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REVIEW

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Dynamics of the terrestrial radiation belts: a review of recent results during the VarSITI (Variability of the Sun and Its Terrestrial Impact) era, 2014–2018

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Abstract

The Earth's magnetosphere is region that is carved out by the solar wind as it flows past and interacts with the terrestrial magnetic field. The inner magnetosphere is the region that contains the plasmasphere, ring current, and the radiation belts all co-located within about 6.6 Re, nominally taken to be bounding this region. This region is highly dynamic and is home to a variety of plasma waves and particle populations ranging in energy from a few eV to relativistic and ultra-relativistic electrons and ions. The interplanetary magnetic field (IMF) embedded in the solar wind via the process of magnetic reconnection at the sub-solar point sets up plasma convection and creates the magnetotail. Magnetic reconnection also occurs in the tail and is responsible for explosive phenomena known as substorms. Substorms inject low-energy particles into the inner magnetosphere and help generate and sustain plasma waves. Transients in the solar wind such as coronal mass ejections (CMEs), co-rotating interaction regions (CIRs), and interplanetary shocks compress the magnetosphere resulting in geomagnetic storms, energization, and loss of energetic electrons in the outer radiation belt nad enhance the ring current, thereby driving the geomagnetic dynamics. The Specification and Prediction of the Coupled Inner-Magnetospheric Environment (SPeCIMEN) is one of the four elements of VarSITI (Variability of the Sun and Its Terrestrial Impact) program which seeks to quantitatively predict and specify the inner magnetospheric environment based on Sun/solar wind driving inputs. During the past 4 years, the SPeCIMEN project has brought together scientists and researchers from across the world and facilitated their efforts to achieve the project goal. This review provides an overview of some of the significant scientific advances in understanding the dynamical processes and their interconnectedness during the VarSITI era. Major space missions, with instrument suites providing in situ measurements, ground-based programs, progress in theory, and modeling are briefly discussed. Open outstanding questions and future directions of inner magnetospheric research are explored.

Keywords: Inner magnetosphere, Energetic particles, Plasma waves, Wave-particle interactions, Radiation belts, Plasmasphere, Ring current

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1 Introduction

The term "magnetosphere" was introduced by Gold in 1959 (Gold 1959) to describe the region above the ionosphere and coincided with James Van Allen's discovery of the radiation belts (Van Allen et al. 1959). The solar wind (Parker 1958), flows past the Earth forming the magnetopause which is the outer boundary of the magnetosphere. The solar wind is supersonic and forms the bow shock just ahead of the magnetopause. Co-located with the radiation belts is a region containing low-energy plasma which is home to a variety of plasma waves. The radiation belts comprise an outer belt and an inner belt separated by the so-called slot region. The outer belt is populated mostly by electrons ranging in energy from a few hundred keV to tens of MeV and is highly dynamical in nature varying on time scales ranging from minutes to years (Baker and Kanekal 2008). The inner belt comprises mostly of protons and is relatively stable varying slowly over time scales of years and is presumed to be predominantly the result cosmic ray albedo neutron decay (Hess 1959).

In the recent past major missions such as NASA's Van Allen Probes (Mauk et al. 2014; Sibeck et al. 2012), JAXA's Arase (Miyoshi et al. 2018), THEMIS (Angelopoulos 2008), and others vastly improved our understanding of the magnetosphere, particularly the inner magnetosphere which includes the radiation belts and the plasmasphere. New observations such as the discovery of a long-term storage ring or the "third belt" (Baker et al. 2013) to the first direct observation of wave-particle interaction (Fennell et al. 2014; Kurita et al. 2018; Kasahara et al. 2018) are prime examples of new observational in situ measurements enabled by advances in instrumentation. Theoretical understanding of the importance of wave-particle interactions have also enabled understanding the physics behind the particle energization and loss (see, for example, chapter by Bortnik et al. in Balasis et al. (2016)).

