dip can trigger the simultaneous generation of EMIC and MS waves in the inner magnetosphere.

The MS wave occurrence rate and amplitude B_w increases with enhanced geomagnetic activity and decreasing magnetic latitude, and is strongest near the geomagnetic equator within the 08:00–20:00 MLT sector, both inside and outside the plasmapause, while the B_w can reach higher values inside the plasmapause than it does outside the plasmapause as the *Kp* index increases[164,165]. This is different from the finding that narrowband fast MS waves near the lower hybrid resonance frequency were observed mainly outside the plasmapause[166], with a distinct boundary where energies of the low-harmonic fast MS waves cannot penetrate inward in the time-frequency domain[167]. The electric/magnetic fields of MS waves decrease/increase rapidly when propagating across the plasmapause boundary layer from the outside[168]. However, Huang *et al*.[169] performed the first observations of high frequency MS waves with the frequencies of harmonics higher than the lower hybrid frequency in the Earth's magnetosphere. Zou *et al*.[170] presented an unusual event of MS waves with more than six harmonics wavebands ($n = 1, 2, \cdots, 6$). MS waves would be fully reflected near the cut-off point, since only evanescent waves are allowed in the cut-off regions[171].

Sun *et al*.[172] demonstrated that the background plasma density variation can modulate the MS waves and may play an important role in the spatial distribution of MS waves. Yu *et al*.[173] indicated the validation of cold plasma approximation to estimate the electric field components of MS waves from their magnetic counterparts in the inner magnetosphere. Wu *et al*.[174] illustrated a scenario that off-equatorial proton ring distributions could be a significant source of inner magnetosphere MS waves[175], which can first appear at a distant region and then propagate to low *L*-shells[176].

Gu *et al*.[177] indicated that the MS waves associated with the density drop can cause considerable pitch angle and momentum diffusion for radiation belt electrons. Yuan *et al*.[178] provided ionospheric signature of RC ions scattered by MS waves. Zhou *et al*.[179] suggested that the electron butterfly distribution has important implications for revealing the combined scattering of MS wave-particle interactions. Fu and Ge[180] demonstrated that the local acceleration of the RC protons by MS waves contributes to the dynamic evolution of Earth's RC.

3 Outer Magnetosphere

Liu *et al*.[181] presented the first observational evidence for Magnetic Hole (MH) generation by electron mirror instability behind a DF. The reconstructed results of Liu *et al*.[182] showed that the Electron-Scale Magnetic Holes (ESMHs) may have complex cross-section shapes (*e.g.*, saddle-like shapes) and comparable extension lengths in the parallel and perpendicular directions to the magnetic field, which are inconsistent with the cylinder simplifications in previous studies. Kinetic-Scale Magnetic Holes (KSMHs) occur in the magnetosheath at rates far above their occurrence in the solar wind[183]. Huang *et al*.[184] identified whistler waves at the boundary of an ion scale magnetic hole, which should be locally excited rather than propagated from other regions.

Whistler waves were also observed in the Earth's foreshock[185]. There is a clear decreasing trend between the size of foreshock cavitons and their velocity in the solar wind frame[186]. Magnetic reconnection could occur in the foreshock region and heat/accelerate the electrons therein[187]. A correlation between variations of magnetosheath hot ion fluxes and the transverse fluctuations of the ULF waves is found by Cai and Wei[188]. Wang *et al*.[189] for the first time found that the drift-bounce resonances played a major role in modulating the energy of ions with energy dispersions, during the interactions between the ions and the foreshock transient-driven Pc5 ULF wave. There are more than two resonant pitch angles at fixed energy, revealing a new drift-bounce acceleration mechanism in the dayside outer magnetosphere[190].

