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Magnetospheric Physics in China

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Abstract

In the past two years**,** many progresses were made in magnetospheric physics by using the data of Double Star Program, Cluster, THEMIS, RBSP, Swarm, MMS, ARTEMIS, MESSENGER missions *etc*., or by computer simulations. This paper briefly reviews these works based on papers selected from the 227 publications from January 2016 to December 2017. The subjects cover almost sub-branches of magnetospheric physics, including geomagnetic storm, magnetospheric substorm, magnetic reconnection, Solar wind-magnetosphere-ionosphere interaction, radiation belt, plasmasphere, outer magnetosphere, magnetotail, geomagnetic field, auroras and currents.

Key words

Magnetospheric, Geomagnetic storms, Magnetic reconnection

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1. Geomagnetic Storms

Geomagnetic Sudden Commencements (SCs), characterized by a rapid enhancement in the rate of change of the geomagnetic field perturbation (d*B*/d*t*), are considered to be an important source of large Geomagnetically Induced Currents (GICs) in middle- and low-latitude power grids. In Zhang *et al.,* [1], the extreme interplanetary shock of 23 July 2012 is simulated under the assumption that it had hit the Earth with the result indicating the shock-caused SC would be 123 nT. Based on statistics, the occurrence frequency of SCs with amplitudes larger than the simulated one is estimated to be approximately 0.2% during the past 147 years on the Earth. During this extreme event, the simulation indicates that d*B*/d*t*, which is usually used as a proxy for GICs, at a dayside low-latitude substation would exceed 100nT/min; this is very large for low-latitude regions. They then assess the GIC threat level based on the simulated geomagnetic perturbations. The results indicate that the risk remains at low level for the low-latitude power network on a global perspective. However, the GIC risk may reach moderate or even high level for some equatorial power networks due to the influence of the equatorial electrojet. Results of this study have substantial implications for risk management, planning, and design of low-latitude electric power networks.

He, F., *et al.,* [2] present multi satellite observations of the evolution of Subauroral Polarization Streams (SAPS) during Intense Storms (ISs) and Quiet time Substorms (QSs). SAPS occurred during 37 ISs and 30 QSs were analyzed. Generally, SAPS occur after the southward turning of the Interplanetary Magnetic Field (IMF) with time lags of 0–1.5 h for ISs and 0–2.5 h for QSs. SAPS usually occurred 0–3 h after the beginning of storm main phases and 0–2 h after the substorm expansion onsets. The lifetimes of SAPS are generally longer than the durations of southward IMF and storm main phases. During QSs, the lifetimes of SAPS are shorter than the duration of the ISs. Superposed epoch analysis shows different evolution patterns of SAPS during ISs and QSs. The results of this study provide both physical insight and constrains to modeling the magnetosphere-ionosphere-thermosphere coupling.

The geomagnetic activity, which refers to the disturbances of the Earth's magnetic field, is caused by solar eruption phenomena and is one of the important space weather processes. Variations of the geomagnetic field have several time scales, of which the long-term variations of decades to centuries are caused by the Earth's crust and the short-term variations of seconds to years are resulted from solar activity. In recent years, increasing statistical studies have demonstrated that there are significant correlations between geomagnetic and solar activities and Earth's climatic change. The coupling between the geomagnetic field and the Earth's atmospheric system has motivated the researchers to explore the effects of geomagnetic activity on the Earth's weather and climatic systems. The purpose of Jin *et al.,* [3] is to review the progress of the domestic and foreign investigations on the influences of the geomagnetic activity on climatic elements, to present the latest research results, and to explore the characteristics and possible mechanisms of the impact of the geomagnetic activity on climatic elements. This paper provides us with the basis for further investigations of the impact of geomagnetic activity on the Earth's weather and climate, finally achieving a comprehensive and objective understanding on the relationship between the geomagnetic activity and climatic elements.

Applying the method of statistical fitting based on the probability distribution features of Start Pulse Height (STPH) excited by ENA's secondary electron, a set of programs has been developed to process the TWINS (Two Wide-angle Imaging Neutral-atom Spectrometers) satellite Level-0 data aiming to separate compositions of oxygen and hydrogen in ENA. Therein a model of STPH distribution needed for making the separation is set up by fitting the satellite calibration data to the theoretic formula in being. Implementing the separation method to the TWINS satellite measured data during a great magnetic storm, the respective ENA-H and ENA-O differential flux distributions with Line-Of-Sight (LOS) have been obtained, as well as their evolution with the storm main phase growth. Hu *et al.,* [4] found that: (1) There are obvious differences in both magnitudes and distributions of differential fluxes between ENA-H and ENA-O, implying from a certain angle the differences between fluxes of energetic O^+ and H+ ions as ENAs' sources. (2) During the period approaching the storm main phase, ENA-H displays intense Low Altitude Emissions (LAEs) which appear in the aurora and sub-aurora region before midnight, suggesting strong proton precipitation coming from plasma-sheet and RC (Ring Current) region into the lower atmosphere below exobase; while the oxygen has no obvious LAEs, but showing intensive fluxes along LOSs that traverse extensive RC region located mainly in the magnetic local time sectors of post-midnight, pre-dusk and around dawn. (3) During the rapid growth of the storm main phase, the Averaged Total Flux (ATF) of ENA-O continues to increase, while the ENA-H to decrease synchronously. Correspondingly, the ATF ratio of ENA-O to ENA-H grows in a way of being roughly proportional to the increase of the absolute value of the ring current index *Dst*.

Coronal Mass Ejection (CME)-driven or Corotating Interaction Region (CIR)-driven storms can change the electron distributions in the radiation belt dramatically, which can in turn affect the spacecraft in this region or induce geomagnetic effects. The twin Van Allen Probes, launched on 30 August 2012, orbit near the equatorial plane and across a wide range of L^* with apogee at 5.8 R_e and perigee at 620 km. Electron data from Van Allen Probes MagEIS and REPT instruments have been binned every 6 h at L^*=3 (defined as 2.5<L^*<3.5), 4 (3.5<L^*<4.5), 5 (4.5<L^*<5.5). The superposed epoch analysis shows that (1) CME storms induce more electron flux enhancement at L^*=3 for energy channels below 1 MeV than CIR storms; (2) CME storms induce more electron flux enhancement at L^*=4 and 5 in the energy channels above 1 MeV than CIR storms; (3) CIR storms induce more electron flux enhancement at L^*=4 and 5 in the energy channels below 1 MeV than CME storms; (4) intense CME induce more than 50 times flux enhancement for the energy channel around 400 keV at L^*=3; (5) intense CIR induce more than 50 times flux enhancement for the energy channel around 200 keV at L^*=4. The results of Shen *et al.,* [5] are consistent with a general picture of enhanced convection over a longer period for CIR storms which increased flux closer to geosynchronous orbit consistent with earlier studies, while CME storms likely produce deeper penetration of enhanced flux and local heating which is greater at higher energies at lower L^*.

Based on 7 years' observations from Time History of Events and Macroscale Interactions during Substorms (THEMIS), Liu *et al.,* [6] investigate the statistical distribution of electric field Pc5 ULF wave power under different geomagnetic activities and calculate the radial diffusion coefficient due to electric field, for outer radiation belt electrons. A simple empirical expression of is also derived. Subsequently, they compare to previous D-LL models and find similar *Kp* dependence with the model, which is also based on in situ electric field measurements. The absolute value of is constantly higher than, probably due to the limited orbital coverage of CRRES. The differences between and the commonly used and models are significant, especially in *Kp* dependence and energy dependence. Possible reasons for these differences and their implications are discussed. The diffusion coefficient provided in this paper, which also has energy dependence, will be an important contributor to quantify the radial diffusion process of radiation belt electrons.

Using data from ground-based magnetometers and HF Doppler sounder, Ouyang*, et al.,* [7] study ULtralow Frequency (ULF) waves excited during the Storm Sudden Commencement (SSC) on 8 March 2012 and find possible evidence on the link between ULF waves and ionospheric Doppler shifts. Pc1-Pc2 ULF waves are observed from 11:04 to 11:27 UT after the SSC by ground stations of *L* shell ranging from 1.06 to 2.31, mapping to the topside ionosphere. There are weak responses in this frequency range in the power spectra of ionospheric Doppler shift. From 11:19 to 11:23 UT, oscillations of magnetic field in a lower frequency range of Pc3-Pc4 are observed and are well correlated with the trace of Doppler shift. It is thus suggested that ionospheric Doppler shift can response to ULF oscillations in magnetic field in various frequency ranges, especially in the frequency range of Pc3-Pc4 and below. This paper demonstrates a new mechanism of magnetosphere-ionosphere coupling.

Energy transport during a geomagnetic substorm is a very important process for solar wind-magnetosphere energy coupling and the energy cycle in the magnetotail. Yang *et al.,* [8] use magnetotail data from the five THEMIS probes and two Cluster satellites on the dayside to investigate the energy transport of one intense storm during the period from 08 March to 11 March 2008 at large spatial-temporal scales. Simultaneous observations of the five THEMIS probes indicate that there is a stronger and earlier duskward energy flux density in the near-Earth magnetotail than that in the mid-tail in the initial phase. Low energy particles inject earthward from the dusk flank. Stronger and more variable earthward energy flux density is observed in the mid-tail compared to that near Earth in the main phase; mainly caused by high-speed flow. Tailward energy flux was observed in the near-Earth and mid-tail regions during the recovery phase. Dayside data observed by two Cluster satellites show that the duskward energy flux may be related to stable solar wind input. Tailward energy flux on the dayside should experience some energy conversion process in the magnetotail before it can provide the earthward energy flux in the magnetotail for this intense storm. The strongest energy transport observed by the nightside probes occurs in the main phase. However, the strongest energy measured by the dayside satellites is in the recovery phase without intense activities, two hours later. Different features of the energy transport in the three phases of the storm may be closely related to the different physical processes such as the energy entry, westward drift, particle injection or other potential mechanisms.

For the first time, the current density distribution in the inner equatorial magnetosphere ranging from 4 to 12 R_e (R_e is the Earth radius, 6371 km) has been obtained by using Time History of Events and Macroscale Interactions during Substorms (THEMIS) (P3, P4, and P5) three point magnetic measurements. This study mainly focuses on the storm events when the constellation of the three THEMIS spacecraft has relatively small separation distance. Two cases with different storm activities are first displayed to illustrate the effectiveness of the method. The inner magnetospheric equatorial current distribution ranging from 4 to 12 R_e is shown through statistical analysis. The features of current density are separately analyzed for the storm main phase and the recovery phase. The statistical study reveals that with increasing radial distance the predominant ring current density reverses from Eastward (below r=4.8 R_e, where r is the geocentric radial distance) to Westward, but that the distribution behaves differently for the two phases of activity. During the main phase, both the westward and eastward current are enhanced by added signal and are more dynamic so that both radial profile and Magnetic Local Time (MLT) structure is obscured. During the recovery phase, the radial profile of the westward current is smooth and peaks, then falls, between r=5–7.5 R_e showing some MLT dependence in this region. Beyond r=7.5 R_e, the current is lower and nearly constant and shows little MLT variation. Yang *et al.,* [9] also suggest that the change from eastward to westward current depends on the storm phase and hence storm activity.

Lu *et al.,* [10] apply the Support Vector Machine (SVM) combined together with Distance Correlation (DC) to the forecasting of *Dst* index by using 80 intense geomagnetic storms ($Dst \leqslant -100$ nT) from 1995 to 2014. They also train the Neural Network (NN) and the Linear Machine (LM) to verify the effectiveness of SVM. The purpose for us to introduce DC is to make feature screening in input datasets that can effectively improve the forecasting performance of the SVM. For comparison, they estimate the Correlation Coefficients (CC), the RMS errors, the absolute value of difference in minimum *Dst* ($\Delta Dst_{\min}$) and the absolute value of difference in minimum time (Δt_{Dst}) between observed *Dst* and predicted one. K-fold Cross Validation is used to improve the reliability of the results. It is shown that DC-SVM model exhibits the best forecasting performance for all parameters when all 80 events are considered. The CC, the RMS error, the $\Delta Dst_{\min}$ and the Δt_{Dst} of DC-SVM are 0.95, 16.8 nT, 9.7 nT and 1.7 h, respectively. For further comparison, they divide the 80 storm events into two groups depending on minimum value of *Dst*. It is also found that the DC-SVM is better than other models in the two groups.

2. Magnetospheric Substorms

Sun, *et al.,* [11] investigate the plasma sheet pressure variations in the near-Earth magnetotail (radius distance, *R*, from 7.5 R_e to 12 R_e and magnetic local time, MLT, from 18: 00 to 06: 00) during substorm growth phase with Time History of Events and Macroscale Interactions during Substorms (THEMIS) observations. It is found that, during the substorm growth phase, about 39.4% (76/193) of the selected events display a phenomenon of equatorial plasma pressure (P_{eq}) decrease. The occurrence rates of P_{eq} decrease cases are higher in the dawn (04:00 to 06:00) and dusk (18:00 to 20:00) flanks (>50%) than in the midnight region (20:00 to 04:00, <40%). The mean values of the maximum percentages of P_{eq} decrease during the substorm growth phases are larger in the dawn and dusk flanks (similar to –20%) than in the midnight region (similar to>–16%). The mean value of P_{eq} increase percentages at the end of substorm growth phase is the highest (similar to 40%) in the premidnight MLT bin (22:00 to 00:00) and is almost unchanged in the dawn and dusk flanks. Further investigations show that 13.0% of the events have more than 10% of P_{eq} decrease at the end of substorm growth phase comparing to the value before the growth phase, and similar to 28.0% of the events have small changes (<10%), and similar to 59.0% events have a more than 10% increase. This study also reveals the importance of electron pressure (P_e) in the variation of P_{eq} in the substorm growth phase. The Pe variations often account for more than 50% of the P_{eq} changes, and the ratios of P_e to ion pressure often display large variations (similar to 50%). Among the investigated events, during the growth phase, an enhanced equatorial plasma convection flow is observed, which diverges in the midnight tail region and propagates azimuthally toward the dayside magnetosphere with velocity of similar to 20 km/s. It is proposed that the Peq decreases in the near-Earth plasma sheet during the substorm growth phase may be due to the transport of closed magnetic flux toward the dayside magnetosphere driven by dayside magnetopause reconnection. Both solar wind and ionospheric conductivity effects may influence the distributions of occurrence rates for P_{eq} decrease events and the P_{eq} increase percentages in the investigated region.

The feature and origin of current sheet flapping motions are one of most interesting issues of magnetospheric dynamics. Wu *et al.,* [13] reports the flapping motion of the current sheet detected in the tailward flow of a magnetic reconnection event on 7 February 2009. This flapping motion with frequency about 12 mHz was accompanied by magnetic turbulence. The observations by the tail-elongated fleet of five Time History of Events and Macroscale Interactions during Substorms probes indicate that these flapping oscillations were rather confined within the tailward flow than were due to a global process. This flapping motion could be due to the instability driven by the free energy associated with the ion temperature anisotropy in the tailward flow. Our observations indicate that the flapping motion in the tailward flow could have a different generation mechanism with that in the earthward flow.

The temporal and spatial variation in thermospheric winds are studied by Wang *et al.,* [14] at 400 km altitude in response to substorms that start at different Universal Time (UT), using a global ionosphere and thermosphere model. The substorm-induced disturbance winds at high latitudes are mainly in the poleward, westward, and upward directions in the dusk sector and in the equatorward, westward, and upward directions in the nighttime. The daytime perturbation is due to ion drag, driven by variations in interplanetary magnetic field B_z, whereas the nighttime perturbation is due to both the B_z and hemispheric power input. The nightside disturbed winds respond somewhat later than the dayside owing to low background ion density. Ion drag is the dominant driving force in the daytime for both meridional and zonal disturbed winds, whereas Joule heating is the dominant factor for the vertical winds. The nighttime meridional and zonal winds are driven by a combination of ion drag, Joule heating, and heating of the auroral belt, whereas the vertical winds are mainly caused by auroral belt heating. The viscous force acts to resist the ion drag, whereas the Coriolis force is negligible. The disturbed winds exhibit large variations with UT during equinox and local winter conditions. With more solar illumination, stronger disturbed winds can be generated. Weak or even opposite variations with UT in the disturbed winds are found in local summer, which is due to a smaller UT variation of the daytime ion density and a larger contribution from auroral heating than from ion drag.

Magnetic compressional structures ahead of a Dipolarization Front (DF) on 30 August 2002 are investigated by using Cluster data. Wang *et al.,* [15] found: (1) the structures, observed near the neutral sheet, are mainly compressional and dominant in B_z; (2) they are almost nonpropagating relative to the local ion bulk flow and their lengths are several local proton gyroradius; (3) the ion density increases when B_T decreases; (4) ions are partially trapped by the structures with parallel and perpendicular velocities varying in antiphase; and (5) local conditions are favorable for excitation of the mirror instability, and they suggest that these structures are mirror mode-like. Their findings also suggest that local conditions ahead of the DF are viable for exciting the mirror instability to generate mirror mode waves or structures.

Using multipoint data from three Time History of Events and Macroscale Interactions during Substorms (THEMIS) satellites, Zhao *et al.,* [16] reports a magnetospheric flow vortex driven by a negative solar wind dynamic pressure pulse. The observed vortex rotated in a direction opposite to that associated with positive solar wind dynamic pressure pulses. The vortex was moving tailward, as confirmed by a global Magnetohydrodynamics (MHD) simulation. In addition, the Equivalent Ionospheric Currents (EICs) deduced from ground magnetometer station data reveal that a current vortex in the ionosphere near the foot point of the satellites has a rotation sense consistent with that observed in the magnetosphere. The Field Aligned Current (FAC) density estimated from three THEMIS satellites is about $0.15\ \mathrm{nA/m^2}$, and the total FAC of the vortex is about $1.5–3 \times 10^5$ A, on the order of the total FAC in a pseudobreakup, but less than the total FAC in most moderate substorms, 10^6 A.

Based on concurrent observations of the ACE and Geotail satellites from 1998 to 2005, Zhang *et al.,* [17] statistically analyzed and compared the earthward Bursty Bulk Flows (BBFs) with local positive B_z under different Interplanetary Magnetic Field (IMF) conditions. Four different Magnetospheric Activity Levels (MALs), including quiet times and substorm growth/expansion/recovery phases, are considered. The properties of the BBFs, including their ion temperature (T), V_x component, x component of the energy flux density ($Q(x)$), and the solar wind dawn-dusk electric field E_y (observed at similar to 1AU), are analyzed. Main observations include the following: (1) BBF tends to have less penetration distance for NorthWard IMF (NW-IMF) than for SouthWard IMF (SW-IMF). Inward of 15 R_e the BBFs for SW-IMF are dominant. Few BBFs for NW-IMF occur within 15 R_e. (2) The occurrence probabilities of the BBFs at each MAL depend highly on the orientations of the IMF. During quiet times, the BBFs for NW-IMF are dominant. Reversely, during the growth and expansion phases of a substorm, the BBFs for SW-IMF are dominant. (3) The strengths of the BBF have significant evolution with substorm development. For SW-IMF condition, the strengths of the BBFs are the lowest for quiet times. The strength of the BBFs tends to increase during the growth phase and reaches to the strongest value during the expansion phase, then, decays during the recovery phase. For NW-IMF condition, the strengths of the BBFs evolve with the substorm development in a similar way as for SW-IMF condition. (4) For SW-IMF, the solar wind E_y evolves with the substorm development in a similar way to the strength of the BBFs. However, no clear evolution is found for NW-IMF. (5) The strengths of the BBF $Q(x)$ and solar wind E_y are closely related. Both tend to be stronger for growth phase than for quite time, reach the strongest for expansion phase, then decay for recovery phase. It appears that to trigger a substorm, the strength of the BBFs should achieve energy thresholds with values different for NW-IMF and SW-IMF.

Substorm injections bring energetic particles to the inner magnetosphere. But the role of the injected population in building up the storm time ring current is not well understood. By surveying Los Alamos National Laboratory geosynchronous data during 34 storm main phases, He *et al.,* [18] show evidence that at least some substorm injections can contribute to substorm time scale SYM-H/*Dst* depressions in the main phase of storms. For event studies, they analyze two typical events in which the main-phase SYM-H index exhibited stepwise depressions that are correlated with particle flux enhancement due to injections and with AL index. A statistical study is performed based on 95 storm time injection events. The flux increases of the injected population (50–400 keV) are found proportional to the sharp SYM-H depressions during the injection interval. By identifying dispersionless and dispersive injection signals, they estimate the azimuthal extent of the substorm injection. Statistical results show that the injection regions of these storm time substorms are characterized with an azimuthal extent larger than 06:00 magnetic local time. These results suggest that at least some substorm injections may mimic the large-scale enhanced convection and contribute to sharp decreases of *Dst* in the storm main phase.

Singly charged oxygen ions, O^+, energized by Kinetic Alfven Wave Eigenmode (KAWE) in the plasma sheet boundary layer during dipolarizations of two intense substorms, 10:07 UT on 31 August 2004 and 18:24 UT on 14 September 2004, are investigated by Cluster spacecraft in the magnetotail. It is found that after the beginning of the expansion phase of substorms, O^+ ions are clearly energized in the direction perpendicular to the magnetic field with energy larger than 1 keV in the near-Earth plasma sheet during magnetic dipolarizations. The pitch angle distribution of these energetic O^+ ions is significantly different from that of O^+ ions with energy less than 1 keV before substorm onset that is in the quasi-parallel direction along the magnetic field. The KAWE with the large perpendicular unipolar electric field, *E-z* similar to –20 mV/m, significantly accelerates O+ ions in the direction perpendicular to the background magnetic field. Duan*, et al.,* [19] present good evidences that O^+ ion origin from the ionosphere along the magnetic field line in the northward lobe can be accelerated in the perpendicular direction during substorm dipolarizations. The change of the move direction of O^+ ions is useful for O^+ transferring from the lobe into the central plasma sheet in the magnetotail. Thus, KAWE can play an important role in O^+ ion transfer process from the lobe into the plasma sheet during intense substorms.

Although the particle carriers of Field-Aligned Currents (FACs) in the Earth's magnetotail play an important role in the transfer of momentum and energy between the solar wind, magnetosphere, and ionosphere, the characteristics of the FAC carriers have been poorly understood. Taking advantage of multi-instrument magnetic field and plasma data collected by the four spacecraft of the Cluster constellation as they traversed the northern plasma sheet boundary layer in the magnetotail on 14 September 2004, Cheng*, et al.,* [20] identified the species type and energy range of the FAC carriers for the first time. The results indicate that part of tailward FACs is carried by energetic keV ions, which are probably originated from the ionosphere through outflow, and they are not too small (similar to 2 nA/m^2) to be ignored. The earthward (tailward) FACs are mainly carried by the dominant tailward (earthward) motion of electrons, and higher-energy electrons (from similar to 0.5 to 26 keV) are the main carriers.

A multiple auroral onset substorm on 28 March 2010 provides an opportunity to understand the physical mechanism in generating auroral intensifications during a substorm expansion phase. Conjugate observations of magnetic fields and plasma from the Time History of Events and Macroscale Interactions during Substorms (THEMIS) spacecraft, of Field-Aligned Currents (FACs) from the Active Magnetosphere and Planetary Electrodynamics Response Experiment (AMPERE) satellites, and from ground-based magnetometers and aurora are all available. The comprehensive measurements allow us to further our understanding of the complicated causalities among dipolarization, FAC generation, particle acceleration, and auroral intensification. During the substorm expansion phase, the plasma sheet expanded and was perturbed leading to the generation of a slow mode wave, which modulated electron flux in the outer plasma sheet. During this current sheet expansion, field-aligned currents formed, and geomagnetic perturbations were simultaneously detected by ground-based instruments. However, a magnetic dipolarization did not occur until about 3 min later in the outer plasma sheet observed by THEMIS-A spacecraft (THA). Yao*, et al.,* [21] believe that this dipolarization led to an efficient Fermi acceleration to electrons and consequently the cause of a significant auroral intensification during the expansion phase as observed by the All-Sky Imagers (ASIs). This Fermi acceleration mechanism operating efficiently in the outer plasma sheet during the expansion phase could be a common explanation of the poleward auroral development after substorm onset. These results also show a good agreement between the upward FAC derived from AMPERE measurements and the auroral brightening observed by the ASIs.

In cases where substorm injections can be observed simultaneously by multiple spacecraft, they can help elucidate the potential mechanisms of particle transport and energization, of great importance to understanding and modeling the magnetosphere. Using data returned from the BeiDa-IES (BD-IES) instrument onboard a satellite in an Inclined (55A degrees) GeoSynchronous Orbit (IGSO), in combination with two Geo-Transfer Orbiting (GTO) satellite Van Allen Probes (*A* and *B*), Zong *et al.,* [22] analyze a substorm injection event that occurred on the 16th of October 2015. During this substorm injection, the IGSO onboard BD-IES was outbound, while both Van Allen Probe satellites (*A* and *B*) were inbound, a configuration of multiple trajectories that provides a unique opportunity to simultaneously investigate both the inward and outward radial propagation of substorm injection. Indicated by *AE*/*AL* indices, this substorm was closely related to an IMF/solar wind discontinuity that showed a sharp change in IMF B_z direction to the north. The innermost signature of this substorm injection was detected by Van Allen Probes *A* and B at L=3.7, while the outermost signature was observed by the onboard BD-IES instrument at L similar to 10. These data indicate that the substorm had a global, rather than just local, effect. Finally, they suggest that electric fields carried by fast-mode compressional waves around the substorm injection are the most likely candidate mechanism for the electron injection signatures observed in the inner- and outermost inner magnetosphere.

3. Magnetic Reconnection

Magnetic reconnection is an important process in space and laboratory plasmas that effectively converts magnetic energy into plasma kinetic energy within a current sheet. Theoretical work suggested that reconnection occurs through the growth and overlap of magnetic flux ropes that deconstruct magnetic surfaces in the current sheet and enable the diffusion of the magnetic field lines between two sides of the sheet. This scenario was also proposed as a primary mechanism for accelerating energetic particles during reconnection, but experimental evidence has remained elusive. Here, they identify a total of 19 flux ropes during reconnection in the magnetotail. Wang *et al.,* [23] found that the majority of the ropes are embedded in the Hall magnetic field region and 63% of them are coalescing. These observations show that the diffusion region is filled with flux ropes and that their interaction is intrinsic to the reconnection dynamics, leading to turbulence.

Whistler waves that can produce anomalous resistivity by affecting electrons' motion have been suggested as one of the mechanisms responsible for magnetic reconnection in the Electron Diffusion Region (EDR). Such type of waves, however, has rarely been observed inside the EDR so far. Cao *et al.,* [24] report such an observation by Magnetospheric Multiscale (MMS) mission. They find large-amplitude whistler waves propagating away from the X line with a very small wave-normal angle. These waves are probably generated by the perpendicular temperature anisotropy of the –300 eV electrons inside the EDR, according to our analysis of dispersion relation and cyclotron resonance condition; they significantly affect the electron-scale dynamics of magnetic reconnection and thus support previous simulations.

Taking advantage of high-resolution measurements from the MMS mission, Zhang *et al.,* [25] finds evidence for a complete Hall system in the exhaust of asymmetric magnetic reconnection 40D_i downstream of the X line. The investigation of the fine structure of the Hall system reveals that it displays features in the exhaust similar to those reported previously in the ion diffusion region by simulations and observations. This finding confirms the importance of particle-scale processes in the reconnection exhaust as well. On the magnetospheric side of the exhaust, electrons are strongly accelerated by parallel electric fields. This process significantly contributes to feed the Hall current system, resulting in a nonnegligible Hall magnetic field signature on this side despite an otherwise lower density. Calculation of the induced out-of-plane magnetic field by in-plane currents (based on Biot-Savart law) provides direct quantitative evidence for the process of Hall magnetic field generation by the Hall current system. A strong normal Hall electric field is present only on the magnetospheric side of the exhaust region, consistent with previous works. Multipoint data analysis shows that the ion pressure gradient in the ion momentum equation produces this Hall electric field. This global pattern of the Hall system can be explained by kinetic Alfven wave theory.

During a one-hour interval of Interplanetary Magnetic Field (IMF) B_z approximate to 0 nT, the equatorial spacecraft Double Star TC-1 encountered the dawn flank magnetopause many times at the Magnetic Local Time (MLT) of about 08:00 and the latitude of about –27 degrees. During each encounter, reconnection jets were observed with their velocities up to more than 500 km/s, significantly higher than the background flow in the magnetosheath. The fast flows match the theoretical prediction of Alfvenic acceleration well. The medium temperature and density of ions in the boundary layer indicate the open magnetic field topology inside this layer. The mainly southward and tailward flows of the plasma jets alongside with the negative slopes of the Walen test indicate that the spacecraft was located south of the reconnection site, consistent with both anti-parallel and component reconnection models. The accelerated flows were observed lasting for about one hour, with some modulations by the oscillations of the magnetopause, but no reversals in the direction of V-z were found during the interval. The significantly enhanced flows in the boundary layer compared to the adjacent magnetosheath indicate that the reconnection was quasi-continuously active at the magnetopause northward of the spacecraft under such IMF conditions. At the same time, the bipolar signatures in B-N with enhancements of the magnetic field indicate the occurrence of the Flux Transfer Events (FTEs). The observed reconnection was quasi-continuous, whereas the simultaneously accompanied FTEs were time-dependent under the IMF B_z approximate to 0 nT. For this event analyzed by Yan, *et al.,* [26], however, it is not possible to identify whether the reconnection was anti-parallel or component because the TC-1 was far away from the reconnection site.

Magnetic reconnection plays a key role in the conversion of magnetic energy into the thermal and kinetic energy of plasma. On either side of the diffusion region in space plasma, the conditions for the occurrence of reconnections are usually not symmetric. Previous theoretical studies have predicted that reconnections under asymmetric conditions will bear different features compared with those of symmetric reconnections, and numerical simulations have verified these distinct features. However, to date, the features of asymmetric reconnections have not been thoroughly investigated using in situ observations; thus, some results from theoretical studies and simulations have not been tested with observations sufficiently well. Here, spacecraft observations are used in a statistical investigation of asymmetric magnetic reconnection exhaust at the dayside magnetopause. The resulting observational features are consistent with the theoretical predictions. Zhang[27] advances our understanding of the development of reconnections under asymmetric conditions.

Huang *et al.,* [28] and Huang *et al.,* [29] give the full image of whistler waves in the reconnection diffusion region. Whistler waves are believed to play an important role during magnetic reconnection. Huang *et al.,* [28] report the near-simultaneous occurrence of two types of the whistler-mode waves in the magnetotail reconnection region. The first type is observed in the magnetic pileup region of downstream and propagates away to downstream along the field lines and is possibly generated by the electron temperature anisotropy at the magnetic equator. The second type, propagating toward the X line, is found around the separatrix region and probably is generated by the electron beam-driven whistler instability or Čerenkov emission from electron phase-space holes. These observations of two different types of whistler waves are consistent with recent kinetic simulations and suggest that the observed whistler waves are a consequence of magnetic reconnection. Huang *et al.* [29] have performed a statistical study by using the Cluster data to investigate the spatial distribution and the occurrence rate of whistler waves in the magnetotail reconnection region. It is found that the occurrence rate of the whistler waves is large in the separatrix region ($|B_x/B_0|>0.4$) and in the pileup region ($|B_x/B_0|<0.2$, $|\theta|>45°$, where θ=arctan(B_z/B_x)), but is very small in the vicinity of the X-line. These statistical results are well consistent with recent kinetic simulations and with previous observational case studies. These observations give the full image of whistler waves in the reconnection region.

Huang *et al.,* [30] presented the first in situ observations of a small-scale flux rope locally formed at the separatrix region of magnetic reconnection without large guide field. Bidirectional electron beams (cold and hot beams) and density cavity accompanied by intense wave activity substantiate the crossing of the separatrix region. Density compression and one parallel electron beam are detected inside the flux rope. They suggest that this flux rope is locally generated at the separatrix region due to the tearing instability within the separatrix current layer. This observation sheds new light on the 3-D picture of magnetic reconnection in space plasma.