The Variability of the Sun and Its Terrestrial Impact (VarSITI) program (Shiokawa and Georgieva 2020) commenced in 2014 with an aim to promote international collaboration in data analysis, modeling, and theory to understand how the solar variability affects the Earth. The program comprises four scientific elements. The SPeCIMEN (Specification and Prediction of the Coupled Inner-Magnetospheric Environment) element's main goal is "the quantitative prediction and specification of the Earth's inner magnetospheric environment based on Sun/solar wind driving inputs".

2 Review

2.1 Solar drivers of magnetospheric dynamics

It is by now well established that the Sun is the ultimate driver of magnetospheric phenomena; indeed, it is the steady solar wind that carves out the magnetosphere and delineates it from the surrounding interplanetary space. The Sun produces many transient eruptions, of which coronal mass ejections (CMEs), co-rotating interaction regions (CIRs), and interplanetary shocks affect the terrestrial magnetosphere. The consequences, i.e., magnetospheric responses, encompass phenomena such as substorms, geomagnetic storms, and aurore and affect plasma waves and energetic particle populations. The time scales of magnetospheric response, particularly the inner magnetosphere, range from minutes to years (Baker and Kanekal 2008).

2.1.1 Coronal mass ejections

Coronal mass ejections are large eruptions of plasma together with the embedded magnetic field from the Sun that are now understood as major drivers of geomagnetic activity and were first observed as late as the 1970s (Gopalswamy 2016). CMEs propagate at different speeds through the solar wind and often are preceded by an interplanetary shock. They may contain well-ordered magnetic fields, e.g., magnetic flux ropes and clouds (Klein and Burlaga 1982), and the interplanetary shock ahead of the CME is a prime acceleration site for solar energetic particles SEP (Desai and Giacalone 2016). A schematic illustrating the topology of a CME is shown in Fig. 1 (reproduced from Zurbuchen and Richardson (2006)).

2.1.2 Corotating Interaction Regions and High-Speed Streams

A stream interaction region is formed when slow solar wind is overtaken by the fast solar wind which originates from coronal holes. The coronal holes move down to lower heliospheric latitudes during the descending phase of the solar cycle and usually persist for periods longer than the solar rotation period of about 27 days (as seen from the Earth). During these times, the stream interaction regions are somewhat stable and rotate with the Sun and are termed CIRs. Figure 2 shows a conceptual schematic of a CIR (adapted from Owens and Forsyth (2013)).

2.1.3 Interplanetary shocks

Interplanetary shocks are known to accelerate charged particles (Jones and Ellison 1991) and are also responsible for accelerating electrons in the outer zone on very short time scales of the order of a few drift times (Blake et al. 1992). The acceleration and injection are quite distinct (Li et al. 2018) from either radial transport or wave-particle interactions (see the Section 2.5 section).

2.2 The inner magnetosphere

2.2.1 Morphology and structure

Until recently, observations of the Van Allen belts indicated that there are two belts, an outer belt comprised mostly of electrons and an inner belt mostly comprised