A global MHD model is used by Lu *et al*.[191] to study the energy transfer from solar wind to magnetosphere through magnetopause under radial IMFs, when the dayside of the bow shock is located closer to the Earth than the average[192]. Wang *et al*.[193] performed a series of 3D global Magnetohydrodynamic (MHD) simulations and demonstrated the quantitative effects of the IMF B_x component on the locations and shapes of the bow shock and magnetopause during northward IMF. Shang *et al*.[194] demonstrated that the compressed magnetopause is sharply deflected at lunar distances in response to the shock and solar wind *V*-*Y* effects. Man *et al*.[195] presented a comprehensive study of the intense current structures at the dayside magnetopause. There are obvious asymmetries on both flanks of the magnetopause and the dawn side magnetopause is thicker and more active[196]. The statistical results reveal the important role of $P_{\rm dyn}$ in electron dynamics inside the magnetopause. The O^+ density in the duskside magnetopause boundary layer during the recovery phase is larger than that during the expansion phase[197].

Zhu *et al*.[198] provided key parameters to help understand how Hot Flow Anomalies (HFAs) disturb the magnetosphere. The electron velocity within the electron jets is much larger than the local Alfven speed, implying that these jets belong to super-Alfvenic flows[199]. At MHD scales, the spectral indices of the magnetic-field and velocity spectra present a positive and negative correlation with Alfven Mach number[200]. When the IMF is southward and the Alfven Mach number of solar wind is high, the bow shock indentation can be clearly determined[201].

Guo *et al*.[202] for the first time demonstrated the betatron-cooling effect beyond the Earth, which helps to understand the electron dynamics in the planetary magnetosphere. The donut-shaped PADs of magnetic cavity electrons were formed by the combined effects of betatron cooling, radial transport, and pitch angle variations[203]. Based on the multipoint measurements from the Magnetospheric Multiscale (MMS) constellation, Li *et al*.[204] developed a kinetic model which can utilize magnetic cavity observations by one MMS spacecraft to predict measurements from a second/third spacecraft. Liu *et al*.[205] reported evidence of evolution of an identified microscale (*i.e.*, electron gyro-scale) magnetic cavity structure and reveal within it a unique energization process that does not adhere to prevailing adiabatic invariance theory. Observations from the MMS constellation[206] have shown the existence of helical magnetic cavities characterized by the presence of azimuthal magnetic fields, which could not be reconstructed by the previous models.

Non-gyrotropic electron distributions can be generated by the finite electron gyration at an electron-scale boundary, and the electric field normal to this boundary usually contributes to the electron acceleration to make a gyrotropic distributions more apparent[207]. The magnetic field line curvature in the turbulent magnetosheath plasma exhibits two power-law distributions: the low/large curvature follows the scaling of $\kappa^{0.33}$/ $\kappa^{-2.16}$[208]. Three kinds of PADs commonly observed in the magnetotail, Pancake, Rolling pin, and Cigar distributions, are formed in sequence during the propagation of the DFs[209]. These electron pitch-angle distributions, as well as butterfly, are crucial to understanding electron dynamics in the magnetotail. For the first time, Liu *et al.*[210] presented that they couldn't find any statistical correlation between magnetic structures and the rolling-pin distributions, different from previous studies suggesting a close connection between them.

Current sheets with widths of several ion inertial lengths are produced in the magnetosheath after the upstream large-amplitude electromagnetic waves penetrate through the shock and are then compressed in downstream[211]. Yang *et al.*[212] shed new insight on the mechanism for electrostatic wave excitations and possible Electromagnetic wave emissions at young coronal mass ejection-driven shocks in the near-Sun solar wind. Wang *et al.*[213] suggested that the ion-scale magnetic peaks are coherent structures associated with energy dissipation and electron heating in the magnetosheath. Magnetic reconnection can play a significant role for the energy dissipation in these magnetic peaks, which have been investigated by Lu *et al.*[214] in the downstream of a quasi-perpendicular shock. Yang *et al.*[215] provided direct evidence of shock self-reformation, and also shed light on energy dissipation and energetic particle acceleration at collisionless shocks throughout the universe.