Magnetic reconnection has long been regarded as an important site for producing energetic electrons in solar terrestrial and astrophysical plasmas. The motivation of this paper is to provide the average properties of energetic electrons in reconnection region, which are crucial for understanding electron energization mechanism but are rarely known. Zhou *et al.,* [31] statistically analyzed the energetic electrons through 21 magnetotail reconnection events observed by Cluster spacecraft during the years of 2001–2005. Approximately 1200 data points with time resolution of 8 s have been collected for each spacecraft. Two parameters are examined: Energetic Electron Rate (EER) and power law index. EER, which is defined as the ratio of the integrated energetic electron flux to the lower energy electron flux, is used to quantify the electron acceleration efficiency. They find that EER and Energetic Electron Flux (EEF) are positively correlated with the power law index, *i.e.*, the higher rate and flux generally corresponds to softer spectrum. This unexpected correlation is probably caused by some nonadiabatic heating/acceleration mechanisms that tend to soft the spectrum with high temperature. EER is much larger within the earthward flow than the tailward flow. It is positively correlated with the outflow speed V_x, while the correlation between EER and B_z is less clear. With the increment of earthward outflow speed, the occurrence rate of high EER also monotonically increases. They find that EER generally does not increase with the increment of perpendicular electric field $|E_\perp|$, suggesting that adiabatic betatron and Fermi acceleration probably play minor roles in electron energization during magnetotail reconnection.

A series of magnetic flux ropes embedded in the ion diffusion region of a magnetotail magnetic reconnection event were investigated in Wang *et al.,* [32]. Waves near the lower hybrid frequency were measured within each of the flux ropes, and can be associated with the enhancements of energetic electrons in some of the flux ropes. The waves in the largest flux ropes were further explored in more detail. The electrostatic lower-hybrid-frequency-range waves are detected at the edge, while electromagnetic lower-hybrid-frequency-range waves are observed at the center of the flux rope. The electromagnetic waves are right-hand polarized and propagated nearly perpendicular to magnetic field lines, with a wavelength of ion-electron hybrid scale. The observations are analogous to simulations in which the electrostatic lower hybrid waves are confined to the edge of current sheet, but can directly penetrate into the current sheet center in the form of the electromagnetic mode. The observations indicate that the electromagnetic lower-hybrid-frequency-range waves can be excited inside magnetic flux ropes.

An in situ measurement at the magnetopause shows that the quadrupole pattern of the Hall magnetic field, which is commonly observed in a symmetric reconnection, is still evident in an asymmetric component reconnection, but the two quadrants adjacent to the magnetosphere are strongly compressed into the electron scale and the widths of the remaining two quadrants are still ion scale. The bipolar Hall electric field pattern generally created in a symmetric reconnection is replaced by a unipolar electric field within the electron-scale quadrants. Furthermore, it is concluded by Wang *et al.,* [33] that the spacecraft directly passed through the inner electron diffusion region based on the violation of the electron frozen-in condition, the energy dissipation, and the slippage between the electron flow and the magnetic field. Within the inner electron diffusion region, magnetic energy was released and accumulated simultaneously, and it was accumulated in the perpendicular directions while dissipated in the parallel direction. The localized thinning of the current sheet accounts for the energy accumulation in a reconnection.

Using the high-resolution field and plasma data obtained from the Magnetospheric Multiscale mission at the magnetopause, a series of three flux transfer events was observed one after another inside southward ion flows, without time gap between any two successive flux ropes. Using the plasma measurements, the current densities within the flux ropes were studied in detail. The currents within the first two flux ropes, dubbed Fr1 and Fr2, were composed of a series of well-separated filamentary currents. The thickness of the filamentary currents and the gap between them were sub ion scale, occasionally dropped down to electron scale. In the third flux rope Fr3 which was closest to the expected reconnection X line, the current displayed a singular compact current layer, was ion scale in width and concentrated on its center. Considering the location of the flux ropes relative to the reconnection X line, Wang *et al.,* [34] suggested that the current density could be a singular structure when the flux rope was just created and then fragmented into a series of filamentary currents as time. By examining the inter-regions between Fr1 and Fr2, and between Fr2 and Fr3, reconnection was only confirmed to occur between Fr2 and Fr3 and no reconnection signature was found between Fr1 and Fr2. It seems that magnetic field compression resulted from collision of two neighboring flux ropes is one necessary condition for the occurrence of the coalescence.

Secondary magnetic islands may be generated in the vicinity of an X line during magnetic reconnection. In this paper, by performing two-dimensional (2-D) particle-in-cell simulations, Wang *et al.,* [35] investigate the role of a secondary magnetic island in electron acceleration during magnetic reconnection with a guide field. The electron motions are found to be adiabatic, and they analyze the contributions of the parallel electric field and Fermi and betatron mechanisms to electron acceleration in the secondary island during the evolution of magnetic reconnection. When the secondary island is formed, electrons are accelerated by the parallel electric field due to the existence of the reconnection electric field in the electron current sheet. Electrons can be accelerated by both the parallel electric field and Fermi mechanism when the secondary island begins to merge with the primary magnetic island, which is formed simultaneously with the appearance of X lines. With the increase in the guide field, the contributions of the Fermi mechanism to electron acceleration become less and less important. When the guide field is sufficiently large, the contribution of the Fermi mechanism is almost negligible.

Magnetic reconnection is an important process in space and laboratory plasmas effectively converting magnetic energy into plasma kinetic energy in a current sheet. Theoretical work suggested that reconnection occurs via the growth and overlap of magnetic flux ropes destructing magnetic surfaces in the current sheet and enabling the diffusion of the magnetic field lines between two sides of the sheet. This scenario was also proposed as a primary mechanism for accelerating energetic particles during reconnection, but experimental evidence has remained elusive. Wang *et al.,* [23] identify a total of 19 flux ropes during reconnection in the magnetotail. They found that the majority of the ropes are embedded in the Hall magnetic field region and 63% of them are coalescing. These observations show that the diffusion region is filled with flux ropes and their interaction is intrinsic to the reconnection dynamics, leading to turbulence.

The effect of the reconnection rate on the generation of Alfvén wave energy is systematically investigated using Hall MHD. It is well known that a decrease in magnetic energy is proportional to the reconnection rate. Li *et al.,* [36] found that an instantaneous increase in Alfvén wave energy in unit Alfvén time is the square dependence on the reconnection rate. The converted Alfvén wave energy is strongly enhanced due to the large increase in the reconnection rate in Hall MHD. For solar-terrestrial plasmas, the maximum converted Alfvén wave energy in unit Alfvén time with the Hall effect can be over 50 times higher than that without the Hall effect during magnetic reconnection.

In the framework of two-dimensional incompressible MHD, Li *et al.,* [37] investigate the formation of Alfvénic resonance layers with different super-Alfvénic shear flows. It is found that Alfvénic resonance layers are formed in the inflow region for the cases with the shear flow thickness larger than the current sheet thickness. The Alfvénic layers exist at where the flow velocity is equal to the local Alfvén speed and slowly drift away from the current sheet region as a magnetic island develops. The ratio (D) between the separation of the Alfvénic resonance layers and the current sheet thickness plays a crucial role on magnetic reconnection. It is found that D~3 is a critical value, which is about the saturated size of a magnetic island in magnetic reconnection without super-Alfvénic shear flow. For D<3, the super-Alfvénic shear flow shows mainly a suppressing effect on magnetic reconnection and the peaked reconnection rate drops below the rate without a super-Alfvénic shear flow. When D>3, the boosting effect of Kelvin-Helmholtz instability surpasses the suppressing effect by Alfvénic resonance and the peaked reconnection rate is larger than that without a super-Alfvénic shear flow. For D~5, the super-Alfvénic shear flow gives rise to a strongest boosting effect on magnetic reconnection. Possible applications are briefly discussed.

The features of magnetic reconnection with a streaming flow have been investigated on the basis of compressible resistive MHD model. The super-Alfvenic streaming flow largely enhances magnetic reconnection. The maximum reconnection rate is almost four times larger with super-Alfvenic streaming flow than sub-Alfvenic streaming flow. In the nonlinear stage, Wu *et al.,* [38] found that there is a pair of shocks observed in the inflow region, which are manifested to be slow shocks for sub-Alfvenic streaming flow, and fast shocks for super-Alfvenic streaming flow. The quasi-period oscillation of reconnection rates in the decaying phase for super-Alfvenic streaming flow is resulted from the different drifting velocities of the shock and the X point.

Behavior of the fast earthward flow near the braking region in the magnetotail during a substorm is investigated using the Hall MHD simulation. Lu *et al.,* [39] indicates that the high speed earthward plasma flow is associated with fast reconnection in the middle tail. The fast flow is mainly confined in the range $-1.5\ R_e<z<1.5\ R_e$. In the region of $-15\ R_e<x<-9\ R_e$, due to intermittent magnetic reconnection, the earthward flow exhibits a fluctuating property, i.e., the flow is localized in space and is bursty in time. The pile-up of the magnetic flux and plasma in the near-Earth region leads to formation of the fast-flow braking region or dipolarization front. After colliding into the fast-flow braking region, a part of the Earth flow bounces back, and leads to an intermittent tailward flow in the near-Earth magnetotail.

Magnetic reconnection is initiated in a small diffusion region but can drive global-scale dynamics in Earth's magnetosphere, solar flares, and astrophysical systems. Understanding the processes at work in the diffusion region remains a main challenge in space plasma physics. Recent in situ observations from Magnetospheric Multiscale and Time History of Events and Macroscale Interactions during Substorms reveal that the electric field normal to the reconnection current layer, often called the Hall electric field (E_n), is mainly balanced by the ion pressure gradient. Dai *et al.,* [40] presents theoretical explanations indicating that this observation fact is a manifestation of Kinetic Alfven Waves (KAWs) physics. The ion pressure gradient represents the finite gyroradius effect of KAW, leading to ion intrusion across the magnetic field lines. Electrons stream along the magnetic field lines to track ions, resulting in field-aligned currents and the associated pattern of the out-of-plane Hall magnetic field (B_m). The ratio E_n/B_m is on the order of the Alfven speed, as predicted by the KAW theory. The KAW physics further provides new perspectives on how ion intrusion may trigger electric fields suitable for reconnection to occur.

The magnetic flux rope is among the most fundamental magnetic configurations in plasma. Although its presence after solar eruptions has been verified by spacecraft measurements near Earth, its formation on the Sun remains elusive, yet is critical to understanding a broad spectrum of phenomena. Wang *et al.,* [41] study the dynamic formation of a magnetic flux rope during a classic two-ribbon flare. Its feet are identified unambiguously with conjugate coronal dimmings completely enclosed by irregular bright rings, which originate and expand outward from the far ends of flare ribbons. The expansion is associated with the rapid ribbon separation during the flare main phase. Counting magnetic flux through the feet and the ribbon-swept area reveals that the rope's core is more twisted than its average of four turns. It propagates to the Earth as a typical magnetic cloud possessing a similar twist profile obtained by the Grad-Shafranov reconstruction of its three dimensional structure.

Dong *et al.,* [42] investigate a series of three small-scale Flux Transfer Events (FTEs) associated with reconnected flux ropes, recently generated by a nearby, dayside magnetic reconnection line. The data are observed by the Magnetospheric Multiscale spacecraft near noon local time. They find that the associated FTEs are created by secondary magnetic reconnection and have different magnetic field topologies, which is a similar condition to that expected in the multiple X-line Magnetic Reconnection (MR) model. The calculated results show that the sizes of the FTEs become larger with the time elapsed and the MR reconnection jets at the FTEs are all located on the trailing and outer edges. The above features indicate that these FTEs are still in the evolutionary stage after they are ejected from the reconnection region. Their observations suggest that mesoscale or even typical size FTEs can be created from secondary MR, initially, and subsequently can evolve to a typical size in the process of spreading.

A magnetic reconnection event detected by Cluster is analyzed using three methods: Single-spacecraft Inference based on Flow-reversal Sequence (SIFS), Multi-spacecraft Inference based on Timing a Structure (MITS), and the First-Order Taylor Expansion (FOTE). Using the SIFS method, they find that the reconnection structure is an X line; while using the MITS and FOTE methods, they find it is a magnetic island (O line). Fu *et al.,* [43] compare the efficiency and accuracy of these three methods and find that the most efficient and accurate approach to identify a reconnection event is FOTE. In both the guide and non-guide field reconnection regimes, the FOTE method is equally applicable. This study for the first time demonstrates the capability of FOTE in identifying magnetic reconnection events; it would be useful to the forthcoming Magnetospheric MultiScale (MMS) mission.

Magnetic reconnection the process responsible for many explosive phenomena in both nature and laboratory is efficient at dissipating magnetic energy into particle energy. To date, exactly how this dissipation happens remains unclear, owing to the scarcity of multipoint measurements of the diffusion region at the sub-ion scale. Here they report such a measurement by Cluster four spacecraft with separation of 1/5 ion scale. Fu *et al.,* [44] discover numerous current filaments and magnetic nulls inside the diffusion region of magnetic reconnection, with the strongest currents appearing at spiral nulls (O-lines) and the separatrices. Inside each current filament, kinetic-scale turbulence is significantly increased and the energy dissipation, E_j, is 100 times larger than the typical value. At the jet reversal point, where radial nulls (X-lines) are detected, the current, turbulence, and energy dissipations are surprisingly small. All these features clearly demonstrate that energy dissipation in magnetic reconnection occurs at O-lines but not X-lines.

A new mechanism to generate whistler waves in the course of collisionless magnetic reconnection is proposed. It is found that intense whistler emissions occur in association with plasmoid collisions. The key processes are strong perpendicular heating of the electrons through a secondary magnetic reconnection during plasmoid collision and the subsequent compression of the ambient magnetic field, leading to whistler instability due to the electron temperature anisotropy. The emissions have a bursty nature, completing in a short time within the ion timescales, as has often been observed in the Earth's magnetosphere. The whistler waves can accelerate the electrons in the parallel direction, contributing to the generation of high-energy electrons. Fujimoto [45] suggests that the bursty emission of whistler waves could be an indicator of plasmoid collisions and the associated particle energization during collisionless magnetic reconnection.

The present study investigates the linear properties of the Current Sheet Shear Instability (CSSI) based on the two-fluid equations. The mode is typically excited in the thin current layer formed around the X line during a quasi-steady phase of collisionless reconnection and is considered to give rise to the anomalous momentum transport. The linear analyses are carried out for a realistic current sheet as evolved in collisionless reconnection, where the current density profile is produced by the non-uniform ion and electron flows and the pressure balance is maintained due to the temperature gradients. The density profile is assumed to be uniform, so that the lower hybrid drift instability is mostly suppressed. Fujimoto and Sydora [46] confirm that the eigen functions in the numerical analysis are well consistent with the profiles in a kinetic simulation, implying that the two-fluid approximation is valid for the CSSI. The mass ratio dependencies of the wave number and growth rate are remarkable for the electron-scale current sheet, indicating that both the electrons and ions contribute to the wave generation. From the analytical analysis, it is found that these mass ratio dependencies originate from the fact that the ion momentum balance is coupled with the electron dynamics in the electron-scale current layer. In particular, the electron inertia and electron flow shear play a significant role in generating the CSSI through the induction electric and magnetic fields.

Signatures of secondary islands are frequently observed in the magnetic reconnection regions of magnetotail plasmas. In Guo *et al.,* [47], magnetic structures with the secondary-island signatures observed by Cluster are reassembled by a fitting-reconstruction method. The results show three-dimensionally that a secondary island event can manifest the flux rope formed with an A_s-type null and a B_s-type null paired via their spines. They call this A_s-spine-B_s-like configuration the helically wrapped spine model. The reconstructed field lines wrap around the spine to form the flux rope, and an O-type topology is therefore seen on the plane perpendicular to the spine. Magnetized electrons are found to rotate on and cross the fan surface, suggesting that both the torsional-spine and the spine-fan reconnection take place in the configuration. Furthermore, detailed analysis implies that the spiral nulls and flux ropes were locally generated nearby the spacecraft in the reconnection outflow region, indicating that secondary reconnection may occur in the exhaust away from the primary reconnection site.

Magnetic null points and flux ropes play important roles in the three-dimensional process of magnetic reconnection. In Guo *et al.,* [48], a cluster of null points are reconstructed in the reconnection region in the magnetotail by applying a fitting-reconstruction method to measurements from the Cluster mission. The number of reconstructed null points varies rapidly, presenting a turbulent-like evolution of the magnetic structure. The electron density and the flux of the accelerated electrons were enhanced in this turbulent-like region. During this unstable reconnection process, a B-A_s-B null structure was formed, showing flux rope features and resembling a secondary island in the observation.

The Pitch Angle Distribution (PAD) of suprathermal electrons can have both spatial and temporal evolution in the magnetotail and theoretically can be an indication of electron energization/cooling processes there. So far, the spatial evolution of PAD has been well studied, leaving the temporal evolution as an open question. To reveal the temporal evolution of electron PAD, spacecraft should monitor the same flux tube for a relatively long period, which is not easy in the dynamic magnetotail. In this study, they present such an observation by Cluster spacecraft in the magnetotail behind a Dipolarization Front (DF). Liu *et al.,* [49] find that the PAD of suprathermal electrons can evolve from pancake type to butterfly type during <4 s and then to cigar type during <8 s. During this process, the flow velocity is nearly zero and the plasma entropy is constant, meaning that the evolution is temporal. They interpret such temporal evolution using the betatron cooling process, which is driven by quasi-adiabatic expansion of flux tubes, and the magnetic mirror effect, which possibly exists behind the DF as well.

The rolling-pin distribution of suprathermal electrons (40–200 keV), showing electron pitch angles primarily at 0 degrees, 90 degrees, and 180 degrees, has recently been reported behind Dipolarization Fronts (DFs) both in observations and simulations. The formation of such type of distribution, however, has been unclear so far. Liu *et al.,* [50] present an observation of such type of distribution by Cluster in the magnetotail behind a DF. They interpret the formation of such distribution using the global-scale Fermi acceleration together with local-scale betatron acceleration. We quantitatively reproduce these two processes and therefore the rolling-pin distribution of suprathermal electrons using an analytical model. They further reveal that only at energies higher than 26 keV can such distribution be formed. This study, quantitatively explaining the formation of rolling-pin distribution, can improve the understanding of electron dynamics behind DFs.

Flux Pileup Regions (FPRs) are traditionally referred to the strong-*B*-z bundles behind Dipolarization Fronts (DFs) in the Earth's magnetotail and can appear both inside earthward and tailward bursty bulk flows. It has been widely reported that suprathermal electrons (40–200 keV) can be efficiently accelerated inside earthward FPRs, leaving the electron acceleration inside tailward FPRs as an open question. Liu *et al.,* [51] focus on the electron acceleration inside a tailward FPR that is formed due to the flow rebounce in the near-Earth region (X-GSM approximate to –12 R_e) and compare it quantitatively with the acceleration inside an earthward FPR. By examining the Cluster data in 2008, they sequentially observe an earthward FPR and a tailward FPR in the near-Earth region, with the earthward one belonging to decaying type and the tailward one belonging to growing type. Inside the earthward FPR, Fermi acceleration and betatron cooling of suprathermal electrons are found, while inside the tailward FPR, Fermi and betatron acceleration occur. Whistler-mode waves are observed inside the tailward FPR; their generation process may still be at the early stage. They notice that the suprathermal electron fluxes inside the tailward FPR are about twice as large as those inside the earthward FPR, suggesting that the acceleration of suprathermal electrons is more efficient in the flow rebounce region. These acceleration processes have been successfully reproduced using an analytical model; they emphasize the role of flow rebounce in accelerating suprathermal electrons and further reveal how the MHD-scale flow modulates the kinetic-scale electron dynamics in the near-Earth magnetotail.

Within Dipolarization Fronts (DFs) in the Earth's magnetotail, significant magnetic energy is converted to plasma energy, and a significant portion of the electrons and ions therein are accelerated to suprathermal energies. The mechanism that produces these suprathermal particles while simultaneously reducing magnetic field energy is poorly understood, however. Lu *et al.,* [52] use two-dimensional particle-in-cell simulations to explore this process in conventional flux bundle-type DFs, which are formed by single X line reconnection and connected to the Earth, and in newly proposed flux rope-type DFs, which are formed and bracketed by two X lines. In flux bundle-type DFs, electrons are betatron accelerated near the *B-z* peak, and ions are energized through reflection at the front. In flux rope-type DFs, most suprathermal electrons and ions are confined to the flux rope's magnetic structure and are accelerated through repeated reflections at the structure's two ends.

With high-resolution data of the recently launched Magnetospheric Multiscale mission, Peng*, et al.,* [53] report a magnetic reconnection event at the dayside magnetopause. This reconnection event, having a density asymmetry N_{high}/N_{low} approximate to 2 on the two sides of the reconnecting current sheet and a guide field B_g approximate to $0.4B_0$ in the out-of-plane direction, exhibit all the two-fluid features: Alfvenic plasma jets in the outflow region, bipolar Hall electric fields toward the current sheet center, quadrupolar Hall magnetic fields in the out-of-plane direction, and the corresponding Hall currents. Obviously, the density asymmetry N_{high}/N_{low} approximate to 2 and the guide field B_g approximate to $0.4B_0$ are not sufficient to dismiss the quadrupolar pattern of Hall reconnection. This is different from previous simulations, where the bipolar pattern of Hall reconnection was suggested.

A significant enhancement of O^+ is observed by Cluster inside an earthward propagating magnetic island behind a Dipolarization Front (DF). Such enhancement, from 0.005 to 0.03 cm^{-3}, makes the O^+ flux inside the magnetic island similar to 20 times larger than that outside the magnetic island. In the meantime, the H^+ density is nearly a constant, 0.1 cm^{-3}, during the magnetic-island encounter. The results of Wang *et al.,* [54] in a dramatic increase of the density ratio, n_{O+}/n_{H+}, from 0.05 to 0.3 (about 10 times as large as the average value in the plasma sheet) and a dramatic decrease of the local Alfven speed from V_A approximate to 770 km/s to V_A approximate to 430km/s inside the magnetic island. The decrease of Alfven speed indicates an asymmetric reconnection and a slow magnetic reconnection rate near the secondary X line. Since the reconnection rates at the primary X line and secondary X line are imbalanced, the DFs and magnetic islands are pushed to propagate earthward by the outflow of the primary reconnection, as demonstrated in recent simulations.

Dipolarization Front (DF) is a sharp boundary most probably separating the reconnection jet from the background plasma sheet. So far at this boundary, the observed waves are mainly in low-frequency range (*e.g.*, magnetosonic waves and lower hybrid waves). Few high-frequency waves are observed in this region. Yang *et al.,* [55] report the broadband high-frequency wave emissions at the DF. These waves, having frequencies extending from the electron cyclotron frequency f_{ce}, up to the electron plasma frequency f_{pe}, could contribute similar to 10% to the in situ measurement of intermittent energy conversion at the DF layer. Their generation may be attributed to electron beams, which are simultaneously observed at the DF as well.

Energy conversion on the Dipolarization Fronts (DFs) has attracted much research attention through the suggestion that intense current densities associated with DFs can modify the more global magnetotail current system. The current structures associated with a DF are at the scale of one to a few ion gyroradii, and their duration is comparable to a spacecraft's spin period. Hence, it is crucial to understand the physical mechanisms of DFs with measurements at a timescale shorter than a spin period. Yao *et al.,* [56] present a case study whereby they use measurements from the Magnetospheric Multiscale (MMS) Mission, which provides full 3-D particle distributions with a cadence much shorter than a spin period. They provide a cross validation amongst the current density calculations and examine the assumptions that have been adopted in previous literature using the advantages of MMS mission (*i. e.*, small-scale tetrahedron and high temporal resolution). They also provide a cross validation on the terms in the generalized Ohm's law using these advantageous measurements. Our results clearly show that the majority of the currents on the DF are contributed by both ion and electron diamagnetic drifts. Our analysis also implies that the ion frozen-in condition does not hold on the DF, while electron frozen-in condition likely holds. The new experimental capabilities allow us to accurately calculate Joule heating within the DF, which shows that plasma energy is being converted to magnetic energy in our event.

Study of magnetic reconnection has been focused on two-dimensional geometry in the past decades, whereas three-dimensional structures and dynamics of reconnection X line are poorly understood. Zhou *et al.,* [57] report Cluster multispacecraft observations of a three-dimensional magnetic reconnection X line with a weak guide field (similar to 25% of the upstream magnetic field) in the Earth's magnetotail. They find that the X line not only retreated tailward but also expanded across the tail following the electron flow direction with a maximum average speed of (0.04–0.15) V_A, V_{up}, where V_A, V_{up} is the upstream Alfven speed, or (0.14–0.57) V_{de}, where V_{de} is the electron flow speed in the out-of-plane direction. An ion diffusion region was observed by two spacecraft that were separated about 10 ion inertial lengths along the out-of-plane direction; however, these two spacecraft observed distinct magnetic structures associated with reconnection: one spacecraft observed dipolarization fronts, while the other one observed flux ropes. This indicates that reconnection proceeds in drastically different ways in different segments along the X line only a few ion inertial lengths apart.

Dipolarization fronts, earthward propagating structures in the Earth's magnetotail characterized by sharp enhancements of the northward magnetic field, are important sites of energy conversion from electromagnetic to particle energy. The large energy conversion rate observed at these fronts suggests significant particle acceleration and heating, which powers the ambient current sheet to generate plasma flows in the magnetotail plasma sheet and its boundary layer. Using a simple model of ion reflection at the dipolarization front, they estimate ion energy enhancement in the ambient plasma sheet and find it to be comparable with typical electromagnetic energy converted at the front. Validated by dipolarization front statistics from THEMIS (Time History of Events and Macroscale Interactions during Substorms) observations, Li *et al.* [58] suggest the important contribution of ion reflection to the energy budgets of dipolarization fronts during their earthward propagation.

Dipolarization Fronts (DFs), earthward propagating structures in the magnetotail current sheet characterized by sharp enhancements of northward magnetic field, are capable of converting electromagnetic energy into particle kinetic energy. The ions previously accelerated and reflected at the DFs can contribute to plasma flows ahead of the fronts, which have been identified as DF precursor flows in both the near-equatorial plasma sheet and far from it, near the plasma sheet boundary. Using observations from the THEMIS (Time History of Events and Macroscale Interactions during Substorms) spacecraft, they show that the earthward particle and energy flux enhancements ahead of DFs are statistically larger farther away from the neutral sheet (at high latitudes) than in the near-equatorial region. High-latitude particle and energy fluxes on the DF dawnside are found to be significantly greater than those on the duskside, which is opposite to the dawn-dusk asymmetries previously found near the equatorial region. Using forward and backward tracing test-particle simulations, Li *et al.* [59] then explain and reproduce the observed latitude-dependent characteristics of DF precursor flows, providing a better understanding of ion dynamics associated with dipolarization fronts.

Sun, *et al.* [60] perform a statistical study of flux ropes and reconnection fronts based on MErcury Surface, Space ENviroment, GEochemistry, and Ranging (MESSENGER) magnetic field and plasma observations to study the implications for the spatial distribution of reconnection sites in Mercury's near magnetotail. The results show important differences of temporal and spatial distributions as compared to Earth. They have surveyed the plasma sheet crossings between –2 R_{m} and –3 R_{m} downtail from the planet, *i.e.*, the location of Near-Mercury Neutral Line (NMNL). Plasma sheets were defined to be regions with $\beta\geqslant 0.5$. Using this definition, 39 flux ropes and 86 reconnection fronts were identified in the plasma sheet. At Mercury, the distributions of flux ropes and reconnection fronts show clear dawn-dusk asymmetry with much higher occurrence rate on the dawnside plasma sheet than on the duskside. This suggests that magnetic reconnection in Mercury's magnetotail occurs more frequently in the dawnside than in the duskside plasma sheet, which is different than the observations in Earth's magnetotail showing more reconnection signatures in the duskside plasma sheet. The distribution of plasma sheet thickness shows that plasma sheet near the midnight is the thinnest part and does not show obvious asymmetry. Thus, the reasons that cause magnetic reconnection to preferentially occur on the dawnside of the magnetotail at Mercury may not be the plasma sheet thickness and require further study. The peak occurrence rates of flux ropes and reconnection fronts in Mercury's plasma sheet are similar to 60 times higher than that of Earth's values, which they interpret to be due to the highly variable magnetospheric conditions at Mercury. Such higher occurrence rate of magnetic reconnection would generate more plasma flows in the dawnside plasma sheet than in the duskside. These plasma flows would mostly brake and initiate the substorm dipolarization on the postmidnight sector at Mercury rather than the premidnight susbtorm onset location at Earth.

An interesting signature observed shortly after the onset of magnetotail reconnection is the gradual appearance of a local peak of ion Phase Space Density (PSD) in the duskward and downstream direction separated from the colder, nearly isotropic ion population. Such a characteristic ion distribution, served as a diagnostic signature of magnetotail reconnection and well reproduced by a particle-tracing Liouville simulation, are found by Zhao *et al.* [61] to appear only near the off-equatorial boundaries of the reconnection outflow region. Further analysis on ion trajectories suggests that the ions within the local peak and within the neighboring PSD cleft both belong to the outflowing population; on top of their outflowing motion, they both meander across the neutral sheet to exhibit duskward velocities near the off-equatorial edges of their trajectories. The difference between them is that the local peak originates from ions previously constituting the pre-onset plasma sheet, whereas the cleft corresponds to the inflowing lobe ions before they are repelled in the downstream direction. As reconnection proceeds, the local PSD peak gradually attenuates and then disappears, which is a signature of reconnection flushing effect that depletes the ions in the pre-onset plasma sheet and eventually replaces them by lobe ions.

4. Solar Wind-magnetosphere-ionosphere Interaction

Earth's bow shock is the result of interaction between the supersonic solar wind and Earth's magnetopause. However, data limitations mean the model of the shape and position of the bow shock are based largely on near-Earth satellite data. The model of the bow shock in the distant magnetotail and other factors that affect the bow shock, such as the IMF B_y, remain unclear. Based on the bow shock crossings of ARTEMIS from January 2011 to January 2015, new coefficients of the tail-flaring angle alpha of the Chao model (one of the most accurate models currently available) were obtained by fitting data from the middle-distance magnetotail (near-lunar orbit, geocentric distance $-20\ R_e > X > -50\ R_e$). In addition, the effects of the IMF B_y on the flaring angle alpha were analyzed. Results showed that: (1) the new fitting coefficients of the Chao model in the middle-distance magnetotail are more consistent with the observed results; (2) the tail-flaring angle alpha of the bow shock increases as the absolute value of the IMF B_y increases. Moreover, positive IMF B_y has a greater effect than negative IMF B_y on flaring angle. Liu *et al.* [62] provide a reference for bow shock modeling that includes the IMF B_y.

Studying the access of the Cosmic Rays (CRs) into the magnetosphere is important to understand the coupling between the magnetosphere and the solar wind. In this paper they numerically studied CRs' magnetospheric access with vertical geomagnetic cutoff rigidities using the method proposed by Smart and Shea (1999). By the study of CRs' vertical geomagnetic cutoff rigidities at high latitudes they obtain the CRs' Window (CRW) whose boundary is determined when the vertical geomagnetic cutoff rigidities drop to a value lower than a threshold value. Furthermore, they studied the area of CRWs and found out they are sensitive to different parameters, such as the z component of IMF, the solar wind dynamic pressure, AE index, and *Dst* index. Chu and Qin [63] found that both the AE index and *Dst* index have a strong correlation with the area of CRWs during strong geomagnetic storms. However, during the medium storms, only *AE* index has a strong correlation with the area of CRWs, while *Dst* index has a much weaker correlation with the area of CRWs. This result on the CRW can be used for forecasting the variation of the cosmic rays during the geomagnetic storms.

Using the Cluster data during the period from January to April between 2001 and 2006, they find an observation of solar wind entry due to magnetic reconnection occurred in the terrestrial high latitude magnetospheric lobes, tailward of the cusps under northward IMF. Occurrence rate of solar wind entry events in this study is of the same order as that for the Cluster orbital interval from August to October between the years of 2002 and 2004 as reported by Shi *et a*l. (2013). Gou *et al.* [64] further study the role of the IMF B_x and B_y components in the control of solar wind plasma entry based on the investigations of different magnetic dipole tilt variations between our database and Shi *et al*. (2013). This study shows that the asymmetry distribution of solar wind entry events in the northern and southern lobes could be caused by the variation of magnetic dipole tilt, which could influence the locations of the reconnection site on the high - latitude lobe magnetopause. On the other hand, IMF B_x can also affect the solar wind plasma entry rate, which is also consistent with previous results. Therefore, they conclude that the "north-south asymmetry" of solar wind entry events in the lobes could be the combined result of magnetic dipole tilt and IMF B_x. In addition, the IMF B_y component can influence the entry events in conjunction with the variation of IMF B_x component, which is in line with the Parker Spiral of the IMF.