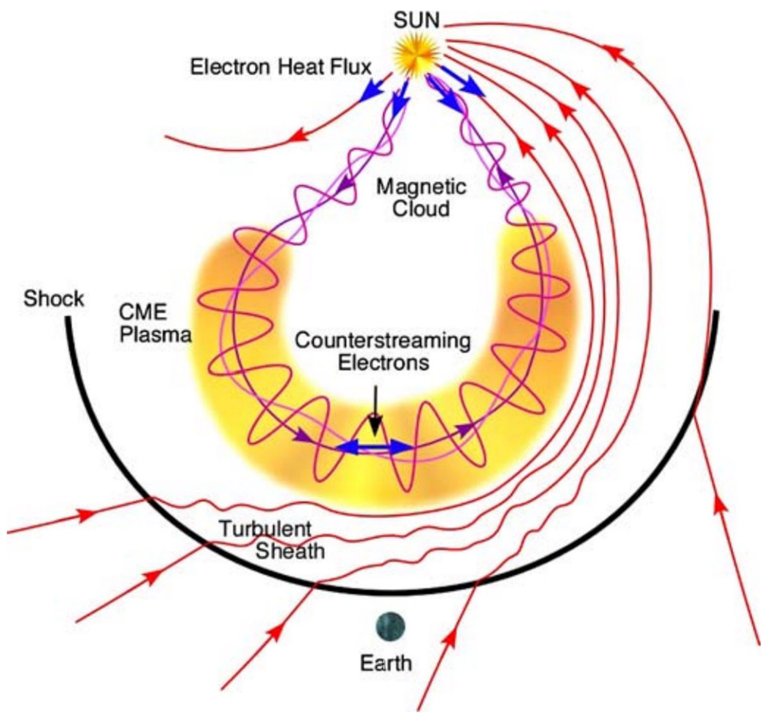

Fig. 1 A schematic illustrating the topology of a CME (reproduced from Zurbuchen and Richardson (2006)). The interplanetary shock ahead of the CME is followed by a turbulent sheath region. Closed magnetic loop lines have counter-streaming particles and may have amagnetic cloud topology

of protons. These two regions were separated by the so-called slot region which was a region that was normally bereft of energetic electrons. Other particle populations include transiently trapped solar particles and somewhat more long-lasting trapped anomalous cosmic rays (Cummings et al. 1993). However, after the launch of the Van Allen Probes, new observations by the REPT (Relativistic Electron Proton Telescope) (Baker et al. 2014a) showed that a third belt or "storage ring" was formed soon after the passage of a CME effectively "splitting" the outer

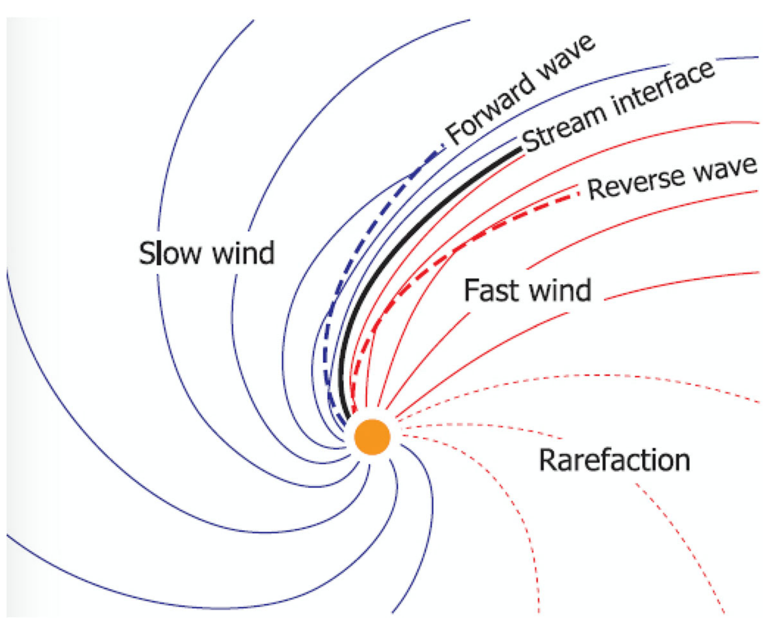

Fig. 2 A conceptual schematic of a CIR (adapted from Owens and Forsyth (2013)). Forward (reverse) shock is shown as a dashed blue (red) line

belt. Figure 3 reproduced from Baker et al. (2013) shows the logarithm of relativistic differential electron fluxes at 3 distinct energy ranges, viz., 3.2 to 4.0 MeV, 4.0 to 5.0 MeV, and 5.0 to 6.2 MeV in panels a, b, and c respectively. The time period is from 1 September to 4 October 2012 with the ordinate showing the L^* parameter (for a detailed discussion of L^*, McIlwain L value, and radiation belt coordinates, see Roederer and Lejosne (2018)) with the fluxes are color coded according to the color bar at right.