Bipolar current densities exist in the cross section of two hole-like mirror-mode structures, referred to as Magnetic Dips (MDs)[216]. Yao *et al.*[217] identified four different types of MDs: "frozen-in," "expanding," "contracting," and "stable-propagating." MDs and the injected protons perform good agreement[218]. The positive slope is responsible for the generation of high-frequency electrostatic wave in the magnetic dip ahead of the DF[219].

Wei *et al.*[220] reported that the wide-range of intense dB/dt (and dH/dt) variations are associated with a large-scale, substorm current system, driven by multiple Bursty Bulk Flows (BBFs). Zhang *et al.*[221] suggested that the strong/weak vorticity field of the plasma bulk (convective) velocity within the BBF corresponds to the ion flux enhancement at high/ medium energy (above 10 keV/2–5 keV). Zhang *et al.*[222] proposed a possible mechanism on the BBF deceleration, *i.e.*, "collision" with the tailward flow. Inside the BBFs, the strongest earthward electron flows are observed in the ion flow boundary, away from the current sheet center[223]. Zhang *et al.*[224] revealed that the cross-tail current sheet at the DF is rolled up, which could decelerate BBF and change the flow structure.

4 Magnetic Reconnection

Wang *et al.*[225] provided the first dynamic picture of magnetic reconnection, demonstrating that the magnetic reconnection in space can develop rapidly during tens of milliseconds. The magnetotail reconnection is possible to occur when the dawnside tail lobe contacts with the duskside tail lobe by a sudden increase of the IMF B_z component[226] with significant B_y[227]. Huang *et al.*[228] demonstrated that the asymmetric upstream plasma conditions during magnetic reconnection can be studied in the laboratory.

When the IMF clock angle is large, the flux ropes can coalesce and form new ones with larger diameters[229]. Man *et al.*[230] showed a typical ion-scale flux rope at the subsolar magnetopause. The energetic electron fluxes inside it were larger than those outside[231]. Chen *et al.*[232] presented the first observation of a Magnetic Flux Rope (MFR) inside an Electron Diffusion Region (EDR). The subion-scale MFRs host more intense plasma activity than the ion-scale MFR[233]. Besides using four spacecraft with separation scale much smaller than the flux ropes, current density, curvature radius of the magnetic field, and the transverse size of flux ropes can also be inferred by a single-point method[234].

Man *et al.*[235] reported an MMS observation of magnetic reconnection occurring at the edge of a large-scale (2 R_e) MFR. Zhong *et al.*[236] presented the first observational evidence for localized secondary reconnection at the separatrix surface of an MFR. Zhou *et al.*[237] presented the first evidence that secondary reconnections occur in the turbulent outflow driven by a primary reconnection in the Earth's magnetotail. Wang *et al.*[238] presented direct evidence of secondary reconnection in the filamentary currents, which are plentiful in both primary flux ropes and the secondary flux ropes[239]. Two re-reconnection processes increase the plasma energy and the magnetic flux connected to the Earth, which favors particle and energy transport toward the Earth's magnetosphere[240].

The particle acceleration processes around magnetotail DFs were reviewed by Fu *et al.*[241]. As found a DF structure behind which energetic-electron fluxes are modulated by MS waves[242] explained both the presence and absence of energetic electrons behind DFs. Liu *et al.*[243] indicated that energy budgets at the DFs are dominated by electron physics, rather than ion dynamics suggested by previous studies. Betatron acceleration dominates at the DF[244]. Only Fermi mechanism is contributory to suprathermal electron acceleration and presented a new explanation for its formation[245].

Ma *et al.*[246] suggested that plasma heating or temperature enhancements are related to both the flow vorticity/shear and current density, but more strongly with flow vorticity/shear. By analyzing the velocity of the electrons, Jiang *et al.*[247] found the first observation of electron vortex at the DF as far as they know. However, magnetic field perturbations induced by this electron vorticity are not significant[248].