Tian *et al.* [65] provide in situ observations of the transient phenomena in the dayside magnetosphere during the Preliminary Impulse (PI) and Main Impulse (MI) event on 30 September 2008. The PI and MI geomagnetic signals are induced by twin traveling convection vortices with opposite polarities in the equivalent ionospheric currents due to a sudden increase of the solar wind dynamic pressure. The two Pis-associated ionospheric current vortices centered at ~07 Magnetic Local Time (MLT), 67° Magnetic LATitude (MLAT) in the dawnside and ~14 MLT, 73° MLAT in the duskside, respectively. The dawnside MI current vortex centered at ~68° MLAT and 6 MLT, while the duskside vortex center was traveling poleward from ~67° MLAT to ~75° MLAT at a speed of ~5.6–7.4 km/s around 14 MLT. It is found that both dawnside PI- and MI- related current vortices were azimuthally seen up to 4 MLT. Following the magnetosphere sudden impulse, a clockwise flow vortex with a radial scale larger than 3 R_E, associated with positive Field-Aligned Current (FAC), was observed by Time History of Events and Macroscale Interactions during Substorms (THEMIS) spacecraft in the outer dayside magnetosphere. The flow vortex expanded and traveled tailward in the magnetosphere, also being reproduced with global MHD simulations. Based on both observation and simulation technique, they show that the MI-related FACs are correlated with the large-scale flow vortex. The PI FACs are partially provided by the mode conversion of fast mode waves into the Alfvén waves near the equatorial plane, while most of it may be generated at a higher-latitude region in the magnetosphere.

The intensity-time profiles of Solar Proton Events (SPEs) are grouped into three types in the present study. The Type-I means that the intensity-time profile of an SPE has one peak, which occurs shortly after the associated solar flare and Coronal Mass Ejection (CME). The Type-II means that the SPE profile has two peaks: the first peak occurs shortly after the solar eruption, the second peak occurs at the time when the CME-driven shock reaches the Earth, and the intensity of the second peak is lower than the first one. If the intensity of the second peak is higher than the first one, or the SPE intensity increases continuously until the CME-driven shock reaches the Earth, this kind of intensity-time profile is defined as Type-III. Gao *et al.* [66] found that most CMEs associated with Type-I SPEs have no geoeffectiveness and only a small part of CMEs associated with Type-I SPEs can produce minor (-50 nT$\leqslant Dst \leqslant -30$ nT) or moderate geomagnetic storms (-100 nT$\leqslant Dst \leqslant -50$ nT), but never an intense geomagnetic storm (-200 nT$\leqslant Dst < -100$ nT). However, most of the CMEs associated with Type-II and Type-III SPEs can produce intense or great geomagnetic storms ($Dst \leqslant -200$ nT). The solar wind structures responsible for the geomagnetic storms associated with SPEs with different intensity-time profiles have also been investigated and discussed.

Wang *et al.* [67] study effects of the IMF orientation on the terrestrial tail bow shock location and shape by using global MHD magnetosphere model and empirical bow shock models. It is shown that the tail bow shock cross section is well approximated by an ellipse with the direction of the major axis roughly perpendicular to the IMF clock angle direction. With the increasing IMF clock angle, the eccentricity of the bow shock cross section increases for northward IMF but decreases for southward IMF.

He *et al.* [68] reports Double-peak SubAuroral Ion Drifts (DSAIDs), which is unique subset of SubAuroral Ion Drifts (SAIDs). A statistical analysis has been carried out for the first time with a database of 454 DSAID events identified from Defense Meteorological Satellite Program observations from 1987 to 2012. Both case studies and statistical analyses show that the two velocity peaks of DSAIDs are associated with two ion temperature peaks and two region-2 field-aligned currents (R2-FACs) peaks in the midlatitude ionospheric trough located in the low-conductance subauroral region. DSAIDs are regional and vary significantly with magnetic local time. DSAIDs can evolve from/to SAIDs during their lifetimes, which are from several minutes to tens of minutes. Comparisons between the ionospheric parameters of DSAIDs and SAIDs indicate that double-layer region-2 field-aligned currents (R2-FACs) may be the main driver of DSAIDs. It is also found that DSAIDs happen during more disturbed conditions compared with SAIDs.

Energetic Particle Precipitation (EPP) plays an important role in the catalytic process of ozone depletion due to the odd nitrogen and odd hydrogen species produced by EPP in the polar middle atmosphere during the geomagnetic activities. It is known that solar UV emission variations have significant effects on ozone generation. So it is interesting to compare the contributions of EPP and solar UV emission to ozone change in the polar upper atmosphere. Huang *et al.* [69] applied annual average *Ap* index to denote the annual mean magnitude of geomagnetic activity which has good relationship with EPP flux and annual average $F_{10.7}$ index to denote annual mean magnitude of solar radiation which has certain relevancy with solar UV emission. They adopted latitude-average dataset of ozone measurements from SBUV instruments on the POES satellites and studied the statistics characters between ozone dataset and *Ap*. $F_{10.7}$ index. The multiple regression analysis shows that the contributions of geomagnetic activities are not negligible and have the similar order of magnitude compared with solar UV emission in polar upper atmosphere (above 30 km). The results also show that HSSWS-Induced (HSSWS, High-Speed Solar Wind Stream) geomagnetic activities and that of CME-Induced (CME, Coronal Mass Ejection) are of the same order of magnitude. There exists differences between two hemispheres according to the multiple regression analysis and they made a discussion to interpret the causes of these differences.

Zong and Dai [70] report on observations of an Extreme-UltraViolet (EUV) wave event in the Sun on 2011 January 13 by Solar Terrestrial Relations Observatory and Solar Dynamics Observatory in quadrature. Both the trailing edge and the leading edge of the EUV wave front in the north direction are reliably traced, revealing generally compatible propagation velocities in both perspectives and a velocity ratio about 1/3. When the wave front encounters a coronal cavity near the northern polar coronal hole, the trailing edge of the front stops while its leading edge just shows a small gap and extends over the cavity, meanwhile getting significantly decelerated but intensified. They propose that the trailing edge and the leading edge of the northward propagating wave front correspond to a non-wave Coronal Mass Ejection (CME) component and a fast-mode Magnetohydrodynamic (MHD) wave component, respecttively. The interaction of the fast-mode wave and the coronal cavity may involve a mode conversion process, through which part of the fast-mode wave is converted to a slow-mode wave that is trapped along the magnetic field lines. This scenario can reasonably account for the unusual behavior of the wave front over the coronal cavity.

Solar Active Region (AR) 12673 produced 4 X-class, 27 M-class, and numerous lower class flares during its passage across the visible solar disk in September 2017. Yang *et al.* [71] is to answer the questions why this AR was so flare-productive and how the X9.3 flare, the largest one of the last decade, took place. They find that there was a sunspot in the initial several days, and then two bipolar regions emerged nearby it successively. Due to the standing of the pre-existing sunspot, the movement of the bipoles was blocked, while the pre-existing sunspot maintained its quasi-circular shaped umbra only with the disappearance of a part of penumbra. Thus, the bipolar patches were significantly distorted, and the opposite polarities formed two semi-circular shaped structures. After that, two sequences of new bipolar regions emerged within the narrow semi-circular zone, and the bipolar patches separated along the curved channel. The new bipoles sheared and interacted with the previous ones, forming a complex topological system, during which numerous flares occurred. At the highly sheared region, a great deal of free energy was accumulated. On September 6, one negative patch near the polarity inversion line began to rapidly rotate and shear with the surrounding positive fields, and consequently the X9.3 flare erupted. Our results reveal that the block-induced complex structures built the flare productive AR and the X9.3 flare was triggered by an erupting filament due to the kink instability. To better illustrate this process, a block-induced eruption model is proposed for the first time.

One-dimensional (1-D) hybrid simulations have demonstrated that a quasi-parallel shock is nonstationary and undergoes a reformation process. Recently, two-dimensional (2-D) hybrid simulations have revealed that ripples along the shock front is an inherent property of a quasi-parallel shock. In this paper, they investigate reformation process of a rippled quasi-parallel shock with a 2-D hybrid simulation model. Hao *et al.* [73] show that at a rippled shock, incident particles behave differently and just can be partially reflected at some specific locations along the rippled shock front, and the reflected particles will form an ion beam that moves back to the upstream along the magnetic field. Then, the beam locally interacts with upstream waves, and the waves are enhanced and finally steepen into a new shock front. As the upstream incident plasma moves to the shock front, the new shock front will approach and merge with the old shock front. Such a process occurs only before these locations along the shock front, and after the merging of the new shock front and old shock front is finished, a relatively plane shock front is formed. Subsequently, a new rippled shock front is again generated due to its interaction with the upstream waves, and it will repeat the previous process. In this pattern, the shock reforms itself quasi periodically, and at the same time, ripples can shift along the shock front. The simulations present a more complete view of reformation for quasi-parallel shocks.

A new method for determining the central axial orientation of a two-dimensional coherent Magnetic Flux Rope (MFR) via multipoint analysis of the magnetic-field structure is developed. The method is devised under the following geometrical assumptions: (1) on its cross section, the structure is left-right symmetric; (2) the projected structure velocity is vertical to the line of symmetry. The two conditions can be naturally satisfied for cylindrical MFRs and are expected to be satisfied for MFRs that are flattened within current sheets. The model test demonstrates that, for determining the axial orientation of such structures, the new method is more efficient and reliable than traditional techniques such as minimum-variance analysis of the magnetic field, Grad-Shafranov (GS) reconstruction, and the more recent method based on the cylindrically symmetric assumption. A total of five flux transfer events observed by Cluster are studied by Li *et al.* [74] using the proposed approach, and the application results indicate that the observed structures, regardless of their actual physical properties, fit the assumed geometrical model well. For these events, the inferred axial orientations are all in excellent agreement with those obtained using the multi-GS reconstruction technique.

Utilizing conjunction observations of the Geotail and ACE satellites from 1998 to 2005, Zhang *et al.* [75] investigated the temporal evolutions of the solar wind conditions prior to the formation of X lines in the near-Earth magnetotail. They first show the statistical properties of B_z, B_y, density, and velocity of the solar wind related to the 374 tail X line events. A superposed epoch analysis is performed to study the temporal evolutions of the solar wind conditions 5 h prior to the tail X lines. The solar wind conditions for tail X lines during SouthWard IMF (SW-IMF) and NorthWard IMF (NW-IMF) are analyzed. The main results are as follows: (1) For events classified as SW-IMF, near-Earth X line observations in the magnetosphere are preceded by similar to 2 h intervals of southward IMF; (2) for events classified as NW-IMF, the northward IMF orientation preceding near-Earth X line observations lasts similar to 40 min.

ULtralow Frequency (ULF) waves play an important role in the transport of the solar wind energy to the magnetosphere. In this paper, Shen *et al.* [76] present a ULF wave event in the dayside magnetosphere which shows a sudden decrease in frequency from 3.1 to 2.3 mHz around 0756 UT on 11 January 2010, when a solar wind dynamic pressure drop (from similar to 5 to similar to 2 nPa) was observed simultaneously. The wave exits globally. The phase differences between electric and magnetic fields indicate that the compressional mode wave is standing before and after the wave frequency decrease. This result suggests that the ULF wave should be associated with a cavity mode and the frequency decrease might be induced by the change of the cavity size. A theoretical calculation was made to estimate the cavity mode frequency. The calculated wave frequency before/after the negative impulse is 3.8/2.6 mHz, which is consistent with the observations.

Hot Flow Anomalies (HFAs) are phenomena frequently observed near Earth's bow shock and form when the interplanetary discontinuities interact with Earth's bow shock. Zhao *et al.* [77] perform a statistical study to determine what kind of discontinuities is more efficient to generate HFAs. They use strict criteria to identify classic HFAs, excluding similar foreshock phenomena such as Spontaneous Hot Flow Anomalies (SHFAs) and foreshock bubbles. Their results show that magnetic field on at least one side of the interplanetary discontinuities has to be connected to the bow shock in order to form HFAs. Discontinuities with large shear angles are more efficient to form HFAs. The thickness of current sheets and the thickness of HFAs are strongly correlated and current sheets with thickness from 1000 km to 3162 km are more efficient to form HFAs. Of the HFAs, 74% have the electric field pointing toward the current sheet on the leading side and 72% have the electric field pointing toward the current sheet on the trailing side. In addition, the variations of plasma parameters and the magnetic field of HFAs with E inward on both sides are more dramatic than those with E inward on only one side. An HFA is more likely to form when the reflected flow from the bow shock is along the discontinuity.

A three-dimensional adaptive MHD model, SWMF, is used by Ma *et al.* [78] to simulate the interaction between the solar wind and magnetosphere for a particular event on 5 June 1998, and the simulated results of this event is used to investigate the balances of the dynamic, thermal and magnetic pressure along the Sun-Earth line for the different conditions of IMF. The conclusions are as follows: (1) outside the magnetopause, the total and thermal pressures are clearly correlated with upstream solar wind dynamic pressure and increase with the solar wind dynamic pressure. In contrast, the magnetic pressure decreases with the increasing intensity of the southward IMF due to the magnetic reconnection and is enhanced with the increasing intensity of the northward IMF due to the magnetic accumulation. It is similar to the variation inside the magnetopause; (2) the solar wind pressure coefficient is larger for the northward IMF than that for the southward IMF, but it has no obvious dependence on the upstream solar wind dynamic pressure; (3) the magnetic field compression ratio just inside the magnetopause is larger and more stable in northward IMF than in southward IMF; and (4) along the Sun-Earth line, the thermal pressure is dominant on the magnetopause in southward IMF, while the magnetic pressure is dominant on the magnetopause in northward IMF. The magnetic reconnection easily occurs for southward IMF, and results in magnetic pressure decreasing just inside the magnetopause. This factor plays a crucial role in the earthward displacement of the Earth's magnetopause for southward IMF. And the increasing of thermal pressure just outside the magnetopause also has contribution to this displacement, especially for lower IMF.

5. Radiation Belt, Ring Current and Whistler Waves

The dispersion relation and electromagnetic polarization of the plasma waves are comprehensively studied by Fu *et al.* [79] in cold electron, proton, and heavy charged particle plasmas. Three modes are classified as the fast, intermediate, and slow mode waves according to different phase velocities. When plasmas contain positively-charged particles, the fast and intermediate modes can interact at the small propagating angles, whereas the two modes are separate at the large propagating angles. The near-parallel intermediate and slow waves experience the linear polarization, circular polarization, and linear polarization again, with the increasing wave number. The wave number regime corresponding to the above circular polarization shrinks as the propagating angle increases. Moreover, the fast and intermediate modes cause the reverse change of the electromagnetic polarization at the special wave number. While the heavy particles carry the negative charges, the dispersion relations of the fast and intermediate modes are always separate, being independent of the propagating angles. Furthermore, this study gives new expressions of the three resonance frequencies corresponding to the highly-oblique propagation waves in the general three-component plasmas, and shows the dependence of the resonance frequencies on the propagating angle, the concentration of the heavy particle, and the mass ratio among different kinds of particles.

Chen *et al.* [80] present Van Allen Probes observation of drift-resonance interaction between energetic electrons and ULtralow Frequency (ULF) waves on 29 October 2013. Oscillations in electron flux were observed at the period of similar to 450 s, which is also the dominant period of the observed ULF magnetic pulsations. The phase shift of the electron fluxes (similar to 50 to 150 keV) across the estimated resonant energy (similar to 104 keV) is similar to 360°. This phase relationship is different from the characteristic 180° phase shift as expected from the drift-resonance theory. They speculate that the additional 180° phase difference arises from the inversion of electron Phase Space Density (PSD) gradient, which in turn is caused by the drift motion of the substorm injected electrons. This PSD gradient adjusts the characteristic particle signatures in the drift-resonance theory, which indicates a coupling effect between the magnetotail and the radiation belt and helps to better understand the wave-particle interaction in the magnetosphere.

Auroral Kilometric Radiation (AKR) is a strong terrestrial radio emission and dominates at higher latitudes because of reflection in vicinities of the source cavity and plasmapause. Recently, Van Allen Probes have observed occurrences of AKR emission in the equatorial region of Earth's radiation belts but its origin still remains an open question. Equatorial AKR can produce efficient acceleration of radiation belt electrons and is a risk to space weather. Xiao *et al.* [81] report high- resolution observations during two small storm periods 4–6 April and 18–20 May 2013 and show, using a 3-D ray tracing simulation, that AKR can propagate downward all the way into the equatorial plane in the radiation belts under appropriate conditions. The simulated results can successfully explain the observed AKR's spatial distribution and frequency range, and the current results have a wide application to all other magnetized astrophysical objects in the universe.

The two classes of whistler mode waves (chorus and hiss) play different roles in the dynamics of radiation belt energetic electrons. Chorus can efficiently accelerate energetic electrons, and hiss is responsible for the loss of energetic electrons. Previous studies have proposed that chorus is the source of plasmaspheric hiss, but this still requires an observational confirmation because the previously observed chorus and hiss emissions were not in the same frequency range in the same time. Zhou *et al.* [82] report simultaneous observations form Van Allen Probes that chorus and hiss emissions occurred in the same range ~300–1500 Hz with the peak wave power density about 10^{-5} nT^2/Hz during a weak storm on 3 July 2014. Chorus emissions propagate in a broad region outside the plasmapause. Meanwhile, hiss emissions are confined inside the plasmasphere, with a higher intensity and a broader area at a lower frequency. A sum of bi-Maxwellian distribution is used to model the observed anisotropic electron distributions and to evaluate the instability of waves. A three-dimensional ray tracing simulation shows that a portion of chorus emission outside the plasmasphere can propagate into the plasmasphere and evolve into plasmaspheric hiss. Moreover, hiss waves below 1 kHz are more intense and propagate over a broader area than those above 1 kHz, consistent with the observation. The current results can explain distributions of the observed hiss emission and provide a further support for the mechanism of evolution of chorus into hiss emissions.

Yang *et al.* [83] study the field-aligned propagating magnetospheric chorus wave instability using a fully relativistic wave growth formula, the previously developed relativistic Kappa-Type (KT) distribution and the regular Kappa distribution of energetic electrons. They demonstrate that the peak growth rate using the nonrelativistic Kappa simulation is higher than that using either the relativistic KT or the Kappa simulation at/above 100 keV, because the significant relativistic effect yields a reduction in the relativistic anisotropy. The relativistic anisotropy A_{rel} basically decreases as the thermal parameter θ^2 increases, allowing the peak growth by relativistic KT or Kappa distribution to stay at the lower frequency region. The growth rates tend to increase with the loss-cone parameter l because the overall anisotropy increases. Moreover, at high energy ~1.0 MeV, both the growth rate and the upper cutoff frequency become smaller as *l* increases for the relativistic KT calculation because the significant relativistic effect reduces both the resonant anisotropy and the number of the hot electrons, which is in contrast to the relativistic and nonrelativistic Kappa distribution calculations because the less relativistic or non-relativistic effect enhances the resonant anisotropy as l increases. The above results can be applied to the whistler-mode wave instability in the outer radiation belts of the Earth, the Jovian inner magnetosphere and other astrophysical plasmas where relativistic electrons often exist.

Van Allen radiation belt electrons exhibit complex dynamics during geomagnetical active periods. Investigation of electron Pitch Angle Distributions (PADs) can provide important information on the dominant physical mechanisms controlling radiation belt behaviors. Here they report a storm time radiation belt event where energetic electron PADs changed from butterfly distributions to normal or flattop distributions within several hours. Van Allen Probes observations showed that the flattening of butterfly PADs was closely related to the occurrence of whistler-mode chorus waves. Two-dimensional quasi-linear STEERB simulations demonstrate that the observed chorus can resonantly accelerate the near-equatorially trapped electrons and rapidly flatten the corresponding electron butterfly PADs. Yang *et al.* [84] provide a new insight on how chorus waves affect the dynamic evolution of radiation belt electrons.

Frequency distribution is a vital factor in determining the contribution of whistler mode chorus to radiation belt electron dynamics. Chorus is usually considered to occur in the frequency range 0.1–0.8 f_{ce_eq} (with the equatorial electron gyro frequency f_{ce_eq}. Gao *et al.* [85] report an event of intense low-frequency chorus with nearly half of wave power distributed below 0.1 f_{ce_eq} observed by Van Allen Probe A on 27 August 2014. This emission propagated quasi-parallel to the magnetic field and exhibited hiss-like signatures most of the time. The low-frequency chorus can produce the rapid loss of low-energy (approximate to 0.1 MeV) electrons, different from the normal chorus. For high-energy (0.5 MeV) electrons, the low-frequency chorus

Recent studies have shown that chorus can efficiently accelerate the outer radiation belt electrons to relativistic energies. Chorus, previously often observed above 0.1 equatorial electron gyro frequency f_{ce}, was generated by energetic electrons originating from Earth's plasma sheet. Chorus below 0.1 f_{ce} has seldom been reported until the recent data from Van Allen Probes, but its origin has not been revealed so far. Because electron resonant energy can approach the relativistic level at extremely low frequency, relativistic effects should be considered in the formula for whistler mode wave growth rate. Xiao *et al.* [86] report high-resolution observations during the 14 October 2014 small storm and firstly demonstrate, using a fully relativistic simulation, that electrons with the high-energy tail population and relativistic pitch angle anisotropy can provide free energy sufficient for generating chorus below 0.1 f_{ce}. The simulated wave growth displays a very similar pattern to the observations. The current results can be applied to Jupiter, Saturn, and other magnetized planet.

Electrostatic Electron Cyclotron Harmonic (ECH) waves generated by the electron loss cone distribution can produce efficient scattering loss of plasma sheet electrons, which has a significant effect on the dynamics in the outer magnetosphere. Here they report two ECH emission events around the same location $L\approx5.7$–5.8, MLT≈12 from Van Allen Probes on 11 February (event A) and 9 January 2014 (event B), respectively. The spectrum of ECH waves was centered at the lower half of the harmonic bands during event A, but the upper half during event B. The observed electron phase space density in both events is fitted by the subtracted bi-Maxwellian distribution, and the fitting functions are used to evaluate the local growth rates of ECH waves based on a linear theory for homogeneous plasmas. ECH waves are excited by the loss cone instability of 50 eV–1 keV electrons in the lower half of harmonic bands in the low-density plasmasphere in event A, and 1–10 keV electrons in the upper half of harmonic bands in a relatively high-density region in event B. Zhou *et al.,* [87] successfully explain observations and provide a first direct evidence on how ECH waves are generated in the lower and upper half of harmonic frequency bands.

Energetic (hundreds of keV) electrons in the radiation belt slot region have been found to exhibit the butterfly pitch angle distributions. Resonant interactions with magnetosonic and whistler-mode waves are two potential mechanisms for the formation of these peculiar distributions. A statistical study is performed of energetic electron pitch angle distribution characteristics measured by Van Allen Probes in the slot region during a 3 year period from May 2013 to May 2016. The results show that electron butterfly distributions are closely related to magnetosonic waves rather than to whistler-mode waves. Both electron butterfly distributions and magnetosonic waves occur more frequently at the geomagnetically active times than at the quiet times. In a statistical sense, more distinct butterfly distributions usually correspond to magnetosonic waves with larger amplitudes and vice versa. The averaged magnetosonic wave amplitude is less than 5 pT in the case of normal and flat-top distributions with a butterfly index BI=1 but reaches ~50–95 pT in the case of distinct butterfly distributions with BI>1.3. For magnetosonic waves with amplitudes >50 pT, the occurrence rate of butterfly distribution is above 80%. Yang *et al.* [88] suggests that energetic electron butterfly distributions in the slot region are primarily caused by magnetosonic waves.

Whistler-mode chorus plays an important role in the radiation belt electron dynamics. In the frequency-time spectrogram, chorus often appears as a hiss-like band and/or a series of short-lived (up to similar to 1 s) discrete elements. Here they present some rarely reported Chorus Emissions With long-lived (up to 25 s) oscillating tones observed by the Van Allen Probes in the dayside (MLT similar to 9–14) mid latitude (|MLAT|>15°) region. An oscillating tone can behave either regularly or irregularly and can even transform into a nearly constant tone (with a relatively narrow frequency sweep range). Gao *et al.* [66] suggest that these highly coherent oscillating tones were generated naturally rather than being related to some artificial VLF transmitters. Possible scenarios for the generation of the oscillating tone chorus are as follows: (1) being nonlinearly triggered by the accompanying hiss-like bands or (2) being caused by the modulation of the wave source. The details of the generation and evolution of such a long-lived oscillating tone chorus need to be investigated both theoretically and experimentally in the future.

Saturation properties of parallel propagating broadband whistler mode waves are investigated using quasilinear theory. By assuming that the electron distribution stays bi-Maxwellian, they combine the previously obtained energy equation of quasilinear theory with wave equation to self-consistently model the excitation of broadband whistler waves. The resulting evolution profile of wave intensity, spectrum, and electron temperature are consistent with those from Particle-In-Cell (PIC) simulations. Tao *et al.* [89] obtain the inverse relation between the saturation temperature anisotropy (A) and parallel plasma beta ($\beta_\parallel$) directly from quasilinear theory. Our A-$\beta_\parallel$ relation agrees very well with previous results from observation and PIC simulation. They also demonstrate that it might be possible to predict the wave amplitude from the initial maximum linear growth rate alone and show that the peak frequency and spectrum width are well-defined functions of the final $\beta_{\parallel}$ at saturation, but not of the initial $\beta_{\parallel}$.

Recently, the generation of rising-tone chorus has been implemented with one-dimensional (1-D) Particle-In-Cell (PIC) simulations in an inhomogeneous background magnetic field, where both the propagation of waves and motion of electrons are simply forced to be parallel to the background magnetic field. Ke *et al.* [90] have developed a two-dimensional (2-D) general curvilinear PIC simulation code, and successfully reproduced rising-tone chorus waves excited from an anisotropic electron distribution in a 2-D mirror field. Our simulation results show that whistler waves are mainly generated around the magnetic equator, and continuously gain growth during their propagation toward higher-latitude regions. The rising-tone chorus waves are formed off the magnetic equator, which propagate quasi-parallel to the background magnetic field with the wave normal angle smaller than 25°. Due to the propagating effect, the wave normal angle of chorus waves is increasing during their propagation toward higher-latitude regions along an enough curved field line. The chirping rate of chorus waves are found to be larger along a field line with a smaller curvature.

Nonlinear physics related to whistler-mode waves in the Earth's magnetosphere are now becoming a hot topic. Based on THEMIS waveform data, Gao *et al*.[91] report several interesting whistler-mode wave events, where the upper band whistler-mode waves are believed to be generated through the nonlinear wave-wave coupling between two lower-band waves. This is the first report on resonant interactions between whistler-mode waves in the Earth's magnetosphere. In these events, the two lower-band whistler-mode waves are observed to have oppositely propagating directions, while the generated upper-band wave has the same propagating direction as the lower-band wave with the relatively higher frequency. Moreover, the wave normal angle of the excited upper-band wave is usually larger than those of two lower-band whistler-mode waves. Gao *et al.* [91] reveals the large diversity of the evolution of whistler-mode waves in the Earth's magnetosphere.

Sun *et al.* [92] perform a 1-D Particle-In-Cell (PIC) simulation model consisting of three species, cold electrons, cold ions and energetic ion ring, to investigate spectral structures of magnetosonic waves excited by ring distribution protons in the Earth's magnetosphere, and dynamics of charged particles during the excitation of magnetosonic waves. As the wave normal angle decreases, the spectral range of excited magnetosonic waves becomes broader with upper frequency limit extending beyond the lower hybrid resonant frequency, and the discrete spectra tends to merge into a continuous one. This dependence on wave normal angle is consistent with the linear theory. The effects of magnetosonic waves on the background cold plasma populations also vary with wave normal angle. For exactly perpendicular magnetosonic waves (parallel wave number=0), there is no energization in the parallel direction for both background cold protons and electrons due to the negligible fluctuating electric field component in the parallel direction. In contrast, the perpendicular energization of background plasmas is rather significant, which is due to the coupling with generated magnetosonic wave fields in the perpendicular direction. For magnetosonic waves with a finite, there exists a non-negligible parallel fluctuating electric field, leading to a significant and rapid energization in the parallel direction for cold electrons. These cold electrons can also be efficiently energized in the perpendicular direction due to the interaction with the magnetosonic wave fields in the perpendicular direction. However, cold protons can be only heated in the perpendicular direction, which is likely caused by the higher-order resonances with magnetosonic waves. The potential impacts of magnetosonic waves on the energization of the background cold plasmas in the Earth's inner magnetosphere are also discussed in this paper.

Multiband chorus waves, where the frequency of upper band chorus is about twice that of lower band chorus, have recently been reported based on THMEIS observations. The generation of multiband chorus waves is attributed to the mechanism of lower band cascade, where upper band chorus is excited via the nonlinear coupling process between lower band chorus and the associated density mode with the frequency equal to that of lower band chorus. In this letter, with a one-dimensional (1-D) Particle-In-Cell (PIC) simulation model, Gao *et al.* [72] have successfully reproduced multiband chorus waves. During the simulation, the significant density fluctuation is driven by the fluctuating electric field along the wave vector of the pump wave (lower band chorus), which can be directly observed in this self-consistent plasma system. Then, the second harmonic of the pump whistler-mode wave (upper band chorus) is generated. After quantitatively analyzing resonant conditions among wave numbers, they can confirm that the generation is caused due to the coupling between the pump wave and the density fluctuation along its wave vector. The third harmonic can also be excited through lower band cascade if the pump whistler-mode wave has a sufficiently large amplitude. Our simulation results not only provide a theoretical support to the mechanism of lower band cascade to generate multiband chorus, but also propose a new pattern of evolution for whistler-mode waves in the Earth's magnetosphere.

By using one-dimensional (1-D) PIC simulations Ke *et al.* [93] investigate the parametric decay of a parallel propagating monochromatic whistler wave with various wave frequencies and amplitudes. The pump whistler wave can decay into a backscattered daughter whistler wave and an ion acoustic wave, and the decay instability grows more rapidly with the increase of the frequency or amplitude. When the frequency or amplitude is sufficiently large, a multiple decay process may occur, where the daughter whistler wave undergoes a secondary decay into an ion acoustic wave and a forward propagating whistler wave. They also find that during the parametric decay a considerable part of protons can be accelerated along the background magnetic field by the enhanced ion acoustic wave through the Landau resonance. The implication of the parametric decay to the evolution of whistler waves in Earth's magnetosphere is also discussed in the paper.

The duration of chorus elements is an important parameter to understand chorus excitation and to quantify the effects of nonlinear wave-particle interactions on energetic electron dynamics. In this work, they analyze the duration of rising tone chorus elements statistically using Van Allen Probes data. Teng *et al.* [94] present the distribution of chorus element duration (τ) as a function of Magnetic Local Time (MLT) and the geomagnetic activity level characterized by Auroral Electrojet (*AE*) index. They show that the typical value of τ for nightside and dawnside is about 0.12 s, smaller than that for dayside and duskside by about a factor of 2 to 4. Using a previously developed hybrid code, DAWN, they suggest that the background magnetic field inhomogeneity might be an important factor in controlling the chorus element duration. They also report that τ is larger during quiet times and shorter during moderate and active periods; this result is consistent with the MLT dependence of τ and the occurrence pattern of chorus waves at different levels of geomagnetic activity. Teng *et al.* [94] then investigate the correlation between τ and the frequency chirping rate (Γ). They show that, from observation, τ scales with Γ as $\tau \propto \Gamma-1.1$, suggesting that statistically the frequency range of chorus elements ($\tau\Gamma$) should be roughly the same for different elements. These findings should be useful to the further development of a theoretical model of chorus excitation and to the quantification of nonlinear wave- particle interactions on energetic electron dynamics.