After about September 4, when the belts were enhanced, the plasmapause was located at very high L^* values (> 4.5) which may have accounted for the stable existence of the newly formed ring. It has been suggested that the electron decay lifetimes which are due to interaction with plasmaspheric hiss inside the plasmapause are long (Thorne et al. 2018). Other competing theories have also been proposed and include rapid storm-time outward ULF wave transport (Mann et al. 2016) and lack of resonant scattering of ultra-relativistic electrons by chorus and hiss (Shprits et al. 2013).

Another hitherto unnoticed morphological feature of the outer electron belt at relativistic and at ultra-relativistic energies is that of the so-called impenetrable barrier (Baker et al. 2014a). The observations of high-energy electron fluxes by the REPT instrument onboard Van Allen Probes showed that over prolonged periods of many years. Figure 4 reproduced from Baker et al. (2014a) shows in a format similar to Fig. 3 color-coded logarithm of differential electron fluxes of energies ranging from 2.0 to 8.8 MeV (panels a through e) for a period ranging from 1 September 2012 to 1 May 2014. It is seen that the electrons do not "penetrate" to L shells lower than 2.8 across all energies for this entire period.

This remarkable feature may be due to extremely slow inward diffusion coupled with pitch angle scattering removing those electrons that reach these low L values. However, there has been some speculation that the "barrier" could also potentially arise from particle scattering by human produced waves by radio transmitters.

Thus, in the recent past, measurements have revealed hitherto unobserved morphological features of the radiation belt in the inner magnetosphere made possible by new missions with state-of-the-art instrumentation

2.3 Inter-connectedness and cross scale/cross-energy coupling

The influence of the plasmasphere on radiation belts via wave-particle interactions is well known (see the "Wave-particle interactions" section) and arises due to the plasmasphere being home to plasmaspheric hiss, while outside the plasmapause injection of low-energy electrons and ions from the magnetotail and their anisotropy results in EMIC and chorus waves (Li et al. 2019; Magnetosphere-Ionosphere Coupling in the Solar System, 2016; See Chapter 9 by Thorne. R., et al. 2016). The plasma waves generated by the low-energy particles (so-called source populations; see Jaynes et al. (2015)) transfer energy to intermediate energy particles ("seed" populations) energizing them. The waves also pitch angle scatter electrons de-trapping them and ultimately leading to particle loss. Thus, a cross-scale coupling exists that connects the lowest energy to the highest energy particle populations in the inner magnetosphere, via the intermediary plasma waves. Figure 5 reproduced from Miyoshi et al. (2018) shows schematically the inter-connectedness and cross-energy coupling.

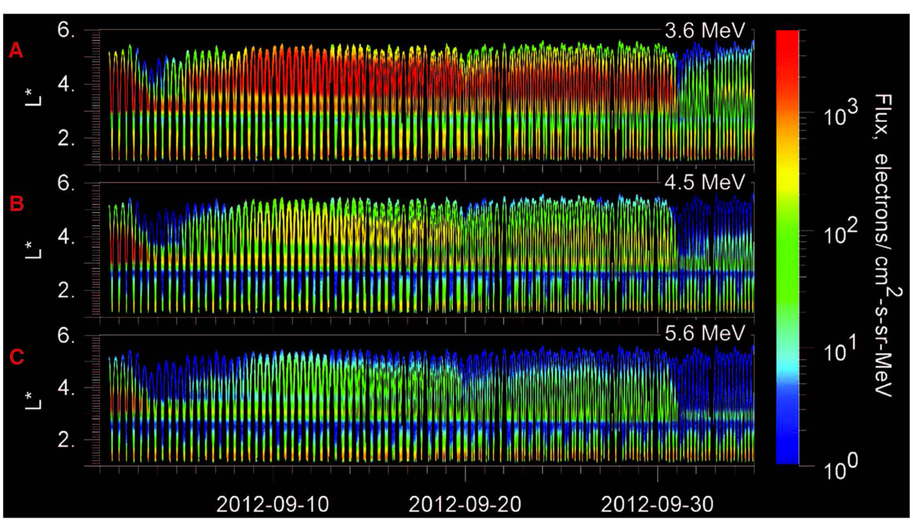

Fig. 3 Formation of the third belt or "storage ring" soon after the passage of a CME effectively "splitting" the outer belt observed by the REPT instrument on Van Allen Probes; reproduced from Baker et al. (2013)