The curvature force continuously accelerates the DF moving outward, while the thermal pressure gradient force hinders the movement of the DF[249]. Wang *et al.*[250] suggested that the downstream magnetic energies of transient magnetic reconnections in the midtail may be transported to the near-Earth region by one DF event after another. Xu *et al.*[251] found an intense current at the Anti-Dipolarization Fronts (ADFs), with the parallel current carried by a fast electron jet and the perpendicular current contributed by ion flow.

Electron current layer in the diffusion region splits into two sublayers at the electron inertial scale, not long after the triggering of reconnection[252]. Zhong *et al.*[253] reported a long EDR that extended at least 20 ion inertial lengths downstream of an X line at the Earth's magnetopause, suggesting that the EDR, where the reconnection electric field is directly proportional to the electron outflow speed[254], probably plays more important roles in the energy conversion in magnetic reconnection than previously thought. Bai *et al.*[255] suggested that the earthward moving flux rope was generated inside the HFA, implying that magnetic reconnection may have occurred inside the HFA.

Cold ions of ionospheric origin are widely observed in the lobe region of Earth's magnetotail and can enter the ion jet region after magnetic reconnection being triggered in the magnetotail. The cold-ion beams inside the explored jet could be accelerated by the Hall electric field in the cold ion diffusion region and the shrinking magnetic field lines through the Fermi effect[256]. The large-amplitude unipolar can fill the entire EDR in the magnetosheath reconnection and thus dominates electron acceleration therein[257]. The gyrotropic effect is more important than the nongyrotropic effect for the viscous dissipation in the diffusion region[258].

A typical ion velocity distribution along the separatrix is found by Huang *et al.*[259]: two counter-streaming populations in the perpendicular direction, with another two populations accelerated into distinct energy levels in the parallel direction. Chen *et al.*[260] demonstrated that patchy magnetic reconnection has the potential to preserve the ion-to-electron temperature ratio under certain conditions. Wu *et al.*[261] reported the D-shaped velocity distribution of O^+ ions produced by the time-of-flight effect in the magnetotail reconnection.

Huang *et al.*[262] quantitatively model the reduction of the reconnection rate and the maximum outflow speed observed in the short X-line limit. The distorted ion velocity distributions lead to a bipolar reversal in an off-diagonal element of the pressure tensor across the X-line, supporting an enhancement of the ion-scale reconnection electric field[263]. But recent observations of Huang *et al.*[264] proposed a new reconnection model: electron-only without ion coupling in an electron-scale current sheet. The spontaneous onset of collisionless magnetic reconnection is controlled by electron kinetics[265]. However, magnetotail reconnection can start from electron reconnection in the presence of a strong external driver, then develops into ion reconnection[266,267]. Tang *et al.*[268] offered an insight into the Hall effect in collisionless magnetic reconnection. The Hall electric field could control the form of reconnection, producing either electron-only reconnection or traditional reconnection[269].

Li *et al.*[270] reported large-amplitude electron Bernstein waves at the electron-scale boundary of the hall current reversal. The flux pileup region hosts whistler waves because of the pancake distribution of electrons, whereas the DF boundary hosts lower hybrid drift waves due to the strong density and magnetic gradients statistically[271]. On the magnetosphere side of reconnection, whistler waves are highly centered around the 1/2 electron cyclotron frequency ω_e[272]. On the magnetosheath side of reconnection, whistler waves are mainly below 1/2 ω_e and peaked around 0.2 ω_e. Yu *et al.*[273] reported the whistler wave with a very narrow frequency band just above $1/2\omega_e$ in the separatrix region, which was accompanied with the ECH waves. Tang *et al.*[274] showed that the lower hybrid waves can also be found at the magnetosheath separatrix in asymmetric guide field reconnection.