The evolution of the electron phase space structures during excitation of a triggered emission is investigated using the nonlinear δf method. Previous studies suggested that the dynamics of phase space structures due to nonlinear wave particle interactions is critical to the excitation of triggered emissions with frequency chirping. Tao *et al.* [95] introduce the use of the nonlinear δf method to simulate triggered emissions. Compared with full-f particle-in-cell method, the nonlinear δf method significantly reduces numerical noise, therefore making the phase space structures more identifiable. Specific to the simulation of triggered emissions, the nonlinear δf method also does not show numerical distortion of the distribution function due to reflecting particle boundary conditions. Using the nonlinear δf method, they show that during the main portion of the chirping element, the phase space structure roughly maintains a shape so that the resonant island moves a distance in phase space that is on the same order as its width during one phase space bounce period of deeply trapped particles, supporting that the interaction is non-adiabatic. They also demonstrate the disappearance of the phase space structure near the end of the chirping. It is suggested that the nonlinear δf method could be very useful for the study of excitation of triggered emissions and to understand the mechanism of frequency chirping.

Nonlinear wave-particle interaction during chorus wave generation was assumed to be in the adiabatic regime in previous studies, i.e., the particle phase-space trapping timescale (τ_{tr}) is considered to be much smaller than the nonlinear dynamics timescale τ_{NL}. In this work, Tao *et al.* [96] use particle-in-cell simulations to demonstrate that $\tau_{tr} \sim \tau_{NL}$, *i.e.*, the interaction regime during chorus generation is in the nonadiabatic regime. The timescale for nonlinear evolution of resonant particle phase-space structures is determined by making the time-averaged power exchange plot, which clearly demonstrates that particles with pitch angle near 80° make the most significant contribution to wave growth. The phase-space trapping timescale is also comparable to the amplitude modulation timescale of chorus, suggesting that chorus subpackets are formed because of the self-consistent evolution of resonant particle phase-space structures and spatiotemporal features of the fluctuation spectrum.

Chorus waves are intense coherent whistler mode waves with frequency chirping which play a dual role in both loss and acceleration of radiation belt electrons in the Earth's magnetosphere. Although the generation of parallel chorus waves has been extensively studied by means of theory, simulations, and observations, the generation mechanism of very oblique chorus waves still remains a mystery. Gao *et al.* [97] have analyzed hundreds of very oblique discrete (rising or falling tone) lower band chorus events collected from 7 years of Time History of Events and Macroscale Interactions during Substorms (THEMIS) waveform data to investigate their potential generation mechanisms. Comparisons between wave normal angles directly measured onboard THEMIS in the dawn-day sector at L=5–9, and inferred from theoretical models on the basis of measured wave characteristics (frequency sweep rate, mean frequency, and amplitude) show that these very oblique waves are more commonly generated through cyclotron resonance with anisotropic electron streams. However, a second generation mechanism via Landau resonance with low-energy electron beams seems to be also operating on the nightside at L<6.7 and at all local times at L>8.5. Moreover, very oblique lower band chorus waves with large frequency chirping rates or small magnetic field amplitudes are more likely excited via cyclotron resonance, while waves with small frequency chirping rates or large magnetic field amplitudes are preferentially generated through Landau resonance. This comprehensive statistical study provides interesting insight into the possible generation mechanisms of very oblique lower band chorus waves in the Earth's magnetosphere.

Chorus waves are intense electromagnetic whistler-mode emissions in the magnetosphere, typically falling into two distinct frequency bands: a lower band (0.1–0.5f_{ce}) and an upper band (0.5–0.8f_{ce}) with a power gap at about 0.5f_{ce}. With the THEMIS satellite, Gao *et al.* [98] observed two special chorus events, which are called as multi-band chorus because upper band chorus is located at harmonics of lower band chorus. They propose a new potential generation mechanism for multi-band chorus, which is called as lower band cascade. In this scenario, a density mode with a frequency equal to that of lower band chorus is caused by the ponderomotive effect (inhomogeneity of the electric amplitude) along the wave vector, and then upper band chorus with the frequency twice that of lower band chorus is generated through wave-wave couplings between lower band chorus and the density mode. The mechanism provides a new insight into the evolution of whistler-mode chorus in the Earth's magnetosphere.

Ion Bernstein modes, also known as magnetosonic waves in the magnetospheric community, are considered to play an important role in radiation belt electron acceleration. The detailed properties of perpendicular magnetosonic waves excited in the inner magnetosphere by a tenuous proton ring distribution are investigated in a two series paper with a combination of the linear theory and one-dimensional (1-D) Particle-In-Cell (PIC) simulations. Sun *et al.* [99] study the properties of the excited magnetosonic waves under different plasma conditions with the linear theory. When the proton to electron mass ratio or the ratio of the light speed to the Alfven speed is small, the excited magnetosonic waves are prone to having a discrete spectrum with only several wave modes. With the increase of the proton to electron mass ratio or the ratio of the light speed to the Alfven speed, the lower hybrid frequency also increases, which leads to the increase of both the number and frequency of the excited wave modes. Meanwhile, the growth rate of these wave modes also increases. When the proton to electron mass ratio or the ratio of the light speed to the Alfven speed is sufficiently large, the spectrum of the excited magnetic waves becomes continuous due to the overlapping of the adjacent wave modes. The increase of the density of the protons with the ring distribution can also result in the increase of the growth rate, which may also change the discrete spectrum of the excited waves to a continuous one, while the increase of the ring velocity of the tenuous proton ring distribution leads to a broader spectrum, but with a smaller growth rate.

Sun *et al.* [100] perform one-dimensional particle-in-cell simulations to investigate the properties of perpendicular magnetosonic waves in a plasma system consisting of three components: cold electrons, cold protons, and tenuous ring distribution protons, where the waves are excited by the tenuous proton ring distribution. Consistent with the linear theory, the spectra of excited magnetosonic waves can change from discrete to continuous due to the overlapping of adjacent unstable wave modes. The increase of the proton to electron mass ratio, the ratio of the light speed to the Alfven speed, or the concentration of protons with a ring distribution tends to result in a continuous spectrum of magnetosonic waves, while the increase of the ring velocity of the tenuous proton ring distribution leads to a broader one, but with a discrete structure. Moreover, the energization of both cold electrons and protons, and the scattering of ring distribution protons due to the excited magnetosonic waves are also observed in our simulations, which cannot be predicted by the linear theory. Besides, a thermalized proton ring distribution may lead to the further excitation of several lower discrete harmonics with their frequencies about several proton gyro frequencies.

Theoretical bounce resonance diffusion coefficient for waves generated near the equatorial plane with arbitrary wave normal angle distributions is derived. Previous studies either assumed waves to cover the whole bounce trajectory or to have only one wave normal angle for a given frequency. Tao and Li [101] theoretically derive a new bounce resonance diffusion coefficient without these limitations. They demonstrate that the pitch angle diffusion from bounce resonance is significant for near-equatorially mirroring particles using a published magnetosonic wave model. Our results suggest that the bounce resonance diffusion by magnetosonic waves could be an important mechanism for pitch angle scattering of near-equatorially mirroring particles; therefore, it might be important to include bounce resonance with magnetosonic waves in global radiation belt modeling.

An efficient and positivity-preserving layer method is introduced to solve the radiation belt diffusion equation and is applied to study the bounce resonance interaction between relativistic electrons and magnetosonic waves. The layer method with linear interpolation, denoted by LM-L (layer method-linear), requires the use of a large number of grid points to ensure accurate solutions. Tao *et al.* [102] introduce a monotonicity- and positivity-preserving cubic interpolation method to be used with the Milstein-Tretyakov layer method. The resulting method, called LM-MC (Layer Method-Monotone Cubic), can be used to solve the radiation belt diffusion equation with a much smaller number of grid points than LM-L while still being able to preserve the positivity of the solution. They suggest that LM-MC can be used to study long-term dynamics of radiation belts. They then develop a 2-D LM-MC code and use it to investigate the bounce resonance diffusion of radiation belt electrons by magnetosonic waves. Using a previously published magnetosonic wave model, it is demonstrated that bounce resonance with magnetosonic waves is as important as gyro-resonance; both can cause several orders of magnitude increase of MeV electron fluxes within 1 day. They conclude that bounce resonance with magnetosonic waves should be taken into consideration together with gyro-resonance.

Hydrogen band ElectroMagnetic Ion Cyclotron (EMIC) waves have received much attention recently because they are found to frequently span larger spatial areas than the other band EMIC waves. Using test particle simulations, Wang *et al.* [103] study the nonlinear effects of hydrogen band EMIC waves on ring current H^+ ions. A dimensionless parameter R is used to characterize the competition between wave-induced and adiabatic motions. The results indicate that there are three regimes of wave-particle interactions for typical 35 keV H+ ions at L=5: diffusive (quasi-linear) behavior when $\alpha_{eq}\leqslant35°$ ($R\geqslant2.45$), the nonlinear phase trapping when $35°<\alpha_{eq}<50°$ ($0.75<R<2.45$), and both the nonlinear phase bunching and phase trapping when $\alpha_{eq}\geqslant50°$ ($R\leqslant0.75$). The phase trapping can transport H^+ ions toward large pitch angle, while the phase bunching has the opposite effect. The phase-trapped H^+ ions can be significantly accelerated (from 35 keV to over 500 keV) in about 4 min and thus contribute to the formation of high energy components of ring current ions. It is suggested that the effect of hydrogen band EMIC waves is not ignorable in the nonlinear aceleration and resonance scattering of ring current H^+ ions.

During geomagnetically active times, O^+ ions from the ionosphere become an important ion component in the ring current, which changes the dispersion relations and significantly enlarges the growth rate of oxygen band EMIC waves. Motivated by a large number of oxygen band EMIC wave observations in the inner magnetosphere, Wang *et al.* [104] study the nonlinear motions of ring current O^+ ions caused by the cyclotron resonance with oxygen band EMIC waves. A dimensionless parameter R is used to characterize the competition between wave-induced and adiabatic motions. The numerical calculations based on gyroaveraged test particle equations are performed. For typical 20 keV O^+ ions at L=5, two kinds of nonlinear processes occur simultaneously when α_{eq}>59° (R<2.16): the phase trapping and phase bunching. The phase trapping tends to transport the O^+ ions away from the loss cone and reduce the overall loss rate estimated from the quasi- linear theory. Instead, phase bunching tends to increase the overall loss rate. The phase-trapped O^+ ions have chance to be accelerated drastically, reaching 750% of the initial energy. These O^+ ions move forward and backward alternatively along the field lines when they are bouncing back to the equator, forming a periodic energy variation which has not been reported before. The results suggest that the oxygen band EMIC waves, which appear frequently during storms, should be considered in the ring current dynamics in terms of nonlinear acceleration and resonance scattering of ring current particles.

Yuan *et al.* [105] report in situ observations by the Van Allen Probes mission that MagnetoSonic (MS) waves are clearly relevant to the background plasma number density. As the satellite moved across dense and tenuous plasma alternatively, MS waves occurred only in lower density region. As the observed protons with “ring” distributions provide free energy, local linear growth rates are calculated and show that magnetosonic waves can be locally excited in tenuous plasma. With variations of the background plasma density, the temporal variations of local wave growth rates calculated with the observed proton ring distributions show a remarkable agreement with those of the observed wave amplitude. Therefore, their paper provides a direct proof that background plasma densities can modulate the amplitudes of magnetosonic waves through controlling the wave growth rates.

During 04:45:00–08:15:00 UT on 13 September in 2015, Yu *et al.* [106] report a case of EMIC waves covering wide L shells (L=3.6–9.4) with observation of the Magnotospheric MultiScale 1 (MMS1). During the same time interval, EMIC waves observed by Van Allen Probes A (VAP-A) only occurred just outside the plasmapause. As the Van Allen Probes moved outside into a more tenuous plasma region, no intense waves were observed. Combined observations of MMS1 and VAP-A suggest that in the terrestrial magnetosphere, an appropriately dense background plasma would make contributions to the growth of EMIC waves in lower L shells, while the ion anisotropy, driven by magnetospheric compression, might play an important role in the excitation of EMIC waves in higher L shells. These EMIC waves are observed over wide L shells after three continuous magnetic storms, which suggests that these waves might obtain their free energy from those energetic ions injected during storm times. These EMIC waves should be included in radiation belt modeling, especially during continuous magnetic storms. Moreover, two-band structures separated in frequencies by local He^{2+} gyrofrequencies were observed in large L shells (L>~6), implying sufficiently rich solar wind origin He^{2+} likely in the outer ring current. It is suggested that multiband-structured EMIC waves can be used to trace the coupling between solar wind and the magnetosphere.

EMIC waves can precipitate the ring current ions and relativistic electrons and heat the cold electrons in the magnetosphere. This requires comprehensive knowledge of the occurrence and wave properties of EMIC waves. Wang *et al.* [107] use the data from one new mission, the Magnetospheric MultiScale (MMS) mission launched in March 2015, to investigate the occurrence and wave properties of H^+-band and He^+-band EMIC waves in the magnetosphere. Our statistical results show the following: (1) H^+-band EMIC waves mostly occur in the higher L-shells (L>5) while He^+-band EMIC waves are mostly observed in the lower L-shells (L<6). (2) The occurrence rate of H^+-band EMIC waves in the dayside is higher than that in the nightside. The highest peak of occurrence rate of H^+-band EMIC waves is in the postnoon sector (5–8 L-shells), and the secondary peak lies in the small area of the dawn sector. (3) The wave power spectral density peaks in the postnoon and predusk sectors, while the wave normal angles are largest in the dawn sector. (4) Linear and right-hand polarized H^+-band EMIC waves are mainly in the regions of peak occurrence, while linear polarized waves are seen to also dominate outside of the regions of peak occurrence. The highest occurrence rate of linear polarized He^+-band EMIC waves is observed in the dawn sector. They discussed the results and compared with previous findings.

With observations of Van Allen Probe A, Yu *et al.* [108] have found fine structured multiple-harmonic electromagnetic emissions at frequencies around the equatorial oxygen cyclotron harmonics are outside the core plasmasphere (L~5) off the magnetic equator (MLAT~–7.5°) during a magnetic storm. They find that the multiple-harmonic emissions have their PSD peaks at 2~8 equatorial oxygen gyro-harmonics (f~nf_{O+}, n=2~8) while the fundamental mode (n=1) is absent, implying that the harmonic waves are generated near the equator and propagate into the observation region. Additionally these electromagnetic emissions are linear polarized. Different from the equatorial noise emission propagating very obliquely, these emissions have moderate wave normal angles (about 40°~60°) which predominately become larger as the harmonic number increases. Considering their frequency and wave normal angle characteristics, it is suggested that these multiple-harmonic emissions might play an important role in the dynamic variation of radiation belt electrons.

Based on the linear theory, Yu *et al.* [109] have derived the detailed growth rate expression of plasma waves for hot ions with ring velocity distributions, which can be directly used to study the wave growth with satellite data. Using linear growth rate calculations with simple magnetic field and background plasma density models, the roles of five parameters (N_e, E_r, T_{perp} and T_{para}) playing in the excitation of O^+ band EMIC waves driven by hot H+ with ring velocity distributions are investigated. Their calculations demonstrate that ring distributions with sufficiently large ring velocity V_r, small perpendicular thermal spread and appropriate parallel thermal spread $V_{||}$ could enhance the wave growth of oblique O^+ band EMIC waves. Moreover, their results show that O^+ band EMIC waves considered here are mainly unstable with large wave normal angles in a dense and rich O^+ background plasma, in consistent with the statistical characteristics of O^+ band EMIC waves previously observed by satellites. Therefore, it is indicated that hot H+ with ring velocity distributions should play an important role in the excitation of O^+ band EMIC waves, as a necessary and useful supplement to ring current ions with temperature-anisotropy bi-Maxwellian distributions.

Using the Polar Orbiting Environment Satellites (POES) in the year 2011, Li *et al.* [110] present global distributions of Energetic Electron Precipitation (EEP) events that may be driven by lower band chorus waves. Since the footprint of plasmapause in the ionospheric height can basically be equal to midlatitude trough minimum, it can be identified through the global total electron content map. Then they distinguish events perhaps driven by chorus waves outside the plasmapause or those driven by hiss waves inside the plasmapause. Based on the simultaneous observations of EEP in the E1 0° (>30 keV) and E2 0° (>100 keV) channels from POES satellites, a total of 4455 potentially chorus-driven events are identified. The potentially chorus-driven events are mainly distributed from midnight to noon which is similar to the distribution of lower band chorus waves. As the level of geomagnetic substorm activity increases, the occurrence rate is higher, which could be due to excitation of chorus waves associated with substorm electron injection. During higher level of substorm, a large number of events occur in lower L shells. Besides, since the magnetosphere on the dayside is compressed and strong chorus waves are limited to the region where the ratio between the plasma frequency and electron gyro frequency is less than 5, under the strong substorm, the events on the nightside are confined to lower L shells due to smaller electron gyro frequencies relative to those on the dayside. The occurrence rate of the events on the dayside also increases with enhancement of solar wind dynamic pressure, which suggests that the solar wind dynamic pressure can contribute to the excitation of events on the dayside. The statistics of potentially chorus-driven events are helpful to analyze the distribution of lower band chorus waves and their contributions to the loss of energetic electrons in the inner magnetosphere.

With observations of the Van Allen Probe B, Yuan *et al.* [111] report in situ evidence of the modification of the parallel propagating EMIC waves by heated He^+ ions. In the outer boundary of the plasmasphere, accompanied with the He^+ ion heating, the frequency bands of H^+ and He^+ for EMIC waves merged into each other, leading to the disappearance of a usual stop band between the gyro frequency of He^+ ions (Ω_{He^+}) and the H^+ cut-off frequency (ω_{H^+co}) in the cold plasma. Moreover, the dispersion relation for EMIC waves theoretically calculated with the observed plasma parameters also demonstrates that EMIC waves can indeed parallel propagate across Ω_{He^+}. Therefore, their paper provides an in situ evidence of the modification of the parallel propagation of EMIC waves by heated He^+ ions.

Utilizing the data from magnetometer instrument of Electric and Magnetic Field Instrument Suite and Integrated Science (EMFISIS) suite on board Van Allen Probe A, Wang *et al.* [112] have investigated the occurrences of EMIC waves during geomagnetic storms and nonstorm periods. The 270 EMIC wave events and 76 geomagnetic storms were identified during the period under research, from 8 September 2012 to 30 April 2014, when the apogee of Van Allen Probe A covered all the Magnetic Local Time (MLT) sectors. Fifty of the 76 storms observed 124 EMIC wave events, of which 80 are found in the recovery phase, more than those observed in the main phase. Majority EMIC wave events (~54%) were observed during the nonstorm periods. Occurrence rates of EMIC waves as a function of L and MLT during different geomagnetic conditions are also examined, whose peaks in main phase are higher than those in recovery phase. However, occurrences of EMIC waves in recovery phase distribute more uniformly than those do in main phase. Evolution of the distribution characteristics of EMIC waves respect to L and MLT in different geomagnetic phases is investigated, consistent with that of the plasmasphere during geomagnetic storms, implying that the cold and dense plasma in the plasmasphere or plasmaspheric plume play a significant role in the generation of EMIC waves in the inner magnetosphere. Few EMIC waves in the dayside sector during the pre-onset periods are observed, suggesting that the effect of solar wind dynamic pressure on the generation of EMIC waves in the inner magnetosphere in those periods is not so significant as expected.

Xiong *et al.* [113] have reported in situ observations by the Cluster spacecraft of energetic ions scattered into the loss cone during the inbound pass from the plasma sheet into the plasmasphere. During the inbound pass of the plasma sheet, Cluster observed the isotropy ratio of energetic ions to gradually decrease from unity and the isotropic boundary extended to lower L value for higher-energy ions, implying that the field line curvature scattering mechanism is responsible for the scattered ions into the loss cone from the plasma sheet. In the outer boundary of a plasmasphere plume, Cluster 3 observed the increase of the isotropy ratio of energetic ions accompanied by enhancements of Pc2 waves with frequencies between the He^+ ion gyro frequency and O^+ ion gyro frequency estimated in the equatorial plane. Those Pc2 waves were left-hand circularly polarized and identified as EMIC waves. Using the observed parameters, the calculations of the pitch angle diffusion coefficients for ring current protons demonstrate that EMIC waves could be responsible for the ions scattering and loss-cone filling. Their observations provide in situ evidence of energetic ion loss in the plasma sheet and the plasmasphere plume. Their results suggest that energetic ions scattering into the loss cone in the central plasma sheet and the outer boundary of the plasmaspheric plume are attributed to the field line curvature scattering mechanism and EMIC wave scattering mechanism, respectively.

Theory predicts that the first adiabatic invariant of a charged particle may be violated in a region of highly curved field lines, leading to significant pitch angle scattering for particles whose gyroradius are comparable to the radius of the magnetic field line curvature. This scattering generates more isotropic particle distribution functions, with important impacts on the presence or absence of plasma instabilities. Using magnetic curvature analysis based on multipoint Cluster spacecraft observations, Zhang *et al.* [114] presents the first investigation of magnetic curvature in the vicinity of an ion diffusion region where reconnected field lines are highly curved. Electrons at energies>8 keV show a clear pitch angle ordering between bidirectional and trapped distribution in surrounding regions, while they show that in the more central part of the ion diffusion region electrons above such energies become isotropic. By contrast, colder electrons (~1 keV) retain their bidirectional character throughout the diffusion regions. The calculated adiabatic parameter K2 for these electrons is in agreement with theory. This study provides the first observational evidence for particle pitch angle scattering due to magnetic field lines with well characterized curvature in a space plasma.

Several Extremely Low-Frequency (ELF)/Very Low-Frequency (VLF) wave generation experiments have been performed successfully at High-Frequency Active Auroral Research Program (HAARP) heating facility and the artificial ELF/VLF signals can leak into the outer radiation belt and contribute to resonant interactions with energetic electrons. Based on the artificial wave properties revealed by many of in-situ observations, Chang *et al.* [115] implement test particle simulations to evaluate the effects of energetic electron resonant scattering driven by the HAARP-induced ELF/VLF waves. The results indicate that for both single-frequency/monotonic wave and multi-frequency/broadband waves, the behavior of each electron is stochastic while the averaged diffusion effect exhibits temporal linearity in the wave-particle interaction process. The computed local diffusion coefficients show that, the local pitch-angle scattering due to HARRP-induced single-frequency ELF/VLF whistlers with an amplitude of ~10 pT can be intense near the loss cone with a rate of $\sim 10^{-2}$ rad^2 s^{-1}, suggesting the feasibility of HAARP-induced ELF/VLF waves for removal of outer radiation belt energetic electrons. In contrast, the energy diffusion of energetic electrons is relatively weak, which confirms that pitch-angle scattering by artificial ELF/VLF waves can dominantly lead to the precipitation of energetic electrons. Moreover, diffusion rates of the discrete, broadband waves, with the same amplitude of each discrete frequency as the monotonic waves, can be much larger, which suggests that it is feasible to trigger a reasonable broadband wave instead of the monotonic wave to achieve better performance of controlled precipitation of energetic electrons. Moreover, our test particle scattering simulation show good agreement with the predictions of the quasi-linear theory, confirming that both methods are applied to evaluate the effects of resonant interactions between radiation belt electrons and artificially generated discrete ELF/VLF waves.

A statistical study of ring current - energy proton Pitch Angle Distributions (PADs) in Earth's inner magnetosphere is reported by Shi *et al.* [116]. The data are from the Radiation Belt Storm Probes Ion Composition Experiment (RBSPICE) on board the Van Allen Probe B spacecraft from 1 January 2013 to 15 April 2015. By fitting the data to the functional form sin nα, where α is the proton pitch angle, they examine proton PADs at the energies 50, 100, 180, 328, and 488 keV in the *L* shell range from $L=2.5$ to $L=6$. Three PAD types are classified: trapped (90° peaked), butterfly, and isotropic. The proton PAD dependence on the particle energy, Magnetic Local Time (MLT), *L* shell, and geomagnetic activity are analyzed in detail. They shows a strong dependence of the proton PADs on MLT. On the nightside, the n values outside the plasmapause are clearly lower than those inside the plasmapause. At higher energies and during intense magnetic activity, nightside butterfly PADs can be observed at L shells down to the vicinity of the plasmapause. The averaged n values on the dayside are larger than on the nightside. A maximum of the averaged n values occurs around $L=4.5$ in the postnoon sector (12:00–16:00 MLT). The averaged n values show a dawn-dusk asymmetry with lower values on the dawnside at high L shells, which is consistent with previous studies of butterfly PADs. The MLT dependence of the proton PADs becomes more distinct with increasing particle energy. These features suggest that drift shell splitting coupled with a radial flux gradient play an important role in the formation of PADs, particularly at $L>\sim 4.5$.

Since EMIC waves in the terrestrial magnetosphere play a crucial role in the dynamic losses of relativistic electrons and energetic protons and in the ion heating, it is important to pursue a comprehensive understanding of the EMIC wave dispersion relation under realistic circumstances, which can shed significant light on the generation, amplification, and propagation of magnetospheric EMIC waves. The full kinetic linear dispersion relation is implemented in the present study to evaluate the linear growth of EMIC waves in a multi-ion (H^+, He^+, and O^+) magnetospheric plasma that also consists of hot ring current protons. Introduction of anisotropic hot protons strongly modifies the EMIC wave dispersion surface and can result in the simultaneous growth of H^+-, He^+-, and O^+-band EMIC emissions. Wang *et al.* [117] demonstrates that an increase in the hot proton concentration can produce the generation of H^+- and He^+-band EMIC waves with higher possibility. While the excitation of H^+-band emissions requires relatively larger temperature anisotropy of hot protons, He^+-band emissions are more likely to be triggered in the plasmasphere or plasmaspheric plume where the background plasma is denser. In addition, the generation of He^+-band waves is more sensitive to the variation of proton temperature than H^+-band waves. Increase of cold heavy ion (He^+ and O^+) density increases the H^+ cutoff frequency and therefore widens the frequency coverage of the stop band above the He^+ gyrofrequency, leading to a significant damping of H^+-band EMIC waves. In contrast, O^+-band EMIC waves characteristically exhibit the temporal growth much weaker than the other two bands, regardless of all considered variables, suggesting that O^+-band emissions occur at a rate much lower than H^+- and He^+-band emissions, which is consistent with the observations.

A new digital low-frequency receiver system has been developed at Wuhan University for sensitive reception of low-latitude broadband Extremely Low Frequency (ELF) and Very Low Frequency (VLF) radio waves originating from either natural or artificial sources. These low-frequency radio waves are useful for ionospheric remote sensing, geospace environment monitoring, and submarine communications. Chen *et al.* [118] present the principle and architecture of the system framework, including magnetic loop antenna design, low-noise analog front-end and digital receiver with data sampling and transmission. A new structure is adopted in the analog front end to provide high common-mode rejection and to reduce interference. On basis of Field Programmable Gate Array (FPGA) device and Universal Serial Bus (USB) architecture, the digital receiver is developed along with time keeping and synchronization module. The validity and feasibility of the self-developed ground-based ELF/VLF receiver system is evaluated by first results of experimental data that show the temporal variation of broadband ELF/VLF wave spectral intensity in Wuhan (30.54° N, 114.37° E). In addition to the acquisition of VLF transmitter signals at various frequencies, tweek atmospherics are also clearly captured to occur at multiple modes up to n=6.

Multiband EMIC waves can drive efficient scattering loss of radiation belt relativistic electrons. However, it is statistically uncommon to capture the three bands of EMIC waves concurrently. Utilizing data from the Electric and Magnetic Field Instrument Suite and Integrated Science magnetometer onboard Van Allen Probe A, He *et al.* [119] report the simultaneous presence of three (H^+, He+, and O+) emission bands in an EMIC wave event, which provides an opportunity to look into the combined scattering effect of all EMIC emissions and the relative roles of each band in diffusing radiation belt relativistic electrons under realistic circumstances. Their quantitative results, obtained by quasi-linear diffusion rate computations and 1-D pure pitch angle diffusion simulations, demonstrate that the combined resonant scattering by the simultaneous three-band EMIC waves is overall dominated by He^+ band wave diffusion, mainly due to its dominance over the wave power (the mean wave amplitudes are approximately 0.4 nT, 1.6 nT, and 0.15 nT for H+, He^+, and O^+ bands, respectively). Near the loss cone, while 2–3 MeV electrons undergo pitch angle scattering at a rate of the order of 10^{-6}–10^{-5} s^{-1}, 5–10 MeV electrons can be diffused more efficiently at a rate of the order of 10^{-3}–10^{-2} s^{-1}, which approaches the strong diffusion level and results in a moderately or heavily filled loss cone for the atmospheric loss. The corresponding electron loss timescales (i.e., lifetimes) vary from several days at the energies of ~2 MeV to less than 1 h at ~10 MeV. This case study indicates the leading contribution of He^+ band waves to radiation belt relativistic electron losses during the coexistence of three EMIC wave bands and suggests that the roles of different EMIC wave bands in the relativistic electron dynamics should be carefully incorporated in future modeling efforts.

Radiation belt electron flux dropouts are a kind of drastic variation in the Earth's magnetosphere, understanding of which is of both scientific and societal importance. Using electron flux data from a group of 14 satellites, Xiang *et al.* [120] report multi-satellite simultaneous observations of magnetopause and atmospheric losses of radiation belt electrons during an event of intense solar wind dynamic pressure pulse. When the pulse occurred, magnetopause and atmospheric loss could take effect concurrently contributing to the electron flux dropout. Losses through the magnetopause were observed to be efficient and significant at about L >5, owing to the magnetopause intrusion into L ~6 and outward radial diffusion associated with sharp negative gradient in electron phase space density. Losses to the atmosphere were directly identified from the precipitating electron flux observations, for which pitch angle scattering by plasma waves could be mainly responsible. While the convection and substorm injections strongly enhanced the energetic electron fluxes up to hundreds of keV, they could delay other than avoid the occurrence of electron flux dropout at these energies. It is demonstrated that the pulse-time radiation belt electron flux dropout depends strongly on the specific interplanetary and magnetospheric conditions and that losses through the magnetopause and to the atmosphere and enhancements of substorm injection play an essential role in combination, which should be incorporated as a whole into future simulations for comprehending the nature of radiation belt electron flux dropouts.

Gyro-averaged test particle simulations are implemented to quantitatively investigate interactions between linearly polarized magnetosonic waves (i.e., equatorial noises) and ring current protons inside and outside the plasmasphere at $L = 4.5$. For magnetosonic waves at the frequency of 33.3 Hz ($f_w/f_{cp} = 6.4$ at the magnetic equator, for $L = 4.5$), Fu *et al.* [121] found that wave-particle interactions at the resonance order corresponding to the lowest resonant proton energy (*i.e., N* = 6) are dominant. The interactions at other resonance orders make much less contribution. Near the equatorial loss cone at L = 4.5, magnetosonic waves produce strongest proton pitch angle diffusion at ~ 20 keV inside the plasmasphere and at ~ 100 keV outside the plasmasphere, respectively, reaching a rate above 10^{-6} s^{-1}. The corresponding energy diffusion dominates over pitch angle diffusion at high pitch angles; therefore, magnetosonic waves are likely to accelerate protons at a few keV inside the plasmasphere and at ~ 10 keV outside the plasmasphere. Due to the emission equatorial confinement, the effect of transit time scattering also occurs for interactions of magnetosonic waves with ring current protons and tends to be increasingly important outside the plasmasphere, which is consistent with previous studies on interactions of magnetosonic waves with radiation belt electrons.