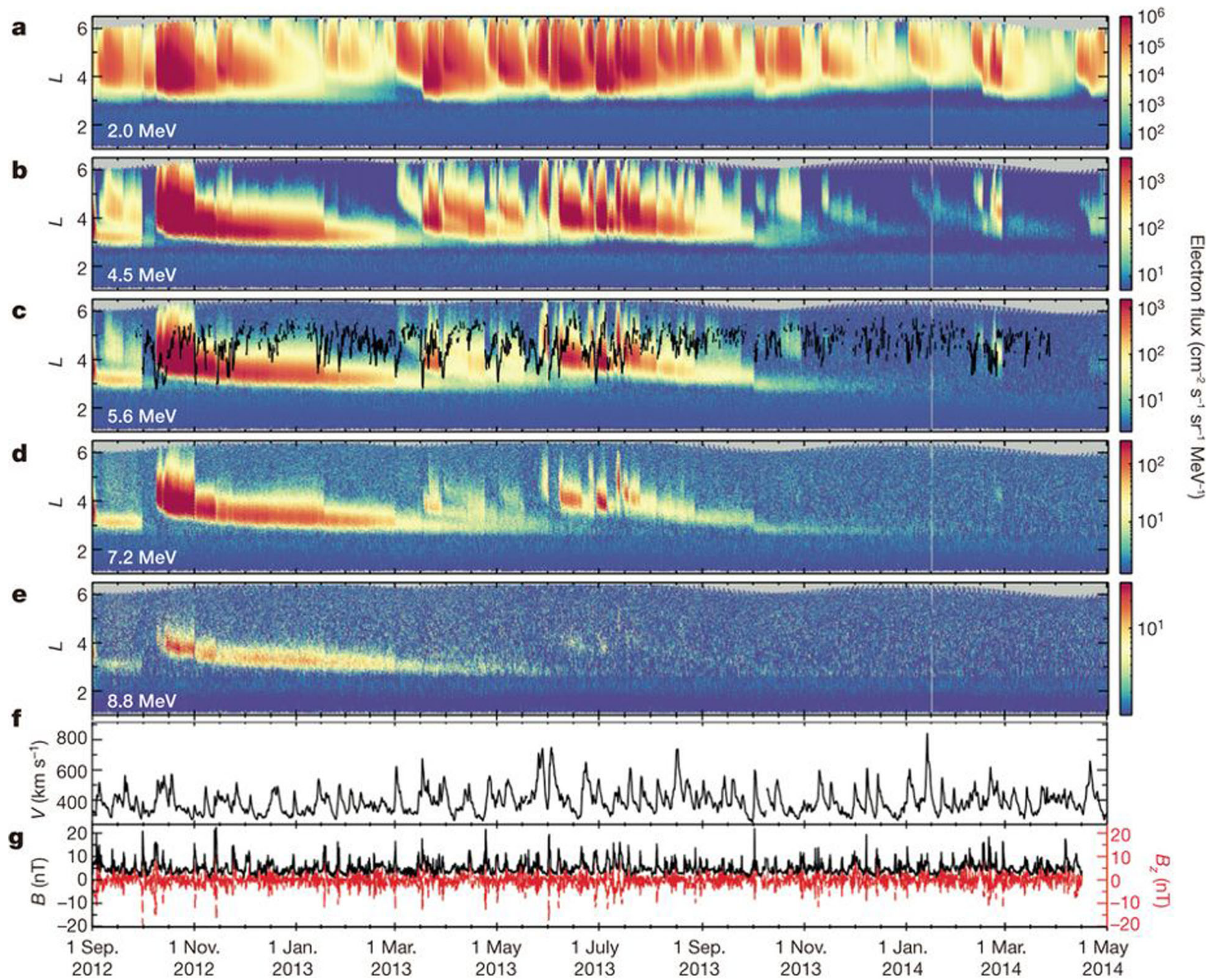

Fig. 4 The "impenetrable barrier" for relativistic electrons as observed by the REPT instrument on Van Allen Probes (reproduced from Baker et al. (2014a)). At all energies, inward radially diffusing electrons do not penetrate below $L \approx 2.8$