Li *et al.*[275] reported for the first time that the Upper-Hybrid (UH) waves were observed on both sides of the X-line and may play an important role in controlling the reconnection rate. Shu *et al.*[276] concluded that the reconnection rate can only represent the energy conversion at the reconnection site but not at the reconnection fronts for non-steady state magnetic reconnection. Yi *et al.*[277] examined the energy conversion in multiple X-line reconnection and found that the magnetic energy releases predominantly through primary islands and second at X-lines.

Two-dimensional Particle-in-Cell (PIC) simulations were performed by Chang *et al.*[278] to investigate the characteristics of Electrostatic Solitary Waves (ESWs) in asymmetric magnetic reconnection. Fu *et al.*[279] reported the first measurements of an electrostatic ESW's interior in a magnetotail reconnection jet and challenged the conventional belief that ESWs are efficient at particle acceleration. Using high-resolution MMS data, Guo *et al.*[280] reported the observations of broadband electrostatic waves including electrostatic solitary waves and electron cyclotron waves associated with parallel electron temperature anisotropy ($T_{e\parallel} > T_{e\perp}$) behind a DF.

Yu *et al.*[281] observed unique electron thermalization and associated electrostatic turbulence inside a special Dipolarizing Flux Tube (DFT) hosting both hot-tenuous and cold-dense electrons. While one-dimensional simulation helped Yu *et al.*[282] to reproduce two types of waveforms similar to those observed in the EDR, implying that these electrostatic waves were generated by the bump-on-tail instabilities. Tang *et al.*[283] suggested that the electrostatic waves generated by the fast-growing electron two-stream instability can contribute to the rapid isotropization of electron distributions in the reconnection exhaust, indicating that wave-particle interactions play an important role in electron dynamics.

5 Planetary Magnetosphere

Lai *et al.*[284] studied the flux-return process, improving our understanding of the magnetic flux circulation in steady state at Saturn. Slow, global-scale flows resulting from transient noon-to-midnight electric fields[285], which are associated with Saturnian zebra stripe[286], are ultimately responsible for the bulk of the highest energy electrons trapped at Saturn. Using simultaneous measurements of the aurora, particles, magnetic fields, and energetic neutral atoms, Guo *et al.*[287] revealed that a chain of paired currents is formed in Saturn's magnetosphere, which generates separated auroral patches.

Pan *et al.*[288] showed a global picture of low-frequency waves while Long *et al.*[289] performed a statistical analysis of ECH wave spatial distribution in Saturn's magnetosphere. Although a large anisotropy is generally in favor of linear and nonlinear whistler-mode chorus wave growth in Saturn's inner magnetosphere, the nonlinear wave growth for a small anisotropy can still be generated[290]. The occurrence frequency of Saturn radiation belt transient extensions indicates a possible role for corotating integration regions[291]. At $3.5 < L < 6$, the PADs peak near 90° in Saturn's magnetosphere, while at $2.5 < L < 3.5$, the PADs transform to butterfly distributions[292].

For the first time, Xu *et al.*[293] found that the magnetic reconnection could also occur in the dayside magnetosphere of Saturn. Direct observations of plasmoids in Saturn's dayside magnetodisc were reported for the first time[294].

A statistical model is constructed by Liu *et al.*[295], providing us with a starting point for understanding the dynamics of the whole Jupiter's magnetosphere. High-resolution global simulations of Zhang *et al.*[296] showed that the reconnection rate at the interface between the interplanetary and Jovian magnetic fields is too slow to generate a magnetically open, Earth-like polar cap. Wang *et al.*[297] demonstrated the capabilities of their improved heliospheric MHD model in the prediction of the large-scale structures of the solar wind in the inner heliosphere of planets in the solar system such as Earth and Jupiter. Guo *et al.*[298] suggested that the evolution of the double-arc structure of Jupiter is likely a consequence of the non-steady progress of magnetic reconnection. Simultaneous in situ satellite and space-based telescope Jupiter observations showed surprising similarities to terrestrial ion aurora[299]. Yao *et al.*[300] showed six clear examples displaying both Jupiter auroral dawn storms and auroral injection signatures, which could exist during intervals of either relatively low or high auroral activity. Wang *et al.*[301] presented a new method combining Juno multi-instrument data (MAG, JADE, JEDI, UVS, JIRAM and Waves) and modeling tools to estimate these key parameters along Juno's trajectories.