This is a companion study to Liang et al. (2014) which reported a “reversed” energy - latitude dispersion pattern of ion precipitation in that the lower energy ion precipitation extends to lower latitudes than the higher-energy ion precipitation. EMIC waves in the Central Plasma Sheet (CPS) have been suggested to account for this reversed-type ion precipitation. To further investtigate the association, Cao *et al.* [122] perform a comprehensive study of pitch angle diffusion rates induced by EMIC wave and the resultant proton loss timescales at L=8–12 around the midnight. Comparing the proton scattering rates in the Earth's dipole field and a more realistic quiet time geomagnetic field constructed from the Tsyganenko 2001 (T01) model, They find that use of a realistic, non-dipolar magnetic field model not only decreases the minimum resonant energies of CPS protons but also considerably decreases the limit of strong diffusion and changes the proton pitch angle diffusion rates. Adoption of the T01 model increases EMIC wave diffusion rates at > ~ 60° equatorial pitch angles but decreases them at small equatorial pitch angles. Pitch angle scattering coefficients of 1–10 keV protons due to H^+ band EMIC waves can exceed the strong diffusion rate for both geomagnetic field models. While He^+ and O^+ band EMIC waves can only scatter tens of keV protons efficiently to cause a fully filled loss cone at $L > 10$, in the T01 magnetic field they can also cause efficient scattering of ~ keV protons in the strong diffusion limit at $L > 10$. The resultant proton loss timescales by EMIC waves with a nominal amplitude of 0.2 nT vary from a few hours to several days, depending on the wave band and L shell. Overall, the results demonstrate that H^+ band EMIC waves, once present, can act as a major contributor to the scattering loss of a few keV protons at lower L shells in the CPS, accounting for the reversed energy-latitude dispersion pattern of proton precipitation at low energies (~ keV) on the nightside. The pitch angle coverage for H^+ band EMIC wave resonant scattering strongly depends on proton energy, L shell, and field model. He+ and O^+ band EMIC waves tend to cause efficient scattering loss of protons at higher energies, thereby importantly contributing to the isotropic distribution of higher energy (> ~ 10 keV) protons at higher L shells on the nightside where the geomagnetic field line is highly stretched. Our results also suggest that scattering by H^+ band EMIC waves may significantly contribute to the formation of the reversed - type CPS proton precipitation on the dawnside where both the wave activity and occurrence probability is statistically high.

Using Van Allen Probes Relativistic Electron Proton Telescope (REPT) pitch angle resolved electron flux data from September 2012 to March 2015, Ni *et al.* [123] investigate in detail the global occurrence pattern of equatorial ($|\lambda| \leqslant 3°$) butterfly distribution of outer zone relativistic electrons and its potential correlation with the solar wind dynamic pressure. The statistical results demonstrate that these butterfly distributions occur with the highest occurrence rate ~ 80% at ~ 20–04 Magnetic Local Time (MLT) and L>~ 5.5 and with the second peak (>~ 50%) at ~ 11–15 MLT of lower L shells ~ 4.0. They can also extend to L=3.5 and to other MLT intervals but with the occurrence rates predominantly <~25%. It is further shown that outer zone relativistic electron butterfly distributions are likely to peak between 58° and 79° for L=4.0 and 5.0 and between 37° and 58° for L=6.0, regardless of the level of solar wind dynamic pressure. Relativistic electron butterfly distributions at L=4.0 also exhibit a pronounced day- night asymmetry in response to the P_{dyn} variations. Compared to the significant L shell and MLT dependence of the global occurrence pattern, outer zone relativistic electron butterfly distributions show much less but still discernable sensitivity to P_{dyn}, geomagnetic activity level, and electron energy, the full understanding of which requires future attempts of detailed simulations that combine and differentiate underlying physical mechanisms of the geomagnetic field asymmetry and scattering by various magnetospheric waves.

Using the electron flux measurements obtained from five satellites (GOES 15 and POES 15, 16, 18, and 19), Ni *et al.* [124] investigate the flux variations of radiation belt electrons during forty solar wind dynamic pressure pulses identified between September 2012 and December 2014. By utilizing the mean duration of the pressure pulses as the epoch timeline and stretching or compressing the time phases of individual events to normalize the duration by means of linear interpolation, they have performed normalized superposed epoch analysis to evaluate the dynamic responses of radiation belt energetic electrons corresponding to various groups of solar wind and magnetospheric conditions in association with solar wind dynamic pressure pulses. Our results indicate that by adopting the timeline normalization they can reproduce the typical response of the electron radiation belts to pressure pulses. Radiation belt electron fluxes exhibit large depletions right after the P_{dyn} peak during the periods of northward IMF B_z and are more likely to occur during the P_{dyn} pulse under southward IMF B_z conditions. For the pulse events with large negative values of (Dst)min, radiation belt electrons respond in a manner similar to those with southward IMF B_z, and the corresponding post-pulse recovery can extend to L ~ 3 and exceed the pre-pulse flux levels. Triggered by the solar wind pressure enhancements, deeper earthward magnetopause erosion provides favorable conditions for the prompt electron flux dropouts that extend down to L ~ 5, and the pressure pulses with longer duration tend to produce quicker and stronger electron flux decay. In addition, the events with high electron fluxes before the P_{dyn} pulse tend to experience more severe electron flux dropouts during the course of the pulse, while the largest rate of electron flux increase before and after the pulse occurs under the preconditioned low electron fluxes. These new results help us understand how electron fluxes respond to solar wind dynamic pressure pulses and how these responses depend on the solar wind and geomagnetic conditions and on the preconditions in the electron radiation belts.

The Earth's diffuse auroral precipitation provides the major source of energy input into the nightside upper atmosphere and acts as an essential linkage of the magnetosphere-ionosphere coupling. Resonant wave-particle interactions play a dominant role in the scattering of injected plasma sheet electrons, leading to the diffuse auroral precipitation. Ni *et al.* [125] review the recent advances in understanding the origin of the diffuse aurora and in quantifying the exact roles of various magnetospheric waves in producing the global distribution of diffuse auroral precipitation and its variability with the geomagnetic activity. Combined scattering by upper-and lower-band chorus accounts for the most intense inner magnetospheric electron diffuse auroral precipitation on the nightside. Dayside chorus can be responsible for the weaker dayside electron diffuse auroral precipitation. Pulsating auroras, the dynamic auroral structures embedded in the diffuse aurora, can be mainly caused by modulation of the excitation of lower band chorus due to macroscopic density variations in the magnetosphere. Electrostatic electron cyclotron harmonic waves are an important or even dominant cause for the nightside electron diffuse auroral precipitation beyond ~8 R_e and can also contribute to the occurrence of the pulsating aurora at high L-shells. Scattering by electromagnetic ion cyclotron waves could quite possibly be the leading candidate responsible for the ion precipitation (especially the reversed-type events of the energy-latitude dispersion) in the regions of the central plasma sheet and ring current. They conclude the review with a summary of current understanding, outstanding questions, and a number of suggestions for future research.

A new 3-D diffusion code using a recently published layer method has been developed to analyze radiation belt electron dynamics [12]. The code guarantees the positivity of the solution even when mixed diffusion terms are included. Unlike most of the previous codes, our 3-D code is developed directly in equatorial pitch angle (α_0), momentum (p), and L shell coordinates; this eliminates the need to transform back and forth between (α_0, p) coordinates and adiabatic invariant coordinates. Using (α_0, p, L) is also convenient for direct comparison with satellite data. The new code has been validated by various numerical tests, and they apply the 3-D code to model the rapid electron flux enhancement following the geomagnetic storm on 17 March 2013, which is one of the Geospace Environment Modeling Focus Group challenge events. An event-specific global chorus wave model, an AL-dependent statistical plasmaspheric hiss wave model, and a recently published radial diffusion coefficient formula from Time History of Events and Macroscale Interactions during Substorms (THEMIS) statistics are used. The simulation results show good agreement with satellite observations, in general, supporting the scenario that the rapid enhancement of radiation belt electron flux for this event results from an increased level of the seed population by radial diffusion, with subsequent acceleration by chorus waves. Wang *et al.* [12] prove that the layer method can be readily used to model global radiation belt dynamics in three dimensions.

MagnetoSonic (MS) waves have been found capable of creating radiation belt electron butterfly distributions in the inner magnetosphere. To investigate the physical nature of the interactions between radiation belt electrons and MS waves, and to explore a preferential condition for MS waves to scatter electrons efficiently, Lei *et al.* [126] performed a comprehensive parametric study of MS wave-electron interactions using test particle simulations. The diffusion coefficients simulated by varying the MS wave frequency show that the scattering effect of MS waves is frequency insensitive at low harmonics (f<20 f_{cp}), which has great implications on modeling the electron scattering caused by MS waves with harmonic structures. The electron scattering caused by MS waves is very sensitive to wave normal angles, and MS waves with off 90° wave normal angles scatter electrons more efficiently. By simulating the diffusion coefficients and the electron phase space density evolution at different L shells under different plasma environment circumstances, they find that MS waves can readily produce electron butterfly distributions in the inner part of the plasmasphere where the ratio of electron plasma to gyro frequency (f_{pe}/f_{ce}) is large, while they may essentially form a two-peak distribution outside the plasmapause and in the inner radiation belt where f_{pe}/f_{ce} is small.

To achieve a better understanding of the dominant loss mechanisms for the rapid dropouts of radiation belt electrons, three distinct radiation belt dropout events observed by Van Allen Probes are comprehensively investigated. For each event, observations of the pitch angle distribution of electron fluxes and EMIC waves are analyzed to determine the effects of atmospheric precipitation loss due to pitch angle scattering induced by EMIC waves. Last Closed Drift Shells (LCDS) and magnetopause standoff position are obtained to evaluate the effects of magnetopause shadowing loss. Evolution of electron Phase Space Density (PSD) versus L^* profiles and the μ and K (first and second adiabatic invariants) dependence of the electron PSD drops are calculated to further analyze the dominant loss mechanisms at different L^*. Xiang *et al.* [127] suggests that these radiation belt dropouts can be classified into distinct classes in terms of dominant loss mechanisms: magnetopause shadowing dominant, EMIC wave scattering dominant, and combination of both mechanisms. Different from previous understanding, our results show that magnetopause shadowing can deplete electrons at L^*<4, while EMIC waves can efficiently scatter electrons at L^*>4. Compared to the magnetopause standoff position, it is more reliable to use LCDS to evaluate the impact of magnetopause shadowing. The evolution of electron PSD versus L^* profile and the μ, K dependence of electron PSD drops can provide critical and credible clues regarding the mechanisms responsible for electron losses at different L^* over the outer radiation belt.

Using the particle data measured by Van Allen Probe A from October 2012 to March 2016, Tang *et al.* [128] investigate in detail the radiation belt seed population and its association with the relativistic electron dynamics during 74 geomagnetic storms. The period of the storm recovery phase was limited to 72 h. The statistical study shows that geomagnetic storms and substorms play important roles in the radiation belt seed population (336 keV electrons) dynamics. Based on the flux changes of 1 MeV electrons before and after the storm peak, these storm events are divided into two groups of "large flux enhancement" and "small flux enhancement." For large flux enhancement storm events, the correlation coefficients between the peak flux location of the seed population and those of relativistic electrons (592 keV, 1 MeV, 1.8 MeV, and 2.1 MeV) during the storm recovery phase decrease with electron kinetic energy, being 0.92, 0.68, 0.49, and 0.39, respectively. The correlation coefficients between the peak flux of the seed population and those of relativistic electrons are 0.92, 0.81, 0.75, and 0.73. For small flux enhancement storm events, the correlation coefficients between the peak flux location of the seed population and those of relativistic electrons are relatively smaller, while the peak flux of the seed population is well correlated with those of relativistic electrons (correlation coefficients >0.84). It is suggested that during geomagnetic storms there is a good correlation between the seed population and $\leqslant$ 1 MeV electrons and the seed population is important to the relativistic electron dynamics.

Using the electron Phase Space Density (PSD) data measured by Van Allen Probe A from January 2013 to April 2015, Tang *et al.* [129] investigate the effects of magnetospheric processes on relativistic electron dynamics in the Earth's outer radiation belt during 50 geomagnetic storms. A statistical study shows that the maximum electron PSDs for various μ (μ=630, 1096, 2290, and 3311 MeV/G) at L^*~4.0 after the storm peak have good correlations with storm intensity (*cc*~0.70). This suggests that the occurrence and magnitude of geomagnetic storms are necessary for relativistic electron enhancements at the inner edge of the outer radiation belt (L^*=4.0). For moderate or weak storm events (SYM-H_{min}>~−100 nT) with weak substorm activity (AE_{max}<800 nT) and strong storm events (SYM-$H_{min}\leqslant$ ~−100 nT) with intense substorms ($AE_{max}\geqslant$800 nT) during the recovery phase, the maximum electron PSDs for various μ at different L^* values (L^*=4.0, 4.5, and 5.0) are well correlated with storm intensity (*cc*>0.77). For storm events with intense substorms after the storm peak, relativistic electron enhancements at L^*=4.5 and 5.0 are observed. This shows that intense substorms during the storm recovery phase are crucial to relativistic electron enhancements in the heart of the outer radiation belt. Our statistics study suggests that magnetospheric processes during geomagnetic storms have a significant effect on relativistic electron dynamics.

Using multi satellite measurements, a uniquely strong and long-lived relativistic electron slot region refilling event from November 2004 to January 2005 is investigated. This event occurred under remarkable interplanetary and magnetospheric conditions. Both empirically modeled and observationally estimated plasmapause locations demonstrate that the plasmasphere eroded significantly prior to the enhancement phase of this event. The estimated diffusion coefficients indicate that the radial diffusion due to ULF waves is insufficient to account for the observed enhancement of slot region electrons. However, the diffusion coefficients evaluated using the distribution of chorus wave intensities derived from low-altitude POES electron observations indicate that the local acceleration induced by chorus could account for the major feature of observed enhancement outside the plasmapause. When the plasmasphere recovered, the refilled slot region was enveloped inside the plasmapause. In the plasmasphere, while the efficiency of hiss scattering loss increases by including unusually low frequency hiss waves, the interaction with hiss alone cannot fully explain the decay of this event, especially at higher energies, which suggests that electromagnetic ion cyclotron waves contribute to the relativistic electron loss process at such low L shells for this refilling event. Through a comprehensive analysis on the basis of data analyses and numerical calculations, Yang *et al.* [130] sheds light on the underlying physics responsible for the unusual slot refilling by relativistic electrons, which exhibits the complexity of both radiation belt electron dynamics and associated wave-particle interactions.

Based on the nearly three-year wave data from the EMFISIS instrument onboard the Van Allen Probes, a statistical analysis of the global distribution of inner magnetospheric upper-band chorus is performed in detail with respect to the level of geomagnetic activity. The emphasis is placed upon the quantitative variations of average upper-band chorus wave amplitude with L-shell (L), Magnetic Local Time (MLT) and Magnetic LATitude (MLAT) and the occurrence pattern of upper-band chorus waves at different amplitude levels. Xiang *et al.* [131] indicates that there exists a strong positive correlation between the average wave amplitude and the geomagnetic activity level, and the averaged wave amplitude can be larger than 40 pT during geomagnetically active periods. While wave amplitude reaches the maximum in the central region (L=4~6) of outer radiation belt, upper-band chorus cannot be observed at L<~3.Averaged wave amplitude is found to be strongest during the interval from nightside to dawnside and is weakest during the interval from afternoonside to duskside. Dayside upper-band chorus can be observed at different geomagnetical conditions with relatively small wave amplitude. It is found that upper-band chorus is mainly distributed at |MLAT|<10°. Averaged wave amplitude is strongest in the region of 21–09 MLT and |MLAT|<5°, and can be about 100 pT during geomagnetically active periods. In addition, the occurrence rate of moderate amplitude (10~30 pT) upper-band chorus is statistically found to be highest (~15%) near the equatorial region in the MLT sector from nightside to dawnside (23–09 MLT). Upper-band chorus with strong wave amplitude has the lowest occurrence rate and is generally observed at the nightside (01–05 MLT). Combined with the global distribution and occurrence pattern of lower-band chorus they have already established, the global distribution and occurrence pattern of upper-band chorus established in this study will improve the understanding of the quantitative contributions of this important magnetospheric wave to the dynamic behaviors of the Earth's plasma sheet, radiation belts and ring current.

Electron flux in the Earth's outer radiation belt is highly variable due to a delicate balance between competing acceleration and loss processes. It has been long recognized that Electromagnetic Ion Cyclotron (EMIC) waves may play a crucial role in the loss of radiation belt electrons. Previous theoretical studies proposed that EMIC waves may account for the loss of the relativistic electron population. However, recent observations showed that while EMIC waves are responsible for the significant loss of ultra-relativistic electrons, the relativistic electron population is almost unaffected. In this study, they provide a theoretical explanation for this discrepancy between previous theoretical studies and recent observations. Cao *et al.* [132] demonstrates that EMIC waves mainly contribute to the loss of ultra-relativistic electrons. This study significantly improves the current understanding of the electron dynamics in the Earth's radiation belt and also can help us understand the radiation environments of the exoplanets and outer planets.

EMIC waves play an important role in the magnetospheric particle dynamics and can lead to resonant pitch-angle scattering and ultimate precipitation of ring current protons. Commonly, the statistics of in situ EMIC wave measurements is adopted for quantitative investigation of wave-particle interaction processes, which however becomes questionable for detailed case studies especially during geomagnetic storms and substorms. Here they establish a novel technique to infer EMIC wave amplitudes from low-altitude proton measurements onboard the Polar Operational Environmental Satellites (POES). The detailed procedure is elaborated regarding how to infer the EMIC wave intensity for one specific time point. They then test the technique with a case study comparing the inferred Root-Mean-Square (RMS) EMIC wave amplitude with the conjugate Van Allen Probes EMFISIS wave measurements. Zhang *et al.* [133] suggests that the developed technique can reasonably estimate EMIC wave intensities from low-altitude POES proton flux data, thereby providing a useful tool to construct a data-based, near-real-time, dynamic model of the global distribution of EMIC waves once the proton flux measurements from multiple POES satellites are available for any specific time period.

Plasmaspheric hiss plays an important role in driving the precipitation loss of radiation belt electrons via pitch angle scattering, which is also known as the major cause of the formation of the "slot" region between the inner and outer radiation belt. Therefore, it is of scientific importance to acquire a complete picture of the global distribution of plasmaspheric hiss. Using the thirty-three month high-quality wave data of the Van Allen Probes from September 2012 to May 2015, which provide excellent coverage in the entire inner magnetosphere, Xiang *et al.* [131] investigate in detail the characteristics of the global distribution of plasmaspheric hiss bin-averaged wave amplitude and occurrence rate with respect to the geomagnetic activity level, L-shell, geomagnetic latitude, and magnetic local time. It is demonstrated that the bin-averaged hiss amplitude strongly depends on the level of geomagnetic activity and exhibits a pronounced day-night asymmetry. Dayside hiss shows a tendency intensifying with the disturbed geomagnetic condition, which is primarily confined to L=2:5–4.0. In contrast, the average hiss amplitude on the nightside tends to decrease. It should also be noted that plasmaspheric hiss at different amplitude levels varies distinctly with geomagnetic condition. As the geomagnetic disturbance increases, the occurrence rate of hiss wave at a smaller amplitude level (*i.e.*, 5–30 pT) increases on the nightside but decreases on the dayside, while the occurrence pattern of higher amplitude (>30 pT) hiss wave is opposite. For high amplitude hiss wave, the occurrence rate increases on the dayside during intense geomagnetic activities while decreases on the nightside. This is probably because during active times, suprathermal electron fluxes are larger on the nightside, which causes stronger Landau damping of whistler mode waves and thus limits the ability of chorus waves to propagate into the plasmasphere and evolve into plasmaspheric hiss. In addition, plasmaspheric hiss waves with the amplitudes ranging from 5 to 30 pT have the highest occurrence probability both around the geomagnetic equator and at higher latitudes. Our statistical results can provide a reasonable and accurate cognition complementary to the current knowledge of the global features of plasmaspheric hiss, especially in the inner magnetosphere of L=2–6, thereby offering essential input parameters of hiss wave distribution for future simulations of the dynamic spatiotemporal variations of radiation belt electrons at different energies and pitch angles under the influence of diverse solar wind and magentospheric circumstances. Therefore, they suggest that these new properties of hiss wave should be incorporated into the future modeling of radiation belt electron dynamics.

Based on the nearly three-year wave data from the EMFISIS instrument onboard the Van Allen Probes, a statistical analysis of the global distribution of inner magnetospheric lower-band chorus is performed in detail with respect to the level of geomagnetic activity. The emphasis is placed on the quantitative variations of average lower-band chorus wave amplitude with L-shell, Magnetic Local Time (MLT) and geomagnetic latitude and the occurrence pattern of lower-band chorus waves at different amplitude levels. Gu *et al.* [134] indicate that there exists a strong positive correlation between the average wave amplitude and the geomagnetic activity level. The lower-band chorus intensifies with increasing geomagnetic activity. The occurrence rates of lower-band chorus also tend to increase when the geomagnetic condition intensifies. Lower-band chorus mainly occur in the MLT sector from midnight-side to afternoon, and is generally weak at other MLTs. Near the geomagnetic equator, lower-band chorus is manly observed during the interval from nightside to dawn and has a MLT extension to dayside at higher magnetic latitudes. Lower-band chorus is mainly confined within 15° of the magnetic latitude around the midnight-side (21:00–03:00 MLT), while it can propagate to higher latitudes on the dawnside (03:00–09:00 MLT). The global profile of lower-band chorus also manifests a strong L-shell dependence, showing the highest probability of the wave occurrence at L=~4.5 generally and a much broader coverage during geomagnetically active periods. These results concerning the global distribution and occurrence pattern of lower-band chorus are important to deepen the current understanding of the wave driven scattering effect on radiation belt electrons via wave-particle interactions and of the quantitative contributions to the dynamic behaviors of radiation belt electrons.

Electromagnetic Extremely Low Frequency (ELF) waves play an important role in modulating the Earth's radiation belt electron dynamics. High-Frequency (HF) modulated heating of the ionosphere acts as a viable means to generate artificial ELF waves. The artificial ELF waves can reside in two different plasma regions in geo-space by propagating in the ionosphere and penetrating into the magnetosphere. As a consequence, the entire trajectory of ELF wave propagation should be considered to carefully analyze the wave radiation properties resulting from modulated ionospheric heating. They adopt a model of full wave solution to evaluate the Poynting vector of the ELF radiation field in the ionosphere, which can reflect the propagation characteristics of the radiated ELF waves along the background magnetic field and provide the initial condition of waves for ray tracing in the magnetosphere. Wang *et al.* [135] indicate that the induced ELF wave energy forms a collimated beam and the center of the ELF radiation shifts obviously with respect to the ambient magnetic field with the radiation power inversely proportional to the wave frequency. The intensity of ELF wave radiation also shows a weak correlation with the size of the radiation source or its geographical location. Furthermore, the combination of ELF propagation in the ionosphere and magnetosphere is proposed on basis of the characteristics of the ELF radiation field from the upper ionospheric boundary and ray tracing simulations are implemented to reasonably calculate magnetospheric ray paths of ELF waves induced by modulated ionospheric heating.

The recently developed high-quality WHU ELF/VLF receiver system has been deployed in Suizhou, China (geomagnetic latitude 21.81° N, longitude 174.44° E, L=1.16) to detect low latitude extremely-low-frequency (ELF: 0.3–3 kHz) and very-low-frequency(VLF: 3–30 kHz) emissions originating from either natural or artificial sources since February 2016. During the first-month operation of the receiver system, a total of 3039 clear whistlers have been recorded at this low latitude station with the majority (97.0%) occurring on 28 February and 1 March 2016. Observed whistlers manifest various types including single one-hop, echo train, multi-flash, and multi-path. Chen *et al.* [136] tend to intensify after local midnight, reach the peak around 04:00–05:00 LT, and then weaken quickly. Both features of lower cutoff frequencies of most whistlers below 1.6 kHz and almost uniform dispersion for many successive multi-flash whistlers suggest that these whistlers propagate along the geomagnetic field lines in the duct mode. The computed dispersion varies between 15 $s^{1/2}$ and 23 $s^{1/2}$ for observed one-hop whistlers and is greater than 50 $s^{1/2}$ for three-hop echo train whistlers, indicating that the whistlers observed at the Suizhou station are low latitude whistlers.

Cao *et al.* [137] perform a detailed analysis of bounce-resonant pitch angle scattering of radiation belt electrons due to EMIC waves. It is found that EMIC waves can resonate with near-equatorially mirroring electrons over a wide range of L shells and energies. H^+ band EMIC waves efficiently scatter radiation belt electrons of energy >100 keV from near 90° pitch angles to lower pitch angles where the cyclotron resonance mechanism can take over to further diffuse electrons into the loss cone. Bounce-resonant electron pitch angle scattering rates show a strong dependence on L shell, wave normal angle distribution, and wave spectral properties. They find distinct quantitative differences between EMIC wave-induced bounce-resonant and cyclotron-resonant diffusion coefficients. Cyclotron-resonant electron scattering by EMIC waves has been well studied and found to be a potentially crucial electron scattering mechanism. The new investigation here demonstrates that bounce-resonant electron scattering may also be very important. They conclude that bounce resonance scattering by EMIC waves should be incorporated into future modeling efforts of radiation belt electron dynamics.

Bounce resonant interactions with magnetospheric waves have been proposed as an important contributing mechanism for scattering near-equatorially mirroring electrons by violating the second adiabatic invariant associated with the electron bounce motion along a geomagnetic field line. Cao *et al.* [138] demonstrates that low-frequency plasmaspheric hiss with significant wave power below 100 Hz can bounce resonate efficiently with radiation belt electrons. By performing quantitative calculations of pitch angle scattering rates, they show that low-frequency hiss-induced bounce resonant scattering of electrons has a strong dependence on equatorial pitch angle α_{eq}. For electrons with α_{eq} close to 90°, the timescale associated with bounce resonance scattering can be comparable to or even less than 1 h. Cyclotron and Landau resonant interactions between low-frequency hiss and electrons are also investigated for comparisons. It is found that while the bounce and Landau resonances are responsible for the diffusive transport of near-equatorially mirroring electrons to lower α_{eq}, pitch angle scattering by cyclotron resonance could take over to further diffuse electrons into the atmosphere. Bounce resonance provides a more efficient pitch angle scattering mechanism of relativistic (⩾1 MeV) electrons than Landau resonance due to the stronger scattering rates and broader resonance coverage of α_{eq}, thereby demonstrating that bounce resonance scattering by low-frequency hiss can contribute importantly to the evolution of the electron pitch angle distribution and the loss of radiation belt electrons.

Based on the high-resolution FFF wave spectral data obtained from the three innermost Time History of Events and Macroscale Interactions during Substorms spacecraft, electrostatic Electron Cyclotron Harmonic (ECH) emissions are identified, using automatic selection criteria, for the period from May 2010 to December 2015. A statistical analysis of wave spectral intensity, peak wave frequency, and wave occurrence rate is performed for the first harmonic ECH waves that are predominantly strongest among all harmonic bands, in terms of dependence on L shell, Magnetic Local Time (MLT), magnetic latitude, and the level of geomagnetic activity. Ni *et al.* [139] indicates that ECH emissions are preferentially a nightside phenomenon primarily confined to the MLT interval of 21–06 and that the most intense ECH waves are commonly present at $L = 5$–9 and MLT = 23:00–03:00 within 3° of the magnetic equator. As the geomagnetic activity intensifies, averaged nightside ECH wave amplitude can increase from a few tenth mV/m to well above 1 mV/m. The presence of >0.1 mV/m ECH emissions extends from $L < 10$ to $L > \sim 12$ with a broad MLT coverage from the evening to post dawnside at the occurrence rate above 20% for the equatorial emissions and at a rate up to ~7% for higher-latitude waves. Overall, the average peak wave frequency of the first harmonic ECH waves is located ~1.5 f_{ce} (where f_{ce} is the electron gyro frequency) for $L < 10$ and becomes smaller at higher L shells. It also exhibits a tendency to shift to lower frequencies with increasing geomagnetic activity level. By finalizing a numeric table that gives the statistically average values of wave amplitude and peak wave frequency for different ranges of L shell, MLT, and geomagnetic activity level, our detailed investigation provides an improved statistical model of ECH wave global distribution in the Earth's inner and outer magnetosphere, which can be readily adopted as critical inputs in diffusion codes to evaluate the rates of ECH wave-driven pitch angle scattering and to determine the precise contributions of ECH waves to the plasma sheet electron dynamics and diffuse auroral electron precipitation.

Ni *et al.* [140] quantify the electron scattering effects of simultaneous plasmaspheric hiss and magnetosonic waves that occurred in two neighboring time intervals but with distinct wave intensity profiles on 21 August 2013. Their combined scattering is found capable of causing electron distribution variations largely distinguishable from the consequences of individual waves. The net effect of electron diffusion relies strongly on the relative dominance of the two wave intensities, which also controls the relative contribution of each wave mode. In combination, MS waves slow down the hiss-induced loss of ~100 keV electrons, and hiss efficiently inhibits the electron butterfly distribution caused by MS waves to produce a gradual acceleration process. Our results strongly suggest that comprehensive simulations of the radiation belt electron dynamics should carefully incorporate the combined scattering and complex competition resulting from simultaneous occurrences of various magnetospheric emissions, including, but not limited to, plamaspheric hiss and magnetosonic waves.

Under different solar wind dynamic pressures, they observed the MagnetoSonic (MS) wave amplification and attenuation associated with the compression and expansion of the Earth's magnetosphere. By analyzing the wave and particle variations recorded by the twin Van Allen Probes, Li *et al.* [141] found that the magnetospheric compression or expansion can alter the keV proton phase space density distribution in velocity space and thus affects the MS wave intensity in upper band (f>50 Hz) in the dawnside magnetosphere (magnetic local time similar to 4.0–7.9 and L similar to 5.7–3.0). During the magnetospheric compression period, the reduction of the 0.1 to 2 keV protons and the enhancement of the 3 to 7 keV protons form a positive phase space density gradient in their velocity space (*i.e.*, the proton ring distribution), and meanwhile, the upper band MS waves are significantly amplified in the proton ring distribution region. During the subsequent magnetospheric expansion period, the enhancement of the 0.1 to 2 keV protons and the reduction of the protons above 3 keV produce a negative phase space density gradient in their velocity space, and meanwhile, the upper band MS waves are rapidly damped. These observations demonstrate that the intensity of the upper band MS waves in the dawnside magnetosphere is highly variable during the change in solar wind pressure.

Using the Van Allen Probe long-term (2013–2015) observations and quasi-linear simulations of wave-particle interactions, Li *et al.*[142] examine the combined or competing effects of whistler mode waves (chorus or hiss) and MagnetoSonic (MS) waves on energetic (<0.5 MeV) and relativistic (>0.5 MeV) electrons inside and outside the plasmasphere. Although whistler mode chorus waves and MS waves can singly or jointly accelerate electrons from the hundreds of keV energy to the MeV energy in the low-density trough, most of the relativistic electron enhancement events are best correlated with the chorus wave emissions outside the plasmapause. Inside the plasmasphere, intense plasmaspheric hiss can cause the net loss of relativistic electrons via persistent pitch angle scattering, regardless of whether MS waves were present or not. The intense hiss waves not only create the energy-dependent electron slot region but also remove a lot of the outer radiation belt electrons when the expanding dayside plasmasphere frequently covers the outer zone. Since whistler mode waves (chorus or hiss) can resonate with more electrons than MS waves, they play dominant roles in changing the outer radiation belt and the slot region. However, MS waves can accelerate the energetic electrons below 400 keV and weaken their loss inside the plasmapause. Thus, MS waves and plasmaspheric hiss generate different competing effects on energetic and relativistic electrons in the high-density plasmasphere.

During enhancement of solar wind dynamic pressure, Li *et al.* [143] observe the periodic emissions of EMIC waves near the nightside geosynchronous orbit (6.6 R_e). In the hydrogen and helium bands, the different polarized EMIC waves have different influences on relativistic electrons (>0.8 MeV). The flux of relativistic electrons is relatively stable if there are only the linearly polarized EMIC waves, but their flux decreases if the left-hand polarized (L-mode) EMIC waves are sufficiently amplified (Power Spectral Density (PSD) >= 1 nT^2/Hz). The larger-amplitude L-mode waves can cause more electron losses. In contrast, the R-mode EMIC waves are very weak (PSD<1 nT^2/Hz) during the electron flux dropouts; thus, their influence may be ignored here. During the electron flux dropouts, the relativistic electron precipitation is observed by POES satellite near the foot point (similar to 850 km) of the wave emission region. The quasi-linear simulation of wave-particle interactions indicates that the L-mode EMIC waves can cause the rapid precipitation loss of relativistic electrons, especially when the initial resonant electrons have a butterfly-like pitch angle distribution.