That the plasmasphere itself may be affected by solar influences was demonstrated recently by observations from Van Allen Probes of the cold plasma density and electric field in the inner magnetosphere (Thaller et al. 2019). Using long-term observations from Van Allen Probes, Thaller et al. (2019) demonstrated that the outer plasmasphere and the plasmapause boundary were driven by modulations in the solar wind. Furthermore, their findings indicated that these modulations were stronger during the declining phase of the solar cycle, possibly due to the prevalence of CIRs, and were substantial in amplitude. As mentioned earlier, the processes in plasmasphere are intimately connected to the electron populations in the outer radiation belts. Thus, these modulations of the plasmasphere potentially could be important in understanding the driver dependence of outer radiation belt dynamics

2.4 Inner magnetosphere observatories

The VarSITI era saw several major space missions that were either directly dedicated to the study of the inner magnetosphere, e.g., NASA's Van Allen Probes (Mauk et al. 2014; Sibeck et al. 2012) and JAXA's Arase (Miyoshi et al. 2018), or were able to contribute significantly to scientific questions pertaining to the inner magnetosphere. These include THEMIS (Angelopoulos 2008) and MMS (Burch et al. 2016). The VarSITI era also witnessed the maturation of the paradigm shifting technology of CubeSats and associated inexpensive access to space.

In the following, we provide a very brief overview of these major missions and illustrate the CubeSat approach using as an example the CeREs mission (Kanekal et al. 2018).

The Van Allen Probes mission launched in 2012 comprises two identically instrumented spacecraft each

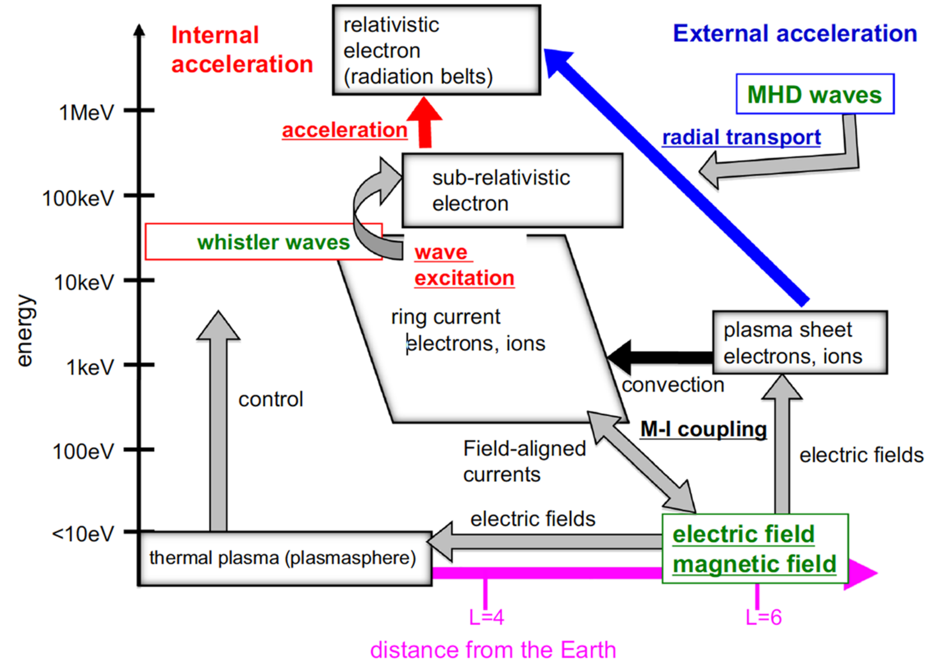

Fig. 5 Diagram illustrating the interconnectedness and cross-scale coupling between particles, waves, and underlying physical processes (reproduced from Miyoshi et al. (2018)). The energy and spatial scales are indicated on the ordinate and abscissa, respectively. The processes and coupling are shown as colored arrows