The draping of IMF penetrates down to low altitudes and governs dynamics of the Martian ionosphere[302]. Shan *et al.*[303] demonstrated that periodic Martian shocks can perform the same functions as a single supercritical shock in a high-speed flow. Shan *et al.*[304] showed an example of small-amplitude, sinusoidal MS waves at the proton gyro frequency upstream of the Martian bow shock. Using global MHD simulations, Wang *et al.*[305] constructed a 3 D parametric Martian bow shock model that employs a generalized conic section function defined by seven parameters. The thermal pressure at the Martian Magnetic Pileup Boundary (MPB) plays a significant role in the compressed magnetic field[306]. Small-scale Linear Magnetic Holes (LMHs) are ubiquitous in the Martian magnetosheath with an occurrence rate of approximately 1.5 events per hour[307]. Gao *et al.*[308] presented a new Spherical Harmonic (SH) model of the crustal magnetic field of Mars, finding that small-scale fields at low altitudes were underestimated by most previous models. The Chinese Mars ROVER Fluxgate Magnetometers (RoMAG) will implement the first mobile magnetic field measurements on the surface of Mars[309].

Zhang *et al.*[310] suggested that the plasma clouds of Mars might be the product of heating due to solar wind precipitation along the open field lines, generated by magnetic reconnection at the dayside Martian-induced magnetopause[311]. Huang *et al.*[312] presented the in situ detection of KSMHs in the Martian magnetosheath using Mars Atmosphere and Volatile EvolutioN (MAVEN) for the first time. Zou *et al.*[313] described the scientific objectives and payloads of Tianwen-1, China's first exploration mission to Mars. The crustal magnetic fields can withstand the solar wind flows and effectively trap heavy ions below 1000 km[314], and significantly attenuate the ion ionospheric motions and raise the flux of returning ions[315]. Nearly 30% of the available nightside suprathermal electron spectra show clear photoelectron signatures in the Martian ionosphere[316].

Sun *et al.*[317] reviewed the research of Mercury's magnetosphere in the Post-MESSENGER era. Zhong *et al.*[318] suggested that during extreme solar wind conditions multiple X-line reconnections may dominate the tail reconnection process and control the global dynamics of Mercury's magnetosphere. Jang *et al.*[319] suggested that the near-cusp region of Mercury may trap energetic particles under particular conditions. Similar to Earth's magnetotail, there are two flapping types existent in Mercury's magnetotail, one is the kink-like flapping that can propagate as traveling waves, and the other one is the steady flapping that does not propagate[320]. The proton density, pressure, and energy spectral index kappa were higher on the dawnside plasma sheet of Mercury than on the duskside[321]. A new Mercury magnetopause model gives a closed magnetopause for the nightside in most cases, and its flaring decreases with the contraction of the magnetosphere. Zhong *et al.*[322] concluded that Mercury's magnetopause is a natural plasma laboratory to study flux rope dynamics and evolution for the upcoming Bepi-Colombo mission. Spectral indices at MHD scales vary from about $-5/3$ in the near-Mercury solar wind (possibly the foreshock) to about -1.3 within the magnetosheath close to bow shock of Mercury[323].