Comprehensive records are available in ENA data of ring current activity recorded by the NUADU instrument aboard TC-2 on 15 May, 2005 during a major magnetic storm (which incorporated a series of substorms). Ion fluxes at 4-min temporal resolution derived from ENA data in the energy ranges 50–81 and 81–158 keV are compared with in situ particle fluxes measured by the LANL-SOPA instruments aboard LANL-01, LANL-02, LANL-97, and LANL-84 (a series of geostationary satellites that encircle the equatorial plane at similar to 6.6 R_e). Also, magnetic fields measured simultaneously by the magetometers aboard GOES-10 and GOES-12 (which are also geostationary satellites) are compared with the particle data. It is demonstrated by Lu *et al.* [144] that ion fluxes in the ring current were enhanced during geomagnetic field tailward stretching in the growth phases of substorms rather than after Earthward directed dipolarization events. This observation, which challenges the existing concept that ring current particles are injected Earthward from the magnetotail following dipolarization events, requires further investigation using a large number of magnetic storm events.

A new method to study a possible temporal correlation between hundreds of keV Van Allen Belt electrons and strong earthquakes is proposed by Tao *et al.*[145]. It consists in measuring the electrons Pitch Angle Distribution (PAD), searching for PAD disturbances, and studying the time correlation between these PAD disturbances and strong earthquakes, occurring within a defined time window. The method was applied to measurements of energetic electrons, which were performed with the Energetic Particle, Composition, and Thermal Plasma (ECT)-MagEIS detector on board the Van Allen Probes (VAPs) mission and strong continental earthquakes, with magnitude M⩾5.0 and hypocenter depth ⩽100 km. They report the correlation studies for electrons with energies of about 350 keV, with which a 3.84 standard deviations correlation peak was found at +[0, 3] hour time bin, and about 450 keV with which no correlation peaks above 2.0 standard deviations were found. Their work proves the feasibility of the proposed method and the obtained results add useful and additional information with respect to past studies.

Based on the Van Allen Probe A observations from 1 October 2012 to 31 December 2014, Yu *et al.* [146] develop two empirical models to respectively describe the hiss Wave Normal Angle (WNA) and amplitude variations in the Earth's plasmasphere for different substorm activities. The long-term observations indicate that the plasmaspheric hiss amplitudes on the dayside increase when substorm activity is enhanced (AE index increases), and the dayside hiss amplitudes are greater than the nightside. However, the propagation angles (WNAs) of hiss waves in most regions do not depend strongly on substorm activity, except for the intense substorm-induced increase in WNAs in the nightside low L-region. The propagation angles of plasmaspheric hiss increase with increasing magnetic latitude or decreasing radial distance (L-value). The global hiss WNAs (the power-weighted averages in each grid) and amplitudes (medians) can be well reproduced by our empirical models.

Using the Van Allen Probes in situ measured magnetic field and electron data, Yu *et al.* [147] examine the solar wind dynamic pressure and IMF effects on global magnetic field and outer radiation belt relativistic electrons (1.8 MeV). The dynamic pressure enhancements (>2 nPa) cause the dayside magnetic field increase and the nightside magnetic field reduction, whereas the large southward IMFs (B_z-IMF<–2 nT) mainly lead to the decrease of the nightside magnetic field. In the dayside increased magnetic field region (magnetic local time (MLT) similar to 06:00–18:00, and L>4), the pitch angles of relativistic electrons are mainly pancake distributions with a flux peak around 90 degrees (corresponding anisotropic index A>0.1), and the higher-energy electrons have stronger pancake distributions (the larger A), suggesting that the compression-induced betatron accelerations enhance the dayside pancake distributions. However, in the nighttime decreased magnetic field region (MLT similar to

18:00–06:00, and L5), the pitch angles of relativistic electrons become butterfly distributions with two flux peaks around 45 degrees and 135° (A<0). The spatial range of the nighttime butterfly distributions is almost independent of the relativistic electron energy, but it depends on the magnetic field day-night asymmetry and the interplanetary conditions. The dynamic pressure enhancements can make the nighttime butterfly distribution extend inward. The large southward IMFs can also lead to the azimuthal expansion of the nighttime butterfly distributions. These variations are consistent with the drift shell splitting and/or magnetopause shadowing effect.

On 23 November 2012, a sudden dropout of the relativistic electron flux was observed after an interplanetary shock arrival. The dropout peaks at approximate to 1 MeV and more than 80% of the electrons disappeared from the drift shell. Van Allen twin Probes observed a sharp electron flux dropout with clear energy dispersion signals. The repeating flux dropout and recovery signatures, or dropout echoes, constitute a new phenomenon referred to as a drifting electron dropout with a limited initial spatial range. The azimuthal range of the dropout is estimated to be on the duskside, from approximate to 1300 to 0100 LT. Hao *et al.* [148] conclude that the shock-induced electron dropout is not caused by the magnetopause shadowing. The dropout and consequent echoes suggest that the radial migration of relativistic electrons is induced by the strong dusk-dawn asymmetric interplanetary shock compression on the magnetosphere.

Hao *et al.* [149] present an analysis of "boomerang-shaped" pitch angle evolutions of outer radiation belt relativistic electrons observed by the Van Allen Probes after the passage of an interplanetary shock on 7 June 2014. The flux at different pitch angles is modulated by Pc5 waves, with equatorially mirroring electrons reaching the satellite first. For 90° pitch angle electrons, the phase change of the flux modulations across energy exceeds 180° and increasingly tilts with time. Using estimates of the arrival time of particles of different pitch angles at the spacecraft location, a scenario is investigated in which shock-induced ULF waves interact with electrons through the drift resonance mechanism in a localized region westward of the spacecraft. Numerical calculations on particle energy gain with the modified ULF wave field reproduce the observed boomerang stripes and modulations in the electron energy spectrogram. The study of boomerang stripes and their relationship to drift resonance taking place at a location different from the observation point adds new understanding of the processes controlling the dynamics of the outer radiation belt.

The variation of the flux of energetic electrons in the magnetosphere has been proven to be strongly related to the solar wind speed. Observations of GEO orbit show that the flux of low-energy electrons is not only modulated by the solar wind speed, but, if a time delay is added, is also positively correlated to the flux of high-energy electrons. This feature provides a possible method to forecast the flux of high-energy electrons in GEO orbit. In Li *et al.* [150], the correlations of the fluxes between the high-energy electrons and low-middle- energy electrons obtained at different L values and in different orbits are investigated to develop the application of this feature. Based on the analysis of long-term data observed by NOAA POES and GOES, the correlation between the fluxes of high-energy electrons and low-middle-energy electrons is good enough at different L values and in different orbits in quiet time, but this correlation is strongly affected by CME-driven geomagnetic storms.

Interaction between ULtralow Frequency (ULF) waves and charged particles plays an important role in the acceleration of particles in the Van Allen radiation belts. The strong wave-particle interaction predicts an energy-dependent observational signature of particle flux variations during different stages of the ULF wave evolution. Li *et al.* [151] find that the energetic particle data newly available from an IGSO spacecraft are quite consistent with theoretical predictions, which enables the application of a best-fit procedure to quantitatively extract key parameters of the ULF waves from the particle data. The general agreement between observations and the best-fit results validates the scenario of wave-particle drift resonance within the entire ULF life span, and provides a new technique to understand the ULF wave characteristics in the absence of electromagnetic field data. They also examine the minor differences between observations and the best-fit results, and propose that the differences may result from a longitudinal dependence of the ULF wave power to be considered in a future study.

The formation and variability of the Van Allen radiation belts are highly influenced by charged particles accelerated via drift-resonant interactions with ULF waves. In the prevailing theory of drift resonance, the ULF wave amplitude is assumed independent of magnetic longitude. This assumption is not generally valid in Earth's magnetosphere, as supported by numerous observations that point to the localized nature of ULF waves. Li *et al.* [152] introduce a longitude dependence of the ULF wave amplitude, achieved via a von Mises function, into the theoretical framework of ULF wave-particle drift resonance. To validate the revised theory, the predicted particle signatures are compared with observational data through a best fit procedure. It is demonstrated that incorporation of nonlocal effects in drift-resonance theory provides an improved understanding of charged particle behavior in the inner magnetosphere through the intermediary of ULF waves.

Liu *et al.* [153] presents Van Allen Probes observations of modulations in the flux of very energetic electrons up to a few MeV and protons between 12:00UT and 14:00UT on 19 February 2014. During this event the spacecraft were in the dayside magnetosphere at L approximate to 5.5. The modulations extended across a wide range of particle energies, from 79.80 keV to 2.85 MeV for electrons and from 82.85 keV to 636.18 keV for protons. The fluxes of $\pi/2$ pitch angle particles were observed to attain maximum values simultaneously with the ULF compressional magnetic field component reaching a minimum. They use peak-to- valley ratios to quantify the strength of the modulation effect, finding that the modulation is larger at higher energies than at lower energies. It is shown that the compressional wave modulation of the particle distribution is due to the mirror effect, which can trap relativistic electrons efficiently for energies up to 2.85 MeV and trap protons up to approximate to 600 keV. Larger peak-to-valley ratios at higher energies also attributed to the mirror effect. Finally, they suggest that protons with energies higher than 636.18 keV cannot be trapped by the compressional ULF wave efficiently due to the finite Larmor radius effect.

Zebra stripes are newly found energetic electron energy-spatial (L shell) distributed structure with an energy between tens to a few hundreds keV in the inner radiation belt. Using high-quality measurements of electron fluxes from Radiation Belt Storm Probes Ion Composition Experiment (RBSPICE) on board the twin Van Allen Probes, they carry out case and statistical studies from April 2013 to April 2014 to study the structural and evolutionary characteristics of zebra stripes below L=3. Liu *et al.* [154] revealed that the zebra stripes can be transformed into evenly spaced patterns in the electron drift frequency coordinate: the detrended logarithmic fluxes in each L shell region can be well described by sinusoidal functions of drift frequency. The wave number of this sinusoidal function, which corresponds to the reciprocal of the gap between two adjacent peaks in the drift frequency coordinate, increases in proportion to real time. Further, these structural and evolutionary characteristics of zebra stripes can be reproduced by an analytic model of the evolution of the particle distribution under a single monochromatic or static azimuthal electric field. It is shown that the essential ingredient for the formation of multiple zebra stripes is the periodic drift of particles. The amplitude of the zebra stripes shows a good positive correlation with *Kp* index, which indicates that the generation mechanism of zebra stripes should be related to geomagnetic activities.

"Electron dropout echo" as indicated by repeated moderate dropout and recovery signatures of the flux of energetic electron in the outer radiation belt region has been investigated systematically. The electron moderate dropout and its echoes are usually found for higher- energy (>300 keV) channel fluxes, whereas the flux enhancements are obvious for lower energy electrons simultaneously after the interplanetary shock arrives at the Earth's geosynchronous orbit. The electron dropout echo events are found to be usually associated with the interplanetary shocks arrival. The 104 dropout echo events have been found from 215 interplanetary shock events from 1998 to 2007 based on the Los Alamos National Laboratory satellite data. In analogy to substorm injections, these 104 events could be naturally divided into two categories: dispersionless (49 events) or dispersive (55 events) according to the energy dispersion of the initial dropout. It is found that locations of dispersionless events are distributed mainly in the duskside magnetosphere. Further, the obtained locations derived from dispersive events with the time-of-flight technique of the initial dropout regions are mainly located at the duskside as well. Statistical studies have shown that the effect of shock normal, interplanetary magnetic field *B-z* and solar wind dynamic pressure may be insignificant to these electron dropout events. Liu *et al.* [155] suggest that the similar to 1 min electric field impulse induced by the interplanetary shock produces a more pronounced inward migration of electrons at the duskside, resulting in the observed duskside moderate dropout of electron flux and its consequent echoes.

Ren *et al.* [156] report observational evidence of cold plasmaspheric electron (<200 eV) acceleration by ULtralow Frequency (ULF) waves in the plasmaspheric boundary layer on 10 September 2015. Strongly enhanced cold electron fluxes in the energy spectrogram were observed along with second harmonic mode waves with a period of about 1 min which lasted several hours during two consecutive Van Allen Probe B orbits. Cold electron (<200 eV) and energetic proton (10–20 keV) bidirectional pitch angle signatures observed during the event are suggestive of the drift-bounce resonance mechanism. The correlation between enhanced energy fluxes and ULF waves leads to the conclusions that plasmaspheric dynamics is strongly affected by ULF waves. Van Allen Probe A and B, GOES 13, GOES 15, and MMS 1 observations suggest that ULF waves in the event were strongest on the duskside magnetosphere. Measurements from MMS 1 contain no evidence of an external wave source during the period when ULF waves and injected energetic protons with a bump-on-tail distribution were detected by Van Allen Probe B. This suggests that the observed ULF waves were probably excited by a localized drift-bounce resonant instability, with the free energy supplied by substorm- injected energetic protons. The observations by Van Allen Probe B suggest that energy transfer between particle species in different energy ranges can take place through the action of ULF waves, demonstrating the important role of these waves in the dynamical processes of the inner magnetosphere.

ULF waves can accelerate/decelerate the charged particles including the ring current ions via drift-bounce resonance, which play an important role in the dynamics of ring current during storm times. Ren *et al.* [157] compare the different behaviors of oxygen ions (10.5–35.1 keV) and protons (0.3–12.3 keV) which simultaneously interact with Pc5 ULF waves observed by Cluster on 3 June 2003. The ULF waves are identified as the fundamental mode oscillations. Both oxygen ions and protons show periodic energy dispersion and pitch angle dispersion signatures, which satisfy the drift-bounce resonance condition of N=2. The different behaviors of oxygen ions and protons include (1) the resonant energy of oxygen ions is higher than that of protons due to mass difference; (2) the Phase Space Density (PSD) of oxygen ions show relative variations (3.6–6.3) that are much larger than that of protons (<0.4), which indicates a more efficient energy exchange between oxygen ions and ULF waves; (3) the PSD spectra show that oxygen ions are accelerated, while protons are decelerated, which depend on the radial gradient of their PSD; (4) the Pitch Angle Distributions (PADs) of the oxygen ions and protons show negative slope and bidirectional field-aligned features, respectively, which is related to the preexisting state of ion PADs before the interaction with the ULF waves. In addition, the resonant ions with peak fluxes tracing back to the magnetic equator are always collocated with the accelerating (westward) electric field, which indicate that the ions are mainly accelerated near the magnetic equator and the electric field intensity of ULF waves peaks there.

Ren *et al.* [158] explore the phase relationship between the poloidal mode ULF wave electric field oscillations and drift-bounce resonant oxygen ions under the resonant condition of N=2 at the magnetic equator. Using Cluster data from 2001 to 2004, they identify 55 fundamental poloidal mode wave events, among which 42 show "negative slope" pitch angle dispersion signatures in the southern hemisphere, 11 show "positive slope" dispersion in the northern hemisphere, and two near-equatorial events are associated with in-phase field-aligned signatures. For each event, the off-equatorial resonant ions are traced along their bouncing trajectories to determine the last time they moved across the equator. The resulting time series of the resonant oxygen ion fluxes at the equator are found to be statistically in antiphase with the wave electric fields. The resonant ion flux variation depends on both ion energy change and radial transportation. This antiphase relationship in statistics suggests two possibilities: (1) the fundamental poloidal mode wave electric fields are generally characterized by electric field intensity peaking near the magnetic equator if the flux variation is mainly caused by energy change and (2) the radial gradient of phase space density is positive if the flux variation caused by radial transportation is dominant.

Based on the data from the Medium-Energy Proton and Electron Detector (MEPED) onboard NOAA-17, 141 anomalies of a Chinese Sun-Synchronous satellite (SSO-X) that occurred between 02/01/2010 and 09/31/2012 were studied statistically. About 26 out of the 52 anomalies that occurred outside the South Atlantic Anomaly (SAA) were accompanied by energetic electron storms. Superposed Epoch Analysis (SEA) was used to analyze the properties of the anomalies and the dynamics of the space environments during these 26 events. Then, a Monte Carlo method was utilized to simulate the electron deposition and the interactions of the injected electrons with an aluminum shield and polyethylene dielectric. The average, median, and 75th percentile values of the maximum electric field strength inside the dielectric were calculated. The results showed the following. (1) SSO-X anomalies are more likely to occur within the SAA, as 89 out of 141 anomalies (63%) occurred there. (2) Twenty-six of the anomalies that occurred outside the SAA during energetic electron storms were located near the outer boundaries of the outer radiation belts, and these were more frequent in the Southern Hemisphere than in the Northern Hemisphere. (3) Electron flux enhancements occurred around the failure time at all energy levels but were more profound in the lower energy channels. The maximum fluxes of electrons >30 keV, >100 keV, and >300 keV were 10^6, 3.5×10^5, and 1.2×10^6 $cm^{-2}\cdot s^{-1}\cdot sr^{-1}$, respectively. (4) The average, median, and 75th percentile values of the maximum electric field strengths inside the dielectric for the aforementioned 26 events remained in the range from 10^6 to 10^7 V/m for long time periods, which suggests that the 'potential hazards' of internal discharges cause SSO-X anomalies. Tian *et al.* [159] can provide useful information for the design and protection of sun-synchronous spacecraft.

Deep dielectric charging, which is a coupling process of charge deposition and charge relief, is a significant factor in spacecraft anomalies and failures. With the aim of developing a method for evaluating the deep dielectric charging hazards, Xiang *et al.* [160] investtigated the leakage current and charging electric field of grounded dielectrics in space usage by a method combining Monte Carlo simulation and a model of radiation-induced conductivity. The analysis adopts multiple cases of electron spectra and various thicknesses of the shielding layer and dielectric. The analysis results show that the leakage current, which can be easily measured, is strongly related to the charging electric field in various situations. Therefore, monitoring the leakage current can be a more effective approach for evaluating deep dielectric charging hazards than monitoring electron flux.

Ye *et al.* [161] carry out a comprehensive analysis of secular variation of the South Atlantic Anomaly. The center location of the South Atlantic Anomaly (SAA) is derived from the proton flux measurements of different energy channels by SAMPEX (Solar Anomalous and Magnetospheric Particle Explorer)/PET (Proton/Electron Telescope). The results are compared with National Oceanic and Atmospheric Administration/Medium Energy Proton and Electron Detector observations and the International Geomagnetic Reference Field 12 (IGRF12) geomagnetic field model. It is found that different energy protons have different behaviors while the center location of the SAA changes with altitude. The IGRF12 magnetic field can explain the observations to a limited extent. Possible reasons for the differences are discussed. It is confirmed that center location of the SAA is also affected by atmospheric density at SAMPEX altitudes. The results could be helpful for constructing inner radiation belt models.

ULF electromagnetic waves in Earth's magnetosphere can accelerate charged particles via a process called drift resonance. In the conventional drift resonance theory, a default assumption is that the wave growth rate is time independent, positive, and extremely small. However, this is not the case for ULF waves in the real magnetosphere. The ULF waves must have experienced an earlier growth stage when their energy was taken from external and/or internal sources, and as time proceeds the waves have to be damped with a negative growth rate. Therefore, a more generalized theory on particle behavior during different stages of ULF wave evolution is required. In this paper, Zhou *et al.* [162] introduce a time-dependent imaginary wave frequency to accommodate the growth and damping of the waves in the drift resonance theory, so that the wave-particle interactions during the entire wave lifespan can be studied. They then predict from the generalized theory particle signatures during different stages of the wave evolution, which are consistent with observations from Van Allen Probes. The more generalized theory, therefore, provides new insights into ULF wave evolution and wave-particle interactions in the magnetosphere.

EMIC waves in the H^+, He^+, and O^+ bands are frequently observed in the magnetosphere. Tang *et al.* [163] examines the effects of the thermal pressure of heavy He^+ and O^+ ions on EMIC wave properties. It illustrates that hot and isotropic heavy ions may completely suppress the growth of He^+ band EMIC waves, whereas H^+ band waves are growing irrespective of whether the heavy ions are cool or hot. At large O^+ ion concentration, O^+ band waves grow considerably as hot protons, and heavy ions are anisotropic. Results from the hot fluid model show that anisotropic thermal pressures of heavy ions result in the resonance frequency of EMIC waves larger than that from the cold fluid model, and therefore, narrowing the corresponding stop bands. Furthermore, the anisotropic ion thermal pressures lead to the minimum resonant energy of electrons interacting with EMIC waves at higher frequencies than that predicted by the cold fluid model.

6. Plasmasphere

The Moon-based Extreme Ultraviolet Camera (EUVC) aboard China's Chang'E-3 (CE-3) mission has successfully imaged the entire Earth's plasmasphere for the first time from the side views on lunar surface. An EUVC image on 21 April 2014 is used in this study to demonstrate the characteristics and configurations of the Moon-based EUV imaging and to illustrate the determination algorithm of the plasmapause locations on the magnetic equator. The plasmapause locations determined from all the available EUVC images with the Minimum L Algorithm are quantitatively compared with those extracted from in situ observations (Defense Meteorological Satellite Program, Time History of Events and Macroscale Interactions during Substorms, and Radiation Belt Storm Probes). Excellent agreement between the determined plasmapauses seen by EUVC and the extracted ones from other satellites indicates the reliability of the Moon-based EUVC images as well as the determination algorithm. He *et al.* [164] provides an important basis for future investigation of the dynamics of the plasmasphere with the Moon-based EUVC imaging.

A large database, possibly the largest plasmapause location database, with 49, 119 plasmapause crossing events from the in situ observations and 3957 plasmapause profiles (corresponding to 48, 899 plasmapause locations in 1 h Magnetic Local Time (MLT) intervals) from optical remote sensing from 1977 to 2015 by 18 satellites is compiled. The responses of the global plasmapause to solar wind and geomagnetic changes and the diurnal, seasonal, solar cycle variations of the plasmapause are investigated based on this database. Zhang *et al.* [165] found that the plasmapause shrinks toward the Earth globally and a clear bulge appears in the afternoon to premidnight MLT sector as the solar wind or geomagnetic conditions change from quiet to disturbed. The bulge is clearer during storm times or southward interplanetary magnetic field. The diurnal variations of the plasmapause are most probably the result of the difference between the magnetic dipole tilt and the Earth's spin axis. The seasonal variations of the plasmapause are characterized by equinox valleys and solstice peaks. It is also found that the plasmapause approaches the Earth during high solar activity and expands outward during low solar activity. This database will help us study and understand the evolution properties of the plasmapause shape and the interaction processes of the plasmasphere, the ring current, and the radiation belts in the magnetosphere.

The plasmapause locations determined from the Chang'E-3 (CE-3) Extreme UltraViolet Camera (EUVC) images and the auroral boundaries determined from the Defense Meteorological Satellite Program (DMSP) Special Sensor Ultraviolet Spectrographic Imager (SSUSI) images are used to investigate the plasmaspheric evolutions during substorms. The most important finding is a nightside pointing plasmaspheric plume observed at 23:05 UT on 21 April 2014 under quiet solar wind and geomagnetic conditions, which drifted from the dusk sector. High correlations between the plasmapause evolutions and the auroral signatures exist during substorms. After substorm onset, the plasmapause erosion and the equatorward expansion of the auroral oval occur almost simultaneously in both MLT and UT, and then both the erosion and the expansion propagate westward and eastward. It is suggested that the plasmaspheric erosion and its MLT propagations are induced by the enhanced earthward plasma convection during substorm period, and the substorm dipolarization causes pitch-angle scattering of plasma sheet electrons and the resulting precipitation excites aurora emissions at the same time.

Based on the plasmaspheric images observed by IMAGE EUV imager, the plasmapause locations on the magnetic equatorial plane are reconstructed with the Minimum L Algorithm.3579 plasmaspheric images are selected from 2000 to 2002 and a plasmapause location database is Compiled containing 48899 plasmapause locations in 1h MLT intervals. This database is used to Statistically study the relationships between the plasmapause locations and the geomagnetic activities. Du *et al.* [166] found that the plasmapause shapes are highly dependent on the geomagnetic Activities, and the plasmapause locations are negatively correlated with *Kp, Dst* and *AE* with Their variation tendencies all significantly changing with MLT. It is also found that the effects of The substorm activity on the plasmapause locations are different under different geomagnetic conditions with the effects being larger for quiet periods compared with disturbed periods, results in this paper will provide an important basis for future construction of a plasmapause model and understanding the dynamic structure of the plasmapause.

Based on THEMIS waveform data, Chen *et al.* [167] report two special multiband chorus events, where upper-band waves are located at harmonics of lower- band waves. And they proposed a new generation mechanism to explain this multiband chorus wave, named as lower band cascade. With a 1-D PIC simulation model, they have investigated the lower band cascade of whistler waves excited by anisotropic hot electrons. During each simulation, lower-band whistler-mode waves are firstly excited by the anisotropy of hot electrons. Later, upper-band harmonic waves are generated through the nonlinear coupling between the electromagnetic and electrostatic components of lower-band waves, which supports the scenario of lower band cascade. Moreover, the peak wave number (or frequency) of lower-band waves will continuously drift to smaller values due to the decline of the anisotropy of hot electrons. While, the peak wave number of upper-band harmonic waves will be kept nearly unchanged, but their amplitude continues to decrease after their saturation. They further find the magnetic amplitude of upper-band harmonic waves tends to increase with the increase of the wave normal angle of lower-band waves or the anisotropy of hot electrons. Besides, the amplitude ratio between upper-band and lower-band waves is positively correlated with the wave normal angle of lower-band waves, but is anti-correlated with the anisotropy of hot electrons. Their study has provided a more comprehensive understanding of the lower band cascade of whistler waves.

Although the plasmasphere has been studied for decades, an accurate boundary or model for the core plasma area of the plasmasphere has not been obtained yet. Based on the data of RBSP-A satellite from 2012 to 2014, Feng *et al.*[168] statistically analyze the variations of the plasmaspheric electron density with *L*-values and MLT during geomagnetic quiet-time, respectively. The electron density almost has the same trend with L-values in different MLT, but there is an obvious deviation between their observed electron density of the core plasmasphere and that calculated from the previous empirical plasmaspheric model. Also it has the same trend with MLT for different *L*-values, as well as obvious diurnal and semidiurnal variations. Finally, they obtain the empirical formula of the electron density of the core plasmaphere with *L*-values and MLTs. This model will be important to the research of the plasmasphere.

7. Outer Magnetosphere

The dipole tilt angle has been found to affect Earth's bow shock. Lu *et al.* [169] present a quantitative relationship between the dipole tilt angle and the bow shock location and flaring angle. They collected a large data set of bow shock crossing from four different satellites (IMP 8, Geotail, Magion 4, and Cluster), including some recent crossings obtained 2012–2013. The results from a statistical analysis demonstrate that: (1) the subsolar standoff distance increases but the flaring angle decreases with increasing dipole tilt angle; (2) when the dipole tilt angle changes sign from negative to positive, the dayside bow shock moves toward Earth and the shift can be as much as 2.29 R_e, during which the flaring angle increases; and (3) the shape of bow shock in the northern and southern hemispheres differs. For the northern hemisphere bow shock, with increasing positive/ negative dipole tilt angle, the flaring angle increases/ decreases. While for the southern hemisphere, the trend is the opposite; with increasing positive/negative dipole tilt angle, the flaring angle increases/ decreases. These results are helpful for future bow shock modeling that needs to include the effects of dipole tilt angle.

Using the Cluster data during the period from January to April between 2001 and 2006, they find an observation of solar wind entry due to magnetic reconection occurred in the terrestrial high-latitude magnetospheric lobes, tailward of the cusps under northward IMF. Occurrence rate of solar wind entry events in this study is of the same order as that for the Cluster orbital interval from August to October between the years of 2002 and 2004 as reported by Shi et al. (2013). Gou *et al.* [64] further study the role of the IMF B_x and B_y components in the control of solar wind plasma entry based on the investigations of different magnetic dipole tilt variations between their database and Shi et al. (2013). This study shows that the asymmetry distribution of solar wind entry events in the northern and southern lobes could be caused by the variation of magnetic dipole tilt, which could influence the locations of the reconnection site on the high-latitude lobe magnetopause. On the other hand, IMF B_x can also affect the solar wind plasma entry rate, which is also consistent with previous results. Therefore, they conclude that the north-south asymmetry of solar wind entry events in the lobes could be the combined result of magnetic dipole tilt and IMF B_x. In addition, the IMF B_y component can influence the entry events in conjunction with the variation of IMF B_x component, which is in line with the Parker Spiral of the IMF.

Gyrophase bunched ions were first detected in the upstream region of the Earth’s bow shock in the early 1980s which is formed by the microphysical process associated with reflected solar wind ions at the bow shock. Inside the magnetosphere, the results of computer simulations demonstrated that nonlinear wave-particle interaction can also result in the gyrophase bunching of particles. However, to date direct observations barely exist regarding this issue occurred inside the magnetosphere. Wang *et al.* [170] reports for the first time an event of gyrophase bunched ions observed in the near-Earth plasma sheet. The nongyrotropic distributions of ions were closely accompanied with the electromagnetic waves at the oxygen cyclotron frequency. The phase of bunched ions and the phase of waves mainly have very narrow phase differences (<30°) when the O^+ band waves are remarkably enhanced, which indicates that the wave and particle are closely corotating. The ‘‘electric phase bunching” is considered to be a possible mechanism for the formation of the gyrophase bunched distributions in this case. The MVA analysis suggests that the oxygen band waves possess left helicity with respect to the propagation direction, which agrees with the characteristic of electromagnetic ion cyclotron waves. The observation of O^+ ions composition suggests that the oxygen band waves are excited due to the enhancements of the O^+ ion density. This study suggests that the gyrophase bunching is a significant nonlinear effect that exists not only in the bow shock but also in the inner magnetosphere.

Magnetic Holes (MHs), with a scale much greater than ρ_i (proton gyroradius), have been widely reported in various regions of space plasmas. On the other hand, Kinetic-Size Magnetic Holes (KSMHs), previously called small-size magnetic holes, with a scale of the order of magnitude of or less than ρ_i have only been reported in the Earth's magnetospheric plasma sheet. In this study, they report such KSMHs in the magnetosheath whereby they use measurements from the Magnetospheric Multiscale mission, which provides three-dimensional (3-D) particle distribution measurements with a resolution much higher than previous missions. The MHs have been observed in a scale of 10–20 ρ_e (electron gyroradii) and lasted 0.1–0.3 s. Distinctive electron dynamics features are observed, while no substantial deviations in ion data are seen. Yao*, et al.,* [171] found that at the 90° pitch angle, the flux of electrons with energy 34–66 eV decreased, while for electrons of energy 109–1024 eV increased inside the MHs. They also find the electron flow vortex perpendicular to the magnetic field, a feature self-consistent with the magnetic depression. Moreover, the calculated current density is mainly contributed by the electron diamagnetic drift, and the electron vortex flow is the diamagnetic drift flow. The electron magnetohydrodynamics soliton is considered as a possible generation mechanism for the KSMHs with the scale size of 10–20 ρ_e.

ULF waves play an important role in the transport of the solar wind energy to the magnetosphere. Shen *et al.* [76] present a ULF wave event in the dayside magnetosphere which shows a sudden decrease in frequency from 3.1 to 2.3 mHz around 07:56 UT on 11 January 2010, when a solar wind dynamic pressure drop (from ~5 to ~2 nPa) was observed simultaneously. The wave exits globally. The phase differences between electric and magnetic fields indicate that the compressional mode wave is standing before and after the wave frequency decrease. This result suggests that the ULF wave should be associated with a cavity mode and the frequency decrease might be induced by the change of the cavity size. A theoretical calculation was made to estimate the cavity mode frequency. The calculated wave frequency before/after the negative impulse is 3.8/2.6 mHz, which is consistent with the observations.

Magnetic Holes (MHs), characteristic structures where the magnetic field magnitude decreases signifycantly, have been frequently observed in space plasmas. Particularly, Small Size Magnetic Holes (SSMHs) which the scale is less than or close to the proton gyroradius are recently detected in the magnetospheric plasma sheet. In this study of Cluster observations, by the timing method, the Minimum Directional Difference (MDD) method, and the SpatioTemporal Difference (STD) method, Yao *et al.* [172] obtain the propagation velocity of SSMHs in the plasma flow frame. Furthermore, based on Electron MagnetoHydroDynamics (EMHD) theory they calculate the velocity, width, and depth of the electron solitary wave and compare it to SSMH observations. The result shows a good accord between the theory and the observation.