carrying a comprehensive suite of instruments measuring plasma waves, magnetic fields, and energetic particles (electrons, ions, and ion composition) over a wide energy range. The goal of the mission was to "provide understanding, ideally to the point of predictability, of how populations of relativistic electrons and penetrating ions in space form or change in response to variable inputs of energy from the Sun." The mission and its science goals are fully described by Mauk et al. (2014).

The ERG project is a Japanese geospace exploration project, which consists of three different research teams: Arase (ERG) satellite, ground-based observations, and modeling simulation. The main science target of the project is understanding of transportation, acceleration, and loss of energetic particles in radiation belts and dynamics of geospace during space storms. As a key observation of the ERG project, Arase was launched in 2016 and has started the regular observations since March 2017. Arase has nine science instruments to measure plasma/particles and field and waves. The orbit of Arase is similar to Van Allen Probes, but Arase measures higher magnetic latitudes up to 40 degrees and higher L-shell up to 10. Overview of the project and science goals are fully described by Miyoshi et al. (2018).

The THEMIS mission was launched in 2007 and comprises five identical spacecraft whose main science goal was the study of substorms in the magnetotail. Each spacecraft carries onboard particle instruments that measure low-energy electrons and ions as well as electric and magnetic fields. While the mission's main focus is on the magnetotail, since the spacecraft travers through the radiation belts, the mission also contributes to the study of the inner magnetosphere. The details of the mission are described by Angelopoulos (2008). Since 2010, two of THEMIS spacecraft orbit around the Moon while the remaining three remain in Earth orbits.

2.4.1 The CubeSat/SmallSat paradigm

In the recent past, CubeSats, which comprise 10 cm cubes called 1U, have moved from being a teaching and academic tool to becoming contenders for doing significant science (National Academies of Sciences, Engineering, and et al. 2016). In particular, low earth orbit (LEO) is well suited for CubeSats, since currently due to their power and volume limitations, data transmission rates are somewhat of an issue. However, innovative new instrumentation utilizing advances in detector technology, electronics, and rad-hard processors have brought the capabilities of instruments onboard major missions in the past to these compact space platforms. For example, the MERiT (Kanekal et al. 2019) instrument onboard the CeREs (Kanekal et al. 2018) combines avalanche photodiodes (APD) and solid-state detectors (SSD) to provide electron measurements from a few keV up to ten MeV. Figure 6 shows the CeREs CubeSat with the MERiT instrument at the top. The CubeSat, which was launched December