With 32 Hz magnetic field data of Venus Express from May 2006 to August 2012, the global spatial distributions of 1 Hz waves in the near-Venusian space were presented by Xiao *et al.*[324]. The dayside Venusian induced magnetosphere boundary distance increases with solar activity, but decreases with increasing P_{dyn} and IMF cone angle[325]. The statistical results of Xiao *et al.*[326] suggested that the Venusian bow shock tends to modify the upstream spectra flatter to $1/f$ noise in the MHD regime and steeper to turbulence in the kinetic regime after the magnetic fluctuations crossing the bow shock. In the near-Venusian space, an energy cascade can be developed at the boundary between magnetosheath and wake[327]. In terms of the spectral scaling features of Venus magnetic fluctuations, the dayside-nightside shock crossings exhibit a clear asymmetry[328]. Gao *et al.*[329] reported evidence of crossing the ion diffusion region of magnetic reconnection based on two cases recorded by Venus Express in the Venusian magnetotail.

Zhang *et al.*[330] demonstrated that the solar-wind ions, reflected over the dayside lunar magnetic anomalies, have produced lunar wake magnetic and plasma asymmetries and periodical modulations. Behind the lunar terminator, the wake field reduction is also asymmetric[331].

6 Theory and Technique

Dunlop *et al.*[332] reviewed the range of applications and use of the curlometer technique, initially developed to analyze Cluster multi-spacecraft magnetic field data, but more recently adapted to other 2–5 spacecraft configurations. The normal field analysis method was presented by Shen *et al.*[333] to determine the geometrical configurations of boundary surfaces in the space environment, based on multiple spacecraft measurements. Shen *et al.*[334] presented a novel algorithm that can estimate the quadratic magnetic gradient as well as the complete geometrical features of magnetic field lines, and another one for estimating both the linear and quadratic gradients of physical quantities[335]. Zhu *et al.*[336] gave a general description of the magnetometer onboard the Low Orbit Pearl Satellite.

Space plasmas are composed of charged particles that play a key role in electromagnetic dynamics. Three schemes for measuring charge densities in space are presented in Ref. [337]. Li *et al.*[338] reviewed some of the key results obtained from the wake technique helping us to understand how cold ionospheric outflow varies. Huang *et al.*[339] applied the algebraic reconstruction technique and the minimization of the image total variation method to reconstruct plasmaspheric He^+ density from simulated EUV images. Wang *et al.*[340] demonstrated that the plasma flows at small scales are indeed linear, and thus the First-Order Taylor Expansion (FOTE) method can be applied to such flow fields. Fu *et al.*[341] reviewed and compared the methods for finding magnetic nulls and reconstructing field topology. Tian *et al.*[342] developed a new Grad-Shafranov solver which was applied to reconstruct a Pc5 compressional wave event. Yu *et al.*[343] suggested the important role of the linear dispersion relation in the second-harmonic generation.

Li *et al.*[344] developed a method which can effectively predict the geomagnetic disturbances during geomagnetic storms. The physical-based model in Zhang *et al.*[345] is more applicable than the persistence model in prediction of GICs at low-latitude power grids during storms. Xu *et al.*[346] used the Bagging ensemble-learning algorithm to predict the Dst index 1–6 h in advance. Using magnetic field observations from Van Allen Probe-A (VAP-A), Yang and Wang[347] evaluated the performances of 13 widely used external magnetic field models in the Earth's outer radiation belt region in detail. The previous algorithm has been modified by Yu *et al.*[348] to be capable of producing typical ripples in the electron diffusion coefficient maps, and could be applied to RC protons.

A lot of neural network models were developed to predict the global dynamic variation of the plasmapause location[349], average daily flux of relativistic electrons[350], and the electron number fluxes in the central plasma sheet[351]. Radiation belt electron fluxes can also be simulated by an analytic model[352] or a three-dimensional (3D) assimilation model[353].

Guo *et al.*[354] proposed to use the Moon as a platform to obtain a global view of Earth's magnetosphere by a lunar-based soft X-ray imager. Sun *et al.*[355] introduced a new technique which can find the optimum match of tangent directions derived from the X-ray image and the parameterized magnetopause function. With reasonable assumptions, the large-scale cusp features can be clearly revealed by analyzing X-ray images[356].

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