Huang *et al.* [173], Huang *et al.* [174] and Huang *et al.* [175] reported two new types of coherent structures in the turbulent magnetosheath. One is ion-scale magnetic island, another is electron vortex magnetic hole. Huang *et al.* [173] shown the first observations of ion-scale magnetic island from the Magnetospheric Multiscale mission in the magnetosheath turbulent plasma as new type of coherent structure. The magnetic island is characterized by bipolar variation of magnetic fields with magnetic field compression, strong core field, density depletion, and strong currents dominated by the parallel component to the local magnetic field. The estimated size of magnetic island is about 8 d_i, where di is the ion inertial length. Distinct particle behaviors and wave activities inside and at the edges of the magnetic island are observed: parallel electron beam accompanied with electrostatic solitary waves and strong electromagnetic lower hybrid drift waves inside the magnetic island and bidirectional electron beams, whistler waves, weak electromagnetic lower hybrid drift waves, and strong broadband electrostatic noise at the edges of the magnetic island. These observations demonstrate that highly dynamical, strong wave activities and electron-scale physics occur within ion-scale magnetic islands in the magnetosheath turbulent plasma. In addition, Huang *et al.* [174] reported the observations of an electron vortex magnetic hole corresponding to a new type of coherent structure in the turbulent magnetosheath plasma using the Magnetospheric Multiscale mission data. The magnetic hole is characterized by a magnetic depression, a density peak, a total electron temperature increase (with a parallel temperature decrease but a perpendicular temperature increase), and strong currents carried by the electrons. The current has a dip in the core region and a peak in the outer region of the magnetic hole. The estimated size of the magnetic hole is about 0.23 ρ_i (~30 ρ_e) in the quasi-circular cross-section perpendicular to its axis, where ρ_i and ρ_e are respectively the proton and electron gyro radius. There are no clear enhancements seen in high-energy electron fluxes. However, there is an enhancement in the perpendicular electron fluxes at 90° pitch angle inside the magnetic hole, implying that the electrons are trapped within it. The variations of the electron velocity components Vem and Ven suggest that an electron vortex is formed by trapping electrons inside the magnetic hole in the cross-section in the *M–N* plane. These observations demonstrate the existence of a new type of coherent structures behaving as an electron vortex magnetic hole in turbulent space plasmas as predicted by recent kinetic simulations. Then, Huang *et al.* [175] performed a statistical study to investigate the electron vortex magneto holes with short duration (*i.e.*, <0.5 s) and their cross section smaller than the ion gyroradius. Superposed epoch analysis of all events reveals that an increase in the electron density and total temperature signifycantly increases (resp. decrease) the electron perpendicular (resp. parallel) temperature and an electron vortex inside KSMHs. Electron fluxes at about 90° pitch angles with selective energies increase in the holes are trapped inside holes and form the electron vortex due to their collective motion. It is furthermore shown that electron vortex magnetic holes are likely to heat and accelerate the electrons.

Huang *et al.* [176] have systematically investigated the MHD turbulence and the existence of Kolmogorov Inertial Range in the magnetosheath. In the solar wind, Power Spectral Density (PSD) of the magnetic field fluctuations generally follow the so-called Kolmogorov spectrum $f^{-5/3}$ in the inertial range, where the dynamics is thought to be dominated by nonlinear interactions between counter-propagating incompressible Alfvén wave parquets. These features are thought to be ubiquitous in space plasmas. The present study gives a new and more complex picture of MHD turbulence as observed in the terrestrial magnetosheath. The study uses three years of in situ data from the Cluster mission to explore the nature of the magnetic fluctuations at MHD scales in different locations within the magnetosheath, including flanks and subsolar regions. It is found that the magnetic field fluctuations at MHD scales generally have a PSD close to f^{-1} (shallower than the Kolmogorov one $f^{-5/3}$) down to the ion characteristic scale, which recalls the energy-containing scales of solar wind turbulence. The Kolmogorov spectrum is observed only away from the bow shock toward the flank and the magnetopause regions in 17% of the analyzed time intervals. Measuring the magnetic compressibility, it is shown that only a fraction (35%) of the observed Kolmogorov spectra was populated by shear Alfvénic fluctuations, whereas the majority of the events (65%) was found to be dominated by compressible magnetosonic-like fluctuations, which contrasts with well- known turbulence properties in the solar wind. This study gives a first comprehensive view of the origin of the f^{-1} and the transition to the Kolmogorov inertial range; both questions remain controversial in solar wind turbulence.

Using global MHD simulation, Wang *et al.* [177] investigate the effect of the IMF on the location of the Open-Closed field line Boundary (OCB), in particular the duskside and dawnside OCB and their asymmetry. They first model the typical OCB-crossing events on 22 October 2001 and 24 October 2002 observed by DMSP. The MHD model presents a good estimate of OCB location under quasi-steady magnetospheric conditions. They then systemically study the location of the OCB under different IMF conditions. The model results show that the dawnside and duskside OCBs respond differently to IMF conditions when B-Y is present. An empirical expression describing the relationship between the OCB latitudes and IMF conditions has been obtained. It is found that the IMF conditions play an important role in determining the dawn-dusk OCB asymmetry, which is due to the magnetic reconnection at the dayside magnetopause. The differences between the dawn and dusk OCB latitudes from MHD predictions are in good agreement with the observations.

By splitting magnetic field into two components (internal plus external), they derived an extended formulation of the HLLD Riemann solver for numerical simulation of MHD. This new solver is backward compatible with the standard HLLD Riemann solver when the external component of the magnetic field is zero. Moreover, the solver is more robust than the standard HLLD solver in applications to low plasma beta (the ratio between thermal and magnetic pressures) cases, where the thermal pressure may become negative from subtracting the kinetic and large magnetic energy from the large total energy density in a Godunov type numerical scheme. Guo *et al.* [178] show that the extended HLLD solver works well for the cases of magnetic field decomposition, and maintains high resolution similar to the standard HLLD.

Energetic ion distributions in the near-Earth plasma sheet can provide important information for understanding the entry of ions into the magnetosphere and their transportation, acceleration, and losses in the near-Earth region. In this study, 11 years of energetic proton and oxygen observations (>~274 keV) from Cluster/Research with Adaptive Particle Imaging Detectors were used to statistically study the energetic ion distributions in the near-Earth region. The dawn-dusk asymmetries of the distributions in three different regions (dayside magnetosphere, near-Earth nightside plasma sheet, and tail plasma sheet) are examined in Northern and Southern Hemispheres. Luo *et al.* [179] shows that the energetic ion distributions are influenced by the dawn-dusk IMF direction. The enhancement of ion intensity largely correlates with the location of the magnetic reconnection at the magnetopause. The results imply that substorm-related acceleration processes in the magnetotail are not the only source of energetic ions in the dayside and the near-Earth magnetosphere. Energetic ions delivered through reconnection at the magnetopause significantly affect the energetic ion population in the magnetosphere. They also believe that the influence of the dawn-dusk IMF direction should not be neglected in models of the particle population in the magnetosphere.

Cluster measurements from 2001 to 2011 provide a unique opportunity to study the characteristics of O^+ with full spatial coverage between 4 to 19R_e, especially in the mid-latitude region. Three-dimensional spatial distributions of averaged omnidirectional O^+ differential fluxes in three energy channels (E_1: 40–136 eV; E_2: 136 eV–3 keV; E_3: 3–30 keV) during quiet times (Dst >–20 nT) are presented in Liu *et al.* [180]. Comparing the distributions of O^+ in three energy channels helps us to better understand the transport and energization of O^+. Consistent with previous studies, it is suggested that during quiet times O^+ is heated in the high-altitude cusp and mantle, and part of this heated population is transported through the lobes to the plasmasheet, where it is further heated/accelerated. The distributions presented provide important background information for relevant simulation and observation studies of O^+ behavior during storm and non-storm times.

Pang *et al.* [181] uses Cluster data during the period from 2001 to 2010 to study the polytropic processes of magnetosheath ions. Utilizing the method of homogeneous MHD Bernoulli Integral (MBI), they first identify streamflow tubes, then use the constant of polytropic relation to guarantee that the streamflow tube experiences an unchanged polytropic process, and finally determine the polytropic index of ions in these streamflow tubes. The statistical results show that the magnetosheath is a complicated system in which the polytropic index of ions ranges from –2 to 3. The polytropic index distribution of ions is dependent on the electromagnetic energy flux perpendicular to the streamline. The median polytropic index of ions in the magnetosheath is 0.960, 0.965, and 0.974 for perpendicular electromagnetic energy ratio $(E\times B)$<5%, $(E\times B)$<3%, and $(E\times B)$<1%, respectively. There are two basic polytropic processes in the magnetosheath: the dominant isothermal process and the isobaric process. When there is no exchange of electromagnetic energy between neighboring streamflow tubes, the magnetosheath ions are isothermal. However, when the perpendicular electromagnetic energy ratio increases, the isobaric polytropic process starts to emerge. The magnetosheath ion flows are highly localized because most streamflow tubes experiencing same polytropic processes last less than 60s. Thus, the polytropic index of magnetosheath ion flows is highly variable.

In this paper, using data obtained by Cluster 4 satellite from 2001 to 2012, Wang *et al.* [182] statistically investigate the spatial distributions of H^+ and O^+ in the magnetotail plasmasheet and their relation with geomagnetic indices. Our work outlines the existence of two regions with enhanced O^+ concentration in the tail plasmasheet, one is located in the mid-tail plasmasheet at $R>17\ R_e$, and the other is located near the inner boundary of plasmasheet at $R<10\ R_e$. The existence of the depletion region of O^+ between $10R_e<R<17\ R_e$ indicates that the O^+ ions in the mid-tail plasmasheet, which come from polar cap, are not likely to be able to make important contribution to the formation of ring current. Both the distributions of density and temperature of O^+ ions have a dawn dusk asymmetry. The number density of O^+ during geomagnetic active time (Dst<20 nT/AE>200 nT/Kp≥3) is much larger than that during non-storm time (Dst>–20 nT/AE<200 nT/Kp<3). This dawn dusk asymmetry and the number density of O^+ varying with geomagnetic activity apply for both regions ($R<10\ R_e$ and $R>17\ R_e$) of O^+. Therefore both substorm and enhanced convection provide a large number of O^+ ions to the plasmasheet, which makes favorable condition for the growth of the ring current.

8. Magnetotail

Wang *et al.* [183] report the evidence of compressible turbulence with slow-mode waves in a bursty bulk flow of plasma sheet. This compressible turbulence is characterized by a multiscale (1–60 s) anticorrelation between plasma density and magnetic field strength. Besides, the magnetic compressibility spectrum stays nearly constant at all the measured frequencies. Furthermore, the turbulence energy distributions are anisotropic with k>k, and the dispersion relation is consistent with slow- mode prediction. The fluctuations of density and magnetic field have similar double slope spectrum and kurtosis. These results suggest that the slow waves are involved in the intermittent turbulence cascade from MHD to ion kinetic scales, which may have significant implications for the energy transfer in the plasma sheet.

Using an extended MHD model including the Hall effect and finite Larmor radius effect, they reproduce multiple Dipolarization Fronts (DFs) associated with the interchange instability in the braking region of bursty bulk flow in the plasma sheet. Our simulations reveal that the multiple DFs produced by the interchange instability are "growing" type DFs because the maximum plasma flow speeds are behind the fronts. Both the earthward and tailward moving DFs can be produced by interchange instability in the near-Earth region. The Hall electric field is the dominant electric field component in the dip region and the DF layer. The convective and the electron pressure gradient electric field components are smaller. The sharp B_z changes in both the dip region and DF layer correspond to the oppositely directed currents that are primarily associated with electrons. The ion diamagnetic current due to the strong ion pressure gradient causes an intense downward current in the dip region, which can produce the dip ahead of the front. The energy dissipations in the dip region and DF layer are dominated by ions through the work done by the Lorentz force. Lu *et al.* [184] indicate that the magnetic energy can be converted to plasmas on the DF layer, and vice versa in the dip region.

Measurements of multi satellites and geomagnetic indices are used to investigate the energy budget during an isolated substorm. The calculation of the energy transfer from the solar wind to the magnetosphere (parameter e), the energy increase of the ring current (UR), the Joule heating (UJ), the particle precipitation energy flux (UA) and their time-integrated energy dissipation We, WR, WJ, WA indicates that there should be energy dissipation such as plasma heating and the energy returned to the solar wind by plasmoid ejection from the tail. After calculating the spatial sizes of nine selected BBFs, the energy flux density and energy transported Earthward or tailward by BBFs, using observations from three satellites, are found to be different during an isolated substorm. The flow thermal energy is dominant whether the energy is transported Earthward or tailward under the frozen-in condition in the inner plasma sheet. From results simultaneously observed by three satellites in the magnetotail, Ma *et al.* [185] find that the Earthward energy transported by the flows can provide the energy dissipation of WJ and WA, where the flows are Earthward for more than 60% of the samples, while the tailward energy transport is far larger than UA and close to UJ, where the flows are tailward for less than 40% of the samples. The maximum energy flux density is observed by one satellite to be accompanied by large variations, while the maximum energy transport is observed by another satellite with large energy flux density and small variations. This suggests misleading conclusions would be obtained if there were only data from single (or two) satellites. From our results, BBFs play an important role in the process of energy transport both Earthward and tailward during this isolated substorm. Data based on observations from one satellite in the magnetotail could be easily misinterpreted and should be used cautiously.

Using the data observed by the TC-1 satellite in the magnetotail season from 2004 to 2007, Ma *et al.* [186] extended the earthward high-speed flow to the lower speed and statistically investigated its spatial evolution in the geocentric distances between –13. 4 R_e and –5 R_e. Our findings are as follows: (1) When the earthward flow are moving close to the earth, the occurrence rate of the earthward flow decreases mainly around the sun-earth line, the occurrence rate in the dawn and dusk flank does not fall but rise, the highest occurrence rate locates in the dusk flank, which may indicate that the earthward flow is deflecting to the dawn and dusk flank under its process penetrating to the earth. (2) Closer to the earth, the amplitude of V and V_x is smaller; there are slight variations of V_y and V_z and their distributions are dawn-dusk asymmetry; which indicates that the process penetrating to the earth is accompanied by the dawn-dusk and north-south deflection. (3) During the earthward flow, the plasma density is relatively small on the whole; it gradually increases with the decrease of the geocentric distances. (4) The distribution of the parallel and perpendicular flow speed is dawn-dusk asymmetry. The parallel speed in the dawn is larger than that in the dusk. The perpendicular speed in the dusk is larger than that in the dawn. Considering that the large perpendicular flow speed is easy to trigger the instability closely related to the current disruption, they infer that the current disruption occurs easily in the dusk. (5) The magnetic pressure is mostly dominant with few thermal pressures comparable to the magnetic pressure. The total pressure is large near the sun-earth line and small in the dawn and dusk, so large pressure gradient forms both in the dawn and dusk direction; which cause the earthward flow deflect and the occurrence rate increase in the dawn and dusk flank. Lower pressure than the ambient can be observed in the dawn and dusk flank close to the earth, and that can be observed farther away from the earth around the sun-earth line; which suggest that the current disruption occurred at different locations in the past cases may be caused by the pressure distribution close to the earth.

Unipolar pulses of Kinetic Alfven Waves (KAW) are first observed in the Near-Earth Plasma Sheet (NEPS) associated with dipolarizations during substorm expansion phases. Two similar events are studied by Duan *et al.* [187] with Time History of Events and Macroscale Interactions during Substorms (THEMIS) observations during substorms on 3 February 2008 and 7 February 2008. The unipolar pulses were located at a trough-like Alfven speed profile in the northern plasma sheet at a distance of 10–11 R_e from Earth. The dominant wave components consist of a southward E_z toward the neutral plane and a $+B_y$ toward the dusk. The $|E_z|/|B_y|$ ratio was in the range of a few times the local Alfven speed, a strong indication of KAW nature. The wave Poynting flux was earthward and nearly parallel to the background magnetic field. The pulse was associated with an earthward field-aligned current carried by electrons. These observational facts strongly indicate a KAW eigenmode that is confined by the plasma sheet but propagates earthward along the field line. The KAW eigenmode was accompanied by short timescale (1min) dipolarizations likely generated by transient magnetotail reconnection. The observed polarity of the KAW field/current is consistent with that of the Hall field/current in magnetic reconnection, supporting the scenario that the Hall fields/current propagate out from reconnection site as KAW eigenmodes. Aurora images on the footprint of THEMIS spacecraft suggest that KAW eigenmode may power aurora brightening during substorm expansion phase.

Zhao *et al.* [188] presents an investigation of 35 magnetic flux ropes encountered by Cluster in the Earth's magnetotail during the years between 2001 and 2004. The study shows that the parallel current dominates inside 86% of the identified flux ropes and 71% of the flux ropes are surrounded by the draping regions where the parallel current is comparable to the perpendicular component and steeply changes its direction. Namely, magnetic field is nearly force-free in 86% of the identified flux ropes while it considerably deviates from the force-free in the draping region. Therefore, the observations indicate that energy conversion should take place in the draping region. Moreover, the core fields for most the flux ropes come from the interplanetary magnetic field.

Zhao *et al.* [189] reports a tailward high speed flow event observed by Cluster during 02:03:00UT–02:05:30UT on September 20, 2003. Within the flows, a series of three bipolar signatures were observed. The first and third bipolar signatures are identified as magnetic flux ropes while the middle one is found to result from the collision of the two flux ropes. A vertical thin current layer was embedded in the center of the middle bipolar signature. Combining the plasma, electric field and wave data around the thin current layer, they conclude that the two magnetic flux ropes were coalescing. The observations indicate that coalescence of magnetic flux ropes can happen in the regions away from reconnection site, and can produce energetic electrons and waves. A basic criterion for identify the coalescence in the magnetotail is proposed also.

Liu *et al.* [190] investigate the statistical properties of linear magnetic holes inside the Earth magnetotail plasma sheet region, including the occurrence rate, the temporal and spatial scales, the spatial distribution and the correlation between the occurrence rate and *AE* index, by using THEMIS satellites magnetic field and plasma data for this paper. Our results indicate that the time scale of the magnetic holes inside the magnetotail plasma sheet region varies from several seconds to tens seconds, and the spatial scale is smaller than the local proton gyro-radius. They compare the spatial distribution of satellite observations with the spatial distribution of magnetic holes. The results suggest that linear magnetic holes are often observed in the plasma sheet, while the occurrence rate is significantly lower than that of magnetic holes in the solar wind. They also analyze the correlation of the AE index with magnetic holes, and find that magnetic holes occurrence may be associated with the geomagnetic activity.

Based on Cluster data, Wang *et al.* [191] investigate 263 waves with periods between 40 and 150 s (Pi2 band events) and 161 waves with periods between 150 and 600 s (Pc5 band events) in the magnetotail lobe. Our findings are as follows: (1) 90% of the mean wave amplitudes within 40–150 s (150–600 s) are below ~0.25 (0.36) nT for the transverse components and ~0.16 (0.39) nT for the compressional components; (2) 69.6% (35.4%) of the compressional ratios of the waves with periods 40–150 s (150–600 s) are less than 0.5 with the maximum occurrence at ~0.3 (0.8); (3) waves within 40–150 s are more likely to occur in the lobe region close to the plasma sheet; (4) the wave amplitudes and the AE index are weakly correlated; however, the amplitudes tend to be larger when the AE index is larger; and (5) the amplitudes also tend to be larger when the solar wind velocity and the solar wind dynamic pressure or its variations (ΔPSW) are larger; the correlation coefficient between the wave amplitudes with periods between 150 and 600 s and ΔPSW is up to ~0.58. They suggest that both dynamic processes in the plasma sheet boundary layer or plasma sheet (inner sources) and solar wind conditions (outer sources) can contribute to the generation of the lobe ULF waves; waves within 40–150 s are affected more by inner sources, while strong ΔPSW can drive compressional waves within 150–600 s in the magnetotail lobe.

A kink-like neutral sheet oscillation event observed by Cluster between 1436 and 1445 UT on 15 October 2004 has been investigated. The oscillations with periods between 40 and 60 s, observed at (–13.1, 8.7, –0.5) R_e, are dominant in B_x and B_y. And they propagate mainly duskward with a velocity of (86, 147, 46) km/s. Their periods and velocity can be explained by the magnetic double-gradient instability. These oscillations are accompanied by strong Field-Aligned Currents (FACs), which prefer to occur near the strongly tilted current sheet, and local maximum FAC tends to occur near the neutral sheet. The FACs show one-to-one correlated with a high-latitude Pi2 pulsation event recorded by KTN and TIK stations with a delay time of ~60 and 90 s, respectively. Both the Pi2 and oscillations propagate westward with a comparative conjunctive speed. These findings suggest a strong relation between the FACs and Pi2, and they infer that the Pi2 is caused by the FACs. The periods of the FACs are modulated by the oscillations but not exactly equal, which is one possible reason that the period of the Pi2 caused by the FACs could be different from the oscillations. Wang *et al.* [192] speculates that a current circuit between the plasma sheet and ionosphere can be formed during strongly tilted current sheet, and successive tilted current sheet could generate quasi-periodic multiple FAC systems, which can generate high-latitude Pi2 pulsations and control their periods.

Xiao *et al.* [193] study the average shape and position of the magnetotail neutral sheet based on magnetic field data obtained by Cluster, Geotail, TC-1, and THEMIS from the years 1995 to 2013. All data in the aberrated GSM (Geocentric Solar Magnetospheric) coordinate system are normalized to the same solar wind pressure 2 nPa and downtail distance x~–20 R_e. Our results show characteristics of the neutral sheet, as follows. (1) The neutral sheet assumes a greater degree of curve in the yz cross section when the dipole tilt increases, the Earth dipole tilt angle affects the neutral sheet configuration not only in the xy cross section but also in the xy cross section, and the neutral sheet assumes a more significant degree of tilt in the xy cross section when the dipole tilt increases. (2) Counterclockwise twisting of the neutral sheet with 3.10° is observed, looking along the downtail direction, for the positive iIMF E_y with a value of 3 to 8 nT, and clockwise twisting of the neutral sheet with 3.37° for the negative IMF E_y with a value of –8 to –3 nT, and a northward IMF can result in a greater twisting of the near-tail neutral sheet than southward. The above results can be a reference to the neutral sheet model. Our large database also shows that the displaced ellipse model is effective to study the average shape of the neutral sheet with proper parameters when the dipole tilt angle is larger (less) than 10° (–10°).

Xiao *et al.* [194] investigate the occurrence rate of Dipolarization Fronts (DFs) in the plasma sheet by taking full advantage of all four Cluster satellites (C1–4) from years 2001 to 2009. In total, they select 466 joint-observation DF events, in which 318, 282, 254, and 236 DFs are observed by C1, C2, C3, and C4, respectively. Our findings are as follows: (1) the maximum occurrence rate is ~ 15.3 events per day at x ~ 15 R_e in the XY plane, and the average occurrence rate is ~ 5.4 events per day over the whole observation period; (2) the occurrence rate on the dusk side of the plasma sheet is larger and decreases with increasing $B_{xy}=B_{Lobe}$; (3) the occurrence rate within $|y|<6$ R_e increases gradually from $x\approx-19$ to –15 R_e and then decreases from $x\approx-15$ to –10 R_e; (4) the occurrence rate when AE>200 nT is much larger than that when AE<200 nT, indicating that DFs preferentially occur during high geomagnetic activity. The magnetic pileup and earthward and duskward ion flows could contribute to the increases in the occurrence rate from $x\approx-19$ to –15 R_e. They suggest that both geomagnetic activity and multiple DFs contribute to the high occurrence rate of the DFs. In addition, the finite length of the DF in the dawn–dusk direction can affect the chance that a satellite observes the DF.

Flux-rope/TCR events near the magnetotail lunar orbit (–67 R_e<GSM x^*<–39 R_e) were studied using magnetic-field and plasma data measured by THEMIS B and C between January 2011 and March 2012. The aberrant coordinate GSM*, where the x^* axis is rotated 4° relative to GSM-X, was used to count the occurrence rate. The number ratio of earthward to tailward events was about 3:5. Moreover, the event occurrence rate distribution showed a clear dawn-dusk asymmetry distribution, with dusk-side events accounting for 57.98%. A superposed epoch analysis of the flux-rope events showed that earthward events had a shorter duration in the leading than in the trailing part. Earthward events also displayed a lower temperature and a lower flow speed than tailward events. They studied the relationship between the event occurrence rate and geomagnetic activity level even further. The occurrence rate of tailward flux-rope/TCR events increases with increasing *AE*-index, whereas earthward events occur mainly in the relatively quiet period of geomagnetic activity(*AE*~ 100–300 n T). Flux-rope/TCR events identified within a 10 mm time frame were treated as belonging to a single reconnection event. By comparing the occurrence rates of earthward and tailward events along x^*, Zhao *et al.* [61] estimated the most likely location of the near-Earth reconnection site as x^*=–36 R_e.

Magnetotail plasma sheet is the most active area in Earth's magnetosphere. Zhang *et al.* [195] found that the features of plasma sheet are controlled by the conditions of solar wind and IMF. Some previous statistical studies have found that some parameters of the plasma sheet are dawn-dusk asymmetric. But the thickness of the magnetotail plasma sheet in the near and mid-tail region and how they are influenced by the IMF is still unclear. In this paper, the probability of the Cluster-C1 satellite encountering the plasma sheet is examined statistically by utilizing the proton flux and data from the CODIF and FGM equipment on board the Cluster-C1. Using data from July to November of year 2001–2004, the distributions of the probability of satellite in the plasma sheet are mapped on the y_{Dz} plane (D_z denotes the distance between the satellite and the neutral sheet) during the southward and northward IMF periods, respectively. By comparison, they found that the plasma sheet is thinner during southward IMF periods than that during northward IMF periods. It is more obvious in the flank regions of the plasma sheet. They also found that the plasma sheet in the dusk side is thinner than that in the dawn side.

Using Time History of Events and Macroscale Interactions during Substorms (THEMIS) observations from 2007 to 2011 tail seasons, Pan *et al.* [196] study the plasma properties of High Speed Flows (HSFs) and Background Plasma Sheet events (BPSs) in Earth's magnetotail ($|y_{GSM}|<13\ R_e$, $|z_{GSM}|<5\ R_e$, $-30\ R_e<x_{GSM}<-6\ R_e$), and their correlations with solar wind parameters. Statistical results show that the closer the HSFs and BPSs are to the Earth, the hotter they become, and the temperature increase of HSFs is larger than that of BPSs. The density and temperature ratios between HSFs and BPSs are also larger when events are closer to Earth. They also find that the best correlations between the HSFs (BPSs) density and the solar wind density occur when the solar wind density is averaged 2 (3.5) hours prior to the onset of HSFs (BPSs). The normalized densities of both HSFs and BPSs are correlated with the IMF angles which are averaged 3 hours before the observation time. Further analysis indicates that both HSFs and BPSs become denser during the northward IMF period.

Utilizing conjunction observations of the Geotail and ACE satellites from 1998 to 2005, they investigated the temporal evolutions of the solar wind conditions prior to the formation of X lines in the near-Earth magnetotail. Zhang *et al.* [75] first show the statistical properties of B_z, B_y, density, and velocity of the solar wind related to the 374 tail X line events. A superposed epoch analysis is performed to study the temporal evolutions of the solar wind conditions 5 h prior to the tail X lines. The solar wind conditions for tail X lines during SW-IMF andNW-IMF are analyzed. The main results are as follows: (1) For events classified as SW-IMF, near-Earth X line observations in the magnetosphere are preceded by similar to 2 h intervals of southward IMF; (2) for events classified as NW-IMF, the northward IMF orientation preceding near-Earth X line observations lasts similar to 40 min.

Guo *et al.* [197] employ two-dimensional global hybrid simulations to study the generation, propagation, and polarization of EMIC waves in the near-Earth magnetotail (around x=–10 R_e) during dipolarization. In our simulation, EMIC waves with left-hand polarized signals originate in the low-latitude magnetotail as a result of the ion temperature anisotropy which is due to ion heating by Alfvén waves. Subsequently, EMIC waves can propagate along the ambient magnetic field toward high-latitudes. Our work provides one possible mechanism for the generation of EMIC waves observed in the near-Earth magnetotail.

In Guo *et al.* [198], ion heating by Alfvén waves associated with dipolarization in the near-Earth magnetotail is investigated by performing a two-dimensional (2-D) global-scale hybrid simulation. In our simulation, the earthward propagating plasma flow is initialized by the E×B drift near the equatorial plane due to the existence of the dawn-dusk convection electric field. When the earthward flow reaches the strong dipole field region, it is braked by the geomagnetic field and simultaneously leads to the pileup of the magnetic flux. This continuous pileup finally results in the formation of the large-scale dipolarization. Dipolarization first appears around $(x, z)=(–10.5, 0.3)$ R_e (where R_e is the radius of Earth) and subsequently spreads tailward. In the dipolarization region, Alfvén waves are excited and cause the scattering and heating of ions. The heating is mainly on the perpendicular direction. Therefore, the ion temperature anisotropy can be formed in the dipolarization region. Our work provides one possible mechanism for the ion heating and anisotropic distributions observed near the dipolarization region.

A statistical study of the THEMIS FGM and ESA data is performed by Wu *et al.* [199] on turbulence of magnetic field and velocity for 218 selected 12 min intervals in BBFs. The spectral index α in the frequency range of 0.005–0.06 Hz are Gaussian distributions. The peaks indexes of total ion velocity V_i and parallel velocity V are 1.95 and 2.07 nearly the spectral index of intermittent low frequency turbulence with large amplitude. However, most probable α of perpendicular velocity $V_\perp$ is about 1.75. It is a little bigger than 5/3 of Kolmogorov (1941). The peak indexes of total magnetic field BT is 1.70 similar to $V_\perp$. Compression magnetic field $B_{||}$ are 1.85 which is smaller than 2 and bigger than 5/3 of Kolmogorov (1941). The most probable spectral index of shear $B_\perp$ is about 1.44 which is close to 3/2 of Kraichnan (1965). Max $V_\perp$ have little effect on the power magnitude of VT and $V_{||}$ but is positively correlated to spectral index of $V_\perp$. The spectral power of B_T, $B_{||}$ and $B_\perp$ increase with max perpendicular velocity but spectral indexes of them are negatively correlated to $V_\perp$. The spectral index and the spectral power of magnetic field over the frequency interval 0.005–0.06 Hz is very different from that over 0.08–1 Hz.

Zhao *et al.* [188] present an investigation of 35 magnetic flux ropes encountered by Cluster in the Earth's magnetotail during the years between 2001 and 2004. The study shows that the parallel current dominates inside 86% of the identified flux ropes and 71% of the flux ropes are surrounded by the draping regions where the parallel current is comparable to the perpendicular component and steeply changes its direction. Namely, magnetic field is nearly force-free in 86% of the identified flux ropes while it considerably deviates from the force-free in the draping region. Therefore, the observations indicate that energy conversion should take place in the draping region. Moreover, the core fields for most the flux ropes come from the interplanetary magnetic field.

Zhao *et al.* [189] report a tailward high-speed flow event observed by Cluster during 02:03:00UT–02:05:30UT on 20 September 2003. Within the flows, a series of three bipolar B_z signatures were observed. The first and third bipolar B_z signatures are identified as magnetic flux ropes, while the middle one is found to result from the collision of the two flux ropes. A vertical thin current layer was embedded in the center of the middle bipolar B_z signature. Combining the plasma, electric field, and wave data around the thin current layer, they conclude that the two magnetic flux ropes were coalescing. The observations indicate that coalescence of magnetic flux ropes can happen in the regions away from reconnection site and can produce energetic electrons and waves. A basic criterion for identifying the coalescence in the magnetotail is proposed also.

Electron acceleration in the near-Earth magnetotail during the substorm period is still an unresolved question. In this paper, by tracing electron trajectories in the dynamically evolving electromagnetic fields obtained from a two-dimensional (2D) global hybrid simulation, they investigate electron acceleration in the near-Earth magnetotail during dipolarization. In our simulation, electrons with energies above several keV can gain energy in the plasma sheet due to the adiabatic acceleration mechanism when these electrons propagate earthward. In the near-Earth magnetotail (about 9–15 R_e from the Earth), these electrons can be accelerated by betatron acceleration which is due to the compression of magnetic field associated with dipolarization of magnetotail. Additionally, in the middle and high latitudes of the near-Earth magnetotail, the parallel electric field carrying by kinetic Alfvén waves can also accelerate electrons when these electrons bounce between the mirror points. The combination effects of these three acceleration mechanisms can accelerate electrons from several keV to about one hundred keV. Guo *et al.* [200] indicate that both the large-scale structure and wave-particle interactions need to be taken into account for electron acceleration in the near-Earth magnetotail.

Bursty Bulk Flows (BBFs) have been correlated with Pi2 pulsations and damping oscillations of plasma velocity in many investigations. But the oscillation time scales in BBFs are still an open question. The purpose of Wu *et al.* [201] is to statistically study the oscillated frequency distribution of magnetic field and plasma parameters inside BBFs. The data are obtained by the Time History of Events and Macroscale Interactions during Substorms (THEMIS) probes during the period of 2008 to 2011. For 424 selected BBF events, they use the wavelet spectrum analysis to select the main, second, and third period components of the magnetic field and plasma parameters according to their largest, second, and third largest values of the wavelet power spectral density, respectively. The power spectra show repeated information in the form of multiple peaks or oscillations. The quasi-Gaussian distribution is a good model for the occurrences of the main and secondary periods. The most probable main periods of the magnetic field and plasma parameters are between 143 s and 160 s, which are located in the frequency band of Pi2 and Pi3 pulsations. The second and third period ranges from 63s to 70 s and from 34s to 37 s, respectively. Main periods of these parameters change little with the radial distance. They conclude that periods of these parameters are formed at the beginning of BBF history. Although the distribution model cannot give the dynamic processes, it identifies the intrinsic frequencies in oscillations of magnetic field and ion velocity inside of BBFs.

The magnetic field energy stored in geomagnetotail released during a substorm period, cause significant magnetic disturbance of the space environment. The quantitative relationship between the magnetic field energy and the level of substorm activity, however, is still unclear, although many studies have qualitatively revealed the correlation between them. Here, using data from four selected isolated substorm cases, the evolution of the Magnetic Flux (MF) in the magnetotail observed by Cluster is quantitatively surveyed. The results from the four cases demonstrate that the evolution of magnetotail MF is closely related to the phases of substorm development. For quiet time, the magnetotail is in the ground state with ME being about 0.6 GWb. During the growth phase, however, as the substorm develop the MF keeps increasing, the substorm onset is triggered when the MF has increased up to some threshold. The comparison between the four cases shows that the accumulation of more magnetic field energy corresponds to more released energy, and consistently, the more intense a substorm can be powered. Yang *et al.* [202] also find that there is an imbalance between the increased and decreased MF amplitude, indicating that the substorm may not be the only way to release the stored magnetotail energy.

Using a global magnetospheric MHD model coupled with a kinetic ring current model, they investigate the effects of magnetotail dynamics, particularly the earthward Bursty Bulk Flows (BBFs) produced by the tail reconnection, on the global-scale current systems. The simulation results indicate that after BBFs brake around x=–10 R_e due to the dipolar "magnetic wall, "vortices are generated on the edge of the braking region and inside the inner magnetosphere. Each pair of vortex in the inner magnetosphere disturbs the westward ring current to arc radially inward as well as toward high latitudes. The resultant pressure gradient on the azimuthal direction induces region-1 sense field-aligned component from the ring current, which eventually is diverted into the ionosphere at high latitudes, giving rise to a pair of Field-Aligned Current (FAC) eddies in the ionosphere. On the edge of the flow braking region where vortices also emerge, a pair of region-1 sense FACs arises, diverted from the cross-tail duskward current, generating a substorm current wedge. This is again attributed to the increase of thermal pressure ahead of the bursty flows turning azimuthally. It is further found by Yu *et al.* [203] that when multiple BBFs, despite their localization, continually and rapidly impinge on the " wall, " carrying sufficient tail plasma sheet population toward the Earth, they can lead to the formation of a new ring current. These results indicate the important role that BBFs play in bridging the tail and the inner magnetosphere ring current and bring new insight into the storm-substorm relation.

Using Time History of Events and Macroscale Interactions during Substorms (THEMIS) observations from 2007 to 2011 tail seasons, they study the plasma properties of High Speed Flows (HSFs) and Background Plasma Sheet events (BPSs) in Earth's magnetotail ($|y_{GSM}|$<13 R_e, $|z_{GSM}|$<5 R_e, –30 R_e<x_{GSM}<–6 R_e), and their correlations with solar wind parameters. Statistical results show that the closer the HSFs and BPSs are to the Earth, the hotter they become, and the temperature increase of HSFs is larger than that of BPSs. The density and temperature ratios between HSFs and BPSs are also larger when events are closer to Earth. Pan *et al.* [196] also find that the best correlations between the HSFs (BPSs) density and the solar wind density occur when the solar wind density is averaged 2 (3.5) hours prior to the onset of HSFs (BPSs). The normalized densities of both HSFs and BPSs are correlated with the IMF theta angles which are averaged 3 hours before the observation time. Further analysis indicates that both HSFs and BPSs become denser during the northward IMF period.

The energization and heating processes for protons in the near-Mercury tail are examined with MErcury Surface, Space ENvironment, GEochemistry, and Ranging (MESSENGER) observations. In a case study, Suprathermal Proton Particle Flux (STPF) and proton temperature are observed to be clearly enhanced during near-Mercury substorm dipolarizations, indicating the proton energization and heating processes. STPF and proton temperature distributions in near-Mercury central plasma sheets display dawn-dusk asymmetries, with higher values in the dawnside plasma sheet, *i.e.*, postmidnight, than in the duskside, *i.e.*, premidnight. Further investigations reveal that these asymmetries are more prominent during active periods in Mercury's magnetosphere, as compared to quiet periods. Magnetic field variations in the z_{MSM} component display a similar feature, with variations being more prominent on the dawnside than the duskside during active periods. Sun *et al.* [204] propose that the dawn-dusk asymmetry in the distributions of protons could be due to the fact that more substorm dipolarizations were initiated on the dawnside of Mercury's magnetotail.

In the classical picture of the magnetotail current sheet, the current carriers are mainly ions that undergo nonadiabatic motions. Oxygen ions could contribute a thicker current sheet than the protons due to their large gyroradii. Wu *et al.* [205] report a thin energetic O^+ layer embedded in the magnetotail proton current sheet observed by Cluster on 11 October 2001. The thickness of the O^+ layer is estimated to be smaller than the half thickness of the local current sheet. And the layer is formed by energetic O^+ with energy larger than 20 keV moving along the + direction in GSE coordinates. It is inferred that these energetic O^+ are probably generated due to the selective acceleration effect of the thin reconnection electric field to the upstreaming ionospheric O+ ions with different initial condition.

Magnetic Holes (MHs), characteristic structures where the magnetic field magnitude decreases significantly, have been frequently observed in space plasmas. Particularly, Small Size Magnetic Holes (SSMHs) which the scale is less than or close to the proton gyroradius are recently detected in the magnetospheric plasma sheet. In this study of Cluster observations, by the timing method, the Minimum Directional Difference (MDD) method, and the SpatioTemporal Difference (STD) method, they obtain the propagation velocity of SSMHs in the plasma flow frame. Furthermore, based on Electron Magnetohydrodynamics (EMHD) theory, Yao *et al.* [172] calculate the velocity, width, and depth of the electron solitary wave and compare it to SSMH observations. The result shows a good accord between the theory and the observation.

MHs, with a scale much greater than pi (proton gyroradius), have been widely reported in various regions of space plasmas. On the other hand, Kinetic-Size Magnetic Holes (KSMHs), previously called small-size magnetic holes, with a scale of the order of magnitude of or less than.i have only been reported in the Earth's magnetospheric plasma sheet. Yao *et al.* [171] report such KSMHs in the magnetosheath whereby they use measurements from the Magnetospheric Multiscale mission, which provides three-dimensional (3-D) particle distribution measurements with a resolution much higher than previous missions. The MHs have been observed in a scale of 10–20 ρ_e (electron gyroradii) and lasted 0.1–0.3 s. Distinctive electron dynamics features are observed, while no substantial deviations in ion data are seen. It is found that at the 90 degrees pitch angle, the flux of electrons with energy 34–66 eV decreased, while for electrons of energy 109–1024 eV increased inside the MHs. They also find the electron flow vortex perpendicular to the magnetic field, a feature self-consistent with the magnetic depression. Moreover, the calculated current density is mainly contributed by the electron diamagnetic drift, and the electron vortex flow is the diamagnetic drift flow. The electron magnetohydrodynamics soliton is considered as a possible generation mechanism for the KSMHs with the scale size of 10–20 ρ_e.

Zhao *et al.* [206] present new observations of electron distributions and the accompanying waves during the current sheet activities at similar to 60 R_e in the geomagnetic tail detected by the ARTEMIS (Acceleration, Reconnection, Turbulence, and Electrodynamics of the Moon's Interaction with the Sun) spacecraft. They find that electron flat-top distribution is a common feature near the neutral sheet of the tailward flowing plasmas, consistent with the electron distributions that are shaped in the reconnection region. Whistler mode waves are generated by the anisotropic electron temperature associated with the electron flat-top distributions. These whistler mode waves are modulated by low frequency ion scale waves that are possibly excited by the high- energy ions injected during the current sheet instability. The magnetic and electric fields of the ion scale waves are in phase with electron density variations, indicating that they are compressional ion cyclotron waves. Our observations present examples of the dynamical processes occurring during the current sheet activities far downstream of the geomagnetic tail.

Dipolarization Front (DF) is a thin magnetic structure embedded in fast flows in the magnetotail, which plays an important role in particle acceleration, flow braking, wave excitation, and other related processes. Electromagnetic disturbances near the magnetic dip region in front of DFs are investigated using Time History of Events and Macroscale Interactions during Substorms probe observations in this paper. Strong magnetic field and electric field fluctuations, with several wave bands below and around the lower hybrid frequency, are found by Zhao *et al.* [207] in an event on 21 March 2008. The properties of the wave are similar to that of magnetosonic wave. Detailed analyses show that the phase space density for ions in the perpendicular direction has a positive slope near the local Alfven speed, which is a possible free-energy source for the generation of the wave. This type of ion distribution could result from the earthward reflected ions ahead of DF, though other forming mechanism could not be fully ruled out.

9. Geomagnetic Field, Auroras and Currents

Magnetic field disturbances with a clear bipolar signature are frequently observed when the Cluster spacecraft fleet passes through both southern and northern high-latitude energetic electron boundaries at the nightside magnetosphere. The dominant variation of the bipolar signature is in the azimuthal direction of the local mean field-aligned coordinate, indicating a field- aligned current. From 2001 to 2008, they have examined 110 events with the magnetic field and energetic electron measurements. The main results can be summarized as follows: (1) The density and thickness of the field-aligned current, calculated under the assumption of the one-dimensional sheet, are in order of tens of nA/m^2 and hundreds of kilometers, respectively. (2) Currents flowing into and away from the ionosphere tend to be observed in the postmidnight and premidnight sector, respectively, which have the same polarity as the region 1 current system. (3) These currents mainly distribute in the 60°–75° magnetic latitude region after mapping to the ionosphere. Ren *et al.* [209] also find that the current density and corresponding magnetic field variation are positively correlated with the Kp index and solar wind pressure, but almost independent of the AE index.

Seasonal variation of geomagnetic field around auroral zone is analyzed in terms of geomagnetic latitude, Magnetic Local Time (MLT) and geomagnetic condition in this study. The study uses horizontal component (H) of geomagnetic field obtained from 6 observatories located in geomagnetic latitude of 57.8° N–73.8° N along 115° E longitudinal line. Zhu *et al.* [210] indicates that seasonal variations of geomagnetic field around auroral zone are different combinations of annual and semiannual variations at different latitudinal ranges. Both annual and semiannual variations show distinct MLT dependency: (1) At dayside auroral latitudes (around 72° N geomagnetic latitude), geomagnetic field shows distinct annual variation under both quiet and disturbed conditions. Furthermore, the annual component is mainly contributed by data of dusk sector. (2) At nightside auroral latitudes (around 65° N), geomagnetic field shows semiannual dominated seasonal variation. Under quiet conditions the annual component is comparable to the semiannual component, while under disturbed conditions, the semiannual component is twice as much as the annual component. Under quiet conditions, the semiannual component is mainly contributed by 1300–1400 MLT, while the annual component has two peaks: one is around 1100–1300 MLT and the other is around 2000–2200 MLT. Under disturbed conditions, the semiannual component is mainly contributed by data around midnight, while the annual component is mainly contributed by dusk sector. (3) At subauroral latitudes (around 60° N), annual variation is comparable to semiannual variation under both quiet and disturbed conditions. Both annual and semiannual components show similar MLT dependencies as that of nightside auroral latitudes.

An automatic auroral boundary determination algorithm is proposed in Ding *et al.* [211] based on the partial auroral oval images from the Global UltraViolet Imager (GUVI) aboard the Thermosphere-Ionosphere-Mesosphere Energetics and Dynamics satellite and the Special Sensor Ultraviolet Spectrographic Imager (SSUSI) aboard the Defense Meteorological Satellite Program (DMSP F16). This algorithm based on the fuzzy local information C-means clustering segmentation can be used to extract the auroral oval poleward and equatorward boundaries from merged images with filled gaps from both GUVI and SSUSI. Both extracted poleward and equatorward boundary locations are used to fit the global shape of the auroral oval with a off-center quasi-elliptical fitting technique. Comparison of the extracted auroral oval boundaries with those identified from the DMSP SSJ observations demonstrates that this new proposed algorithm can reliably be used to construct the global configuration of auroral ovals under different geomagnetic activities at different local times. The statistical errors of magnetic latitudes of the fitted auroral oval boundaries were generally less than 3° at 2σ and indicate that the fitted boundaries agree better with b2e and b5e than b1e and b6 boundaries. This proposed algorithm provides us with a useful tool to extract the global shape and position of the auroral oval from the partial auroral images.

On the basis of Field-Aligned Currents (FACs) and Hall currents derived from high-resolution magnetic field data of the Swarm constellation, the average characteristics of these two current systems in the auroral regions are comprehensively investigated by statistical methods. This is the first study considering both current types determined simultaneously by the same spacecraft in both hemispheres. The FAC distribution, derived from the novel Swarm dual-spacecraft approach, reveals the well-known features of Region 1 (R1) and Region 2 (R2) FACs. At high latitudes, Region 0 (R0) FACs appear on the dayside. Their flow direction, up or down, depends on the orientation of the IMF By component. Of particular interest is the distribution of auroral Hall currents. The prominent auroral electrojets are found to be closely controlled by the solar wind input, but Huang *et al.* [212] find no dependence of their intensity on the IMF B_y orientation. The eastward electrojet is about 1.5 times stronger in local summer than in winter. Conversely, the westward electrojet shows less dependence on season. As to higher latitudes, part of the electrojet current is closed over the polar cap. Here the seasonal variation of conductivity mainly controls the current density. During local summer of the Northern Hemisphere, there is a clear channeling of return currents over the polar cap. For positive (negative) IMF B_y a dominant eastward (westward) Hall current circuit is formed from the afternoon (morning) electrojet towards the dawn side (dusk side) polar cap return current. The direction of polar cap Hall currents in the noon sector depends directly on the orientation of the IMF B_y. This is true for both signs of the IMF B_z component. Comparable Hall current distributions can be observed in the Southern Hemisphere but for opposite IMF B_y signs. Around the midnight sector the westward substorm electrojet is dominating. As expected, it is highly dependent on magnetic activity, but it shows only little response to season and IMF B_y polarity. An important finding is that all the IMF B_y dependences of FACs and Hall currents practically disappear in the dark winter hemisphere.

Zhang *et al.* [213] report simultaneous global monitoring of a patch of ionization and in-situ observation of ion upflow at the center of the polar cap region during a geomagnetic storm. Our observations indicate strong fluxes of upwelling O^+ ions originating from frictional heating produced by rapid antisunward flow of the plasma patch. The statistical results from the crossings of the central polar cap region by DMSP F16, F17 and F18 from 2010 to 2013 confirm that the field- aligned flow can turn upward when rapid antisunward flows appear, with consequent significant frictional heating of the ions, which overcomes the gravity effect. They suggest that such rapidly moving patches can provide an important source of upwelling ions in a region where downward flows are usually expected. These observations give new insight into the processes of ionosphere-magnetosphere coupling.

Zhang *et al.* [214] report the continuous monitoring of a polar cap patch, encompassing its creation and a subsequent evolution that differs from the classic behavior. The patch was formed from the Storm Enhanced Density (SED) plume, by segmentation associated with a SubAuroral Polarization Stream (SAPS) generated by a substorm. Its initial anti-sunward motion was halted due to a rapidly changing of IMF conditions from strong southward to strong eastward with weaker northward components and the patch subsequently very slowly evolved behind the duskside of a lobe reverse convection cell in afternoon sectors, associated with high-latitude lobe reconnection, much of it fading rapidly due to an enhancement of the ionization recombination rate. This differs from the classic scenario where polar cap patches are transported across the polar cap along the streamlines of twin-cell convection pattern from day to night. This observation provides us new important insights into patch formation and control by the IMF, which has to be taken into account in F-region transport models and space weather forecasts.

A comparison tool has been developed by Wang *et al.* [215] which mapping the global GPS Total Electron Content (TEC) and large coverage of ionospheric scintillations together on the geomagnetic latitude/magnetic local time coordinates. Using this tool, a comparison between large-scale ionospheric irregularities and scintillations are pursued during a geomagnetic storm. Irregularities, such as Storm Enhanced Density (SED), middle-latitude trough and polar cap patches, are clearly identified from the TEC maps. At the edges of these irregularities, clear scintillations appeared but their behaviors were different. Phase scintillations (σ_φ) were almost always larger than amplitude scintillations (S_4) at the edges of these irregularities, associated with bursty flows or flow reversals with large density gradients. An unexpected scintillation feature appeared inside the modeled auroral oval where S_4 were much larger than σ_φ, most likely caused by particle precipitations around the exiting polar cap patches.

Using two B-spline basis functions of degree 4 and the ionospheric scintillation data from a Global Positioning Satellite System (GPS) scintillation receiver at South Pole, Priyadarshi *et al.* [216] reproduced ionospheric scintillation indices for the periods of the six X-class solar flares in 2013. These reproduced indices have filled the data gaps, and they are serving as a smooth replica of the real observations. In either event, these modeled scintillation indices are minimizing the geometrical effects between GPS satellite and the receiver. Six X-class solar flares have been studied during the summer and winter months, using the produced scintillation indices based on the observations from the GPS receiver at South Pole and the in situ plasma measurement from the associated passing of Defense Meteorological Satellite Program. These results show that the solar flare peak suppresses the scintillation level and builds time-independent scintillation patterns; however, after a certain time from the solar flare peak, complicated scintillation patterns develop at high-latitude ionosphere and spread toward the polar cap boundary region. Substantial consistency has been found between moderate proton fluxes and scintillation enhancement.

Based on in situ and ground-based observations, Zhang *et al.* [217] identified a new type of "polar cap hot patch", of the same order of density enhancement as classical patches in the topside ionosphere. The classical polar cap patches are transported from the dayside sunlit region with dense and cold plasma, while the polar cap hot patches are associated with particle precipitations (therefore field-aligned currents), ion upflows, and flow shears. The hot patches may be produced by transported photoionization plasma into flow channels. Hot patches may lead to slightly stronger ionospheric scintillations of GNSS signals in the polar cap region than classical patches.

SubAuroral Polarization Stream (SAPS) electric field can play an important role in the coupling between the inner magnetosphere and ionosphere; however, the production mechanism of SAPS has not been yet solved. During an energetic ion injection event on 26 March 2004, at latitudes lower than the equatorward boundaries of precipitating plasma sheet electrons and ions, Yuan *et al.* [218] report that the Defense Meteorological Satellite Program (DMSP) F13 satellite simultaneously observed a strong SAPS with the peak velocity of 1294 m/s and downward flowing Field-Aligned Currents (FACs). Conjugate observations of DMSP F13 and NOAA 15 satellites have shown that FACs flowing into the ionosphere just lie in the outer boundary of the Ring Current (RC). The downward flowing FACs were observed in a region of positive latitudinal gradients of the ion energy density, implying that the downward flowing FACs are more likely linked to the azimuthal gradient than the radial gradient of the RC ion pressure. Their result demonstrates that RC ion pressure gradients on the outer boundary of the RC in the evening sector during energetic ion injection events can lead to downward flowing FACs so as to cause strong SAPS in condition of low ionospheric conductivities.

During the energetic ion injection event observed by the Los Alamos National Laboratory geosynchronous spacecraft, with observations of the NOAA 15 satellite and Finnish network of search coil magnetometers, Yuan *et al.* [219] have shown that a sharp enhancement of precipitating Ring Current (RC) ion flux is contributed to the pitch angle scattering caused by EMIC waves. At subauroral latitudes, lower than the equatorward edge of precipitating electrons from the plasma sheet, the DMSP F13 satellite observed a SubAuroral Polarization Stream (SAPS) with a peak velocity of 688 m/s. When passing the region of EMIC waves derived by the Finnish network of search coil magnetometers and NOAA 15 satellite, the DMSP F13 satellite simultaneously observed Field-Aligned Currents (FACs) flowing into the ionosphere and precipitating RC ions in the region of the SAPS. The peak of the SAPS accords to the minimum of the ion density in the region of the SAPS. Their result suggests that loss of RC ions caused by EMIC waves would possibly lead to FACs flowing into the ionosphere and drive the SAPS in the evening sector.

A sounding rocket experiment undertaken by the Chinese Meridian Project from a low latitude station on Hainan Island (19.5° N, 109.1° E), China, measured the DC electric field during 05:45–05:52 LT on April 5, 2013. The data observed using a set of electric field double probes, as part of the rocket's scientific payload, revealed the special profile of how the vectors of the DC electric field vary with altitude between 130 and 190 km. During the experiment, the vertical electric field was downward, and the maximum vertical electric field was nearly 5.1 mV/m near the altitude of 176 km. The zonal electric field was eastward and slightly less than 0.6 mV/m. The plasma drift velocity was estimated from the ExB motion, and the zonal drift velocity was eastward and of the order of 100 m/s. The zonal wind velocity was also estimated using the drift velocity near the maximum density height in the F1-region, and it was found to be nearly 120 m/s. Li *et al.* [220] constituted the first in situ measurement of the DC electric field conducted within the F1-region (between 130 and 190 km) in the East Asian Sector.

The temporal and spatial evolution characteristics of the geomagnetic Secular Acceleration (SA) are investigated, based on CHAOS-4 core field model during the period of 1997–2013. The SA evolution on a short time scale is associated with the phenomenon of the geomagnetic jerk. More details of the global extent and the occurrence time of the successive jerks (the 1999, 2003, 2007, and 2011 jerks) are obtained. The location, size and reversed polarity pattern for the 1999 jerk are similar to those for the 2003 jerk in the Asian-Indian sector. While the 2007 and 2011 jerks mainly take place in the Atlantic sector. The direction and speed of the shift for the four jerks are different, identified by the occurrence time of the jerks. The zonal motions of the SA patches exhibit an oscillation pattern in the Asian-Indian sector, whereas a purely westward drifting pattern is along the equator in the Atlantic sector. Ou *et al.* [221] believes that the shift of the jerks is related to the motion of SA-Br patches observed at the Core-Mantle Boundary (CMB).

Quasi-Biennial Oscillations (QBOs), with periods in the range 1–3 years, have been persistently observed in the geomagnetic field. They provide unique information on the mechanisms by which magnetospheric and ionospheric current systems are modulated on inter annual timescales and are also of crucial importance in studies of rapid core field variations. Ou *et al.* [222] documents the global characteristics of the geomagnetic QBO, using ground-based data collected by geomagnetic observatories between 1985 and 2010, and reexamine the origin of the signals. Fast Fourier transform analysis of second-order derivatives of the geomagnetic x, y, and z components reveals salient QBO signals at periods of 1.3, 1.7, 2.2, 2.9, and 5.0 years, with the most prominent peak at 2.2 years. The signature of geomagnetic QBO is generally stronger in the x and z components and with larger amplitudes on geomagnetically disturbed days. The amplitude of the QBO in the x component decreases from the equator to the poles, then shows a local maximum at sub-auroral and auroral zones. The QBO in the z component enhances from low latitudes toward the polar regions. At high latitudes (poleward of 50°) the geomagnetic QBO exhibits stronger amplitudes during LT 00:00–06:00, depending strongly on the geomagnetic activity level, while at low latitudes the main effect is in the afternoon sector. These results indicate that the QBOs at low-to-middle latitudes and at high latitudes are influenced by different magnetospheric and ionospheric current systems. The characteristics of the multiple peaks in the QBO range are found to display similar latitudinal and local time distributions, suggesting that these oscillations are derived from a common source. The features, including the strong amplitudes seen on disturbed days and during postmidnight sectors, and the results from spherical harmonic analysis, verify that the majority of geomagnetic QBO is of external origin. They furthermore find a very high correlation between the geomagnetic QBO and the QBOs in solar wind speed and solar wind dynamic pressure. This suggests the geomagnetic QBO primarily originates from the current systems due to the solar wind-magnetosphere-ionosphere coupling process.

The curlometer was introduced to estimate the electric current density from four-point measurements in space; anticipating the realization of the four spacecraft Cluster mission which began full science operations in February 2001. The method uses Ampere's law to estimate current from the magnetic field measurements, suitable for the high-conductivity plasma of the magnetosphere and surrounding regions. The accuracy of the method is limited by the spatial separation knowledge, accuracy of the magnetic field measurement, and the relative scale size of the current structures sampled but nevertheless has proven to be robust and reliable in many regions of the magnetosphere. The method has been applied successfully and has been a key element, in studies of the magnetopause currents; the magnetotail current sheet; and the ring current, as well as allowing other current structures such as flux tubes and field aligned currents to be determined. The method is also applicable to situations where less than four spacecraft are closely grouped or where special assumptions (particularly stationarity) can be made. In view of the new four-point observations of the MMS mission taking place now, which cover a dramatically different spatial regime, they comment on the performance, adaptability, and lessons learnt from the curlometer technique. Dunlop *et al.* [223] emphasize the adaptability of the method, in particular, to the new sampling regime offered by the MMS mission; thereby offering a tool to address open questions on small-scale current structures.

Yu *et al.* [224] report a self-consistent electric field coupling between the midlatitude ionospheric electrodynamics and inner magnetosphere dynamics represented in a kinetic ring current model. This implementation in the model features another self-consistency in addition to its already existing self-consistent magnetic field coupling with plasma. The model is therefore named as Ring current-Atmosphere interaction Model with Self-Consistent magnetic (B) and electric (E) fields, or RAM-SCB-E. With this new model, they explore, by comparing with previously employed empirical Weimer potential, the impact of using self-consistent electric fields on the modeling of storm time global electric potential distribution, plasma sheet particle injection, and the SubAuroral Polarization Streams (SAPS) which heavily rely on the coupled interplay between the inner magnetosphere and midlatitude ionosphere. They find the following phenomena in the self-consistent model: (1) The spatially localized enhancement of electric field is produced within $2.5<L<4$ during geomagnetic active time in the dusk-premidnight sector, with a similar dynamic penetration as found in statistical observations. (2) The electric potential contours show more substantial skewing toward the postmidnight than the Weimer potential, suggesting the resistance on the particles from directly injecting toward the low-L region. (3) The proton flux indeed indicates that the plasma sheet inner boundary at the dusk-premidnight sector is located further away from the Earth than in the Weimer potential, and a "tongue" of low-energy protons extends eastward toward the dawn, leading to the Harang reversal. (4) SAPS are reproduced in the subauroral region, and their magnitude and latitudinal width are in reasonable agreement with data.

Using data from the Cluster spacecraft from January 2003 to December 2004, they perform a statistical study on some properties of the Field-Aligned Electron (FAE) events and IMF B_y dependence of FAE events with different durations in high-altitude polar regions. A total of 1335 FAE events were observed by the C3 spacecraft. More down-flowing events were observed in the Southern Hemisphere, and more up-flowing events were observed in the Northern Hemisphere. It proves that down-flowing events mainly originate from magnetosphere or solar wind and up-flowing events are mainly derived from ionosphere. Short-lifetime events showed a morning concentration in the magnetic local time distribution, and long-lifetime events were concentrated both before and after noon. For the IMF B_y dependence of the FAE events, short-lifetime events were much affected by IMF B_y and resulted in a morning concentration, while the long-lifetime events were almost unaffected by IMF B_y. With further analysis, Zhang *et al.* [225] determined that the short-lifetime and long-lifetime events had different sources.

Outflowing ion beams forming four successive inverted-V structures in the energy-time spectrograms of

H^+, He^+, and O^+ were observed at an altitude of 3.4 R_e by Cluster satellites travelling above the Auroral Acceleration Region (AAR) in the southern hemisphere on February 14, 2001. Energization by negative U-shaped potential structures in the AAR is believed by Cui *et al.* [226] to be responsible for the formation of these outflowing ion inverted-V structures. Thus, utilizing the different motion properties of the three ion species, the altitude of the upper boundary of the AAR is estimated to be similar to 11100 km. Moreover, based on multi-satellite observations, each of these U-shaped potential structures involved in this event crosses the latitude in all direction at similar to ~0.4–1° Invariant LATitude (ILAT), moving poleward at an average speed of similar to ~0.2° ILAT per minute, before disappearing at similar to ~71.5° ILAT.

Deep dielectric charging/discharging is a serious space environmental effect. Charging electric fields are the fundamental cause of dielectric discharging. In order to quantitatively mitigate deep dielectric charging effects, the GEANT4 toolkit and radiation-induced conductivity model were used to calculate the maximum possible internal charging potential and electric field with different shielding layer thicknesses, dielectric thicknesses, and ground types. Yu *et al.* [227] selected electron spectra from Geostationary Earth Orbit (GEO) and Jupiter orbits as the input environment. With these calculations, a criterion for shielding, dielectric thickness, and ground types is provided such that spacecraft engineers may choose the appropriate method to decrease the deep dielectric charging effects. The charging time constants of flame retardant 4 and polytetrafluoroethylene are similar to 20 and 500 h, respectively, with a little dependence on input electron spectra, ground type, shield thickness, or dielectric thickness. The dielectric characteristics, ground types, and thicknesses, which can significantly change the value of the electric field, are critical for preventing deep dielectric charging. The maximum saturation charging potential and electric field at Jupiter orbit are much larger than those at GEO.

Zhang *et al.* [214] report the continuous monitoring of a polar cap patch, encompassing its creation, and a subsequent evolution that differs from the classic behavior. The patch was formed from the storm-enhanced density plume, by segmentation associated with a subauroral polarization stream generated by a substorm. Its initial antisunward motion was halted due to a rapidly changing of IMF conditions from strong southward to strong eastward with weaker northward components, and the patch subsequently very slowly evolved behind the duskside of a lobe reverse convection cell in afternoon sectors, associated with high-latitude lobe reconnection, much of it fading rapidly due to an enhancement of the ionization recombination rate. This differs from the classic scenario where polar cap patches are transported across the polar cap along the streamlines of twin-cell convection pattern from day to night. This observation provides us new important insights into patch formation and control by the IMF, which has to be taken into account in F region transport models and space weather forecasts.

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Using multipoint data from three Time History of Events and Macroscale Interactions during Substorms (THEMIS) satellites, Zhao *et al.* [16] report a magnetospheric flow vortex driven by a negative solar wind dynamic pressure pulse. The observed vortex rotated in a direction opposite to that associated with positive solar wind dynamic pressure pulses. The vortex was moving tailward, as confirmed by a global MHD simulation. In addition, the Equivalent Ionospheric Currents (EICs) deduced from ground magnetometer station data reveal that a current vortex in the ionosphere near the foot point of the satellites has a rotation sense consistent with that observed in the magnetosphere. The Field-Aligned Current (FAC) density estimated from three THEMIS satellites is about 0.15 nA/m^2, and the total FAC of the vortex is about $1.5–3\times10^5$ A, on the order of the total FAC in a pseudo breakup, but less than the total FAC in most moderate substorms, 10^6 A.

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