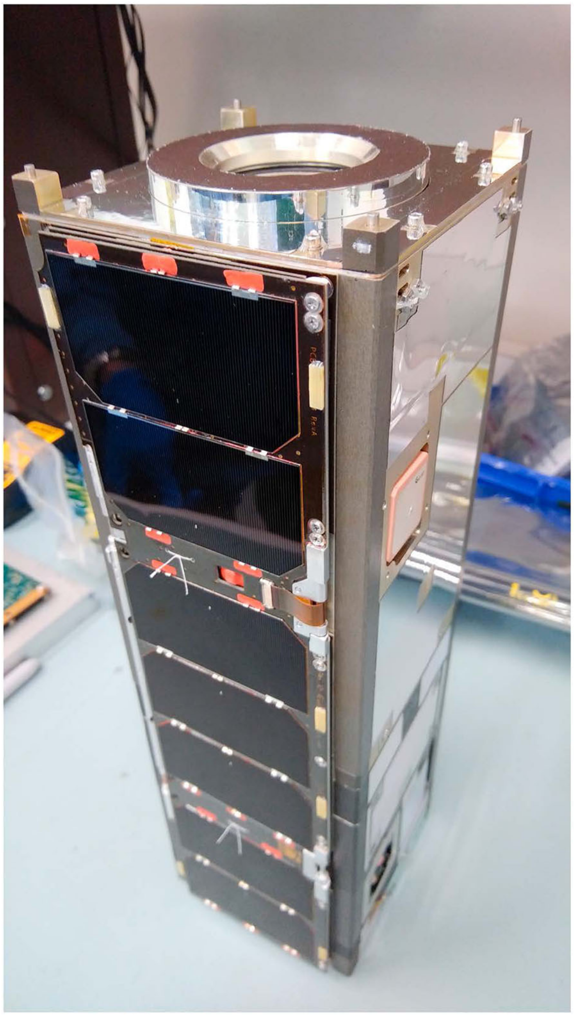

Fig. 6 Photograph of the CeREs (Compact Radiation belt Explorer) CubeSat. CeREs is a typical 3U CubeSat carrying a single instrument, the MERiT (Minaturized Elecgron pRoton Telescope) as the science payload

2018, however soon lost contact with the ground station only about a week into the mission. CubeSats remain a risky proposition while affording the possibility of good science at a low cost.

Another 3U CubeSat, the Colorado Student Space Weather Experiment CubeSat, CSSWE has however been successful and made some significant science contributions (Schiller et al. 2014), such as establishing that energetic electrons from cosmic ray neutrons get trapped in the radiation belts (Li et al. 2017). Other CubeSat missions that are studying terrestrial radiation belts include ELFIN (Shprits et al. 2017), AC6 (Blake and O'Brien 2016), and FireBird (Spence et al. 2012). The latter two have studied electron microburst precipitation and have provided information regarding microburst spatial extent (Blake and O'Brien 2016) and spectra (Crew et al. 2016). CubeSat missions are being considered for interplanetary regions as well, for example, the CUSP (Desai et al. 2019) CubeSat expected to launch early 2020 will measure supra-thermal and solar energetic protons. Figure 7 shows a synoptic view measurements made by the FireBird (Crew et al. 2016) together with those made by the MagEIS (Blake and et al. 2013) instrument onboard Van Allen Probes illustrating the complementary nature of contributions to radiation belt science by CubeSats and major missions.

One of the main advantages that CubeSats bring to the study of inner magnetosphere is the capability to do multipoint measurements. Detailed in situ measurements of particles and waves in the inner magnetosphere have been mostly confined to single point measurements or at most missions comprising two spacecraft. Large major missions are expensive and take many person-years of effort. CubeSats, taking advantage of recent developments in both inexpensive launch vehicle systems and instrumentation, can fill this lacuna and provide valuable scientific insights that arise from multi-point measurements, e.g., resolving spatio-temporal ambiguities.

2.5 Electron dynamics in the outer belt

The Earth's outer radiation belt comprising mostly of electrons is a very dynamic region with electron intensities varying by orders of magnitude in time scales ranging from minutes to days (see, for example, Kanekal (2006); Miyoshi et al. (2018)) which has been well established by observations going back to the nineties (Baker et al. 1994). Figure 8 shows the measurements of energetic electrons spanning nearly a decade by SAMPEX and Polar spacecraft. The dynamic nature of the outer zone is evident from the figure, which shows many electron enhancements as well as loss over a nearly a solar cycle. Furthermore, the global coherent nature (Kanekal et al. 2001) of electron energization is also well illustrated in Fig. 8. Note that SAMPEX was in low Earth orbit while Polar was in a high-inclination, high-altitude orbit during this period. It has long been established that the causative agents for electron energization are high solar wind speeds (Paulikas and Blake 1979; Baker et al. 1989) and a persistent southward component of the interplanetary magnetic field (Blake et al. 1997). Electron losses are important as it is currently known that the net flux of energetic electrons is a "delicate balance" between energization and loss processes. Figure 9 illustrates this by showing observations of three storms of similar geomagnetic intensities wherein net energization, loss, and no change in pre- and post-storm electron fluxes are seen.

In the following sections below, we discuss and review the current understanding of electron energization and loss processes in the context of focusing on recent results during the SPECiMEN era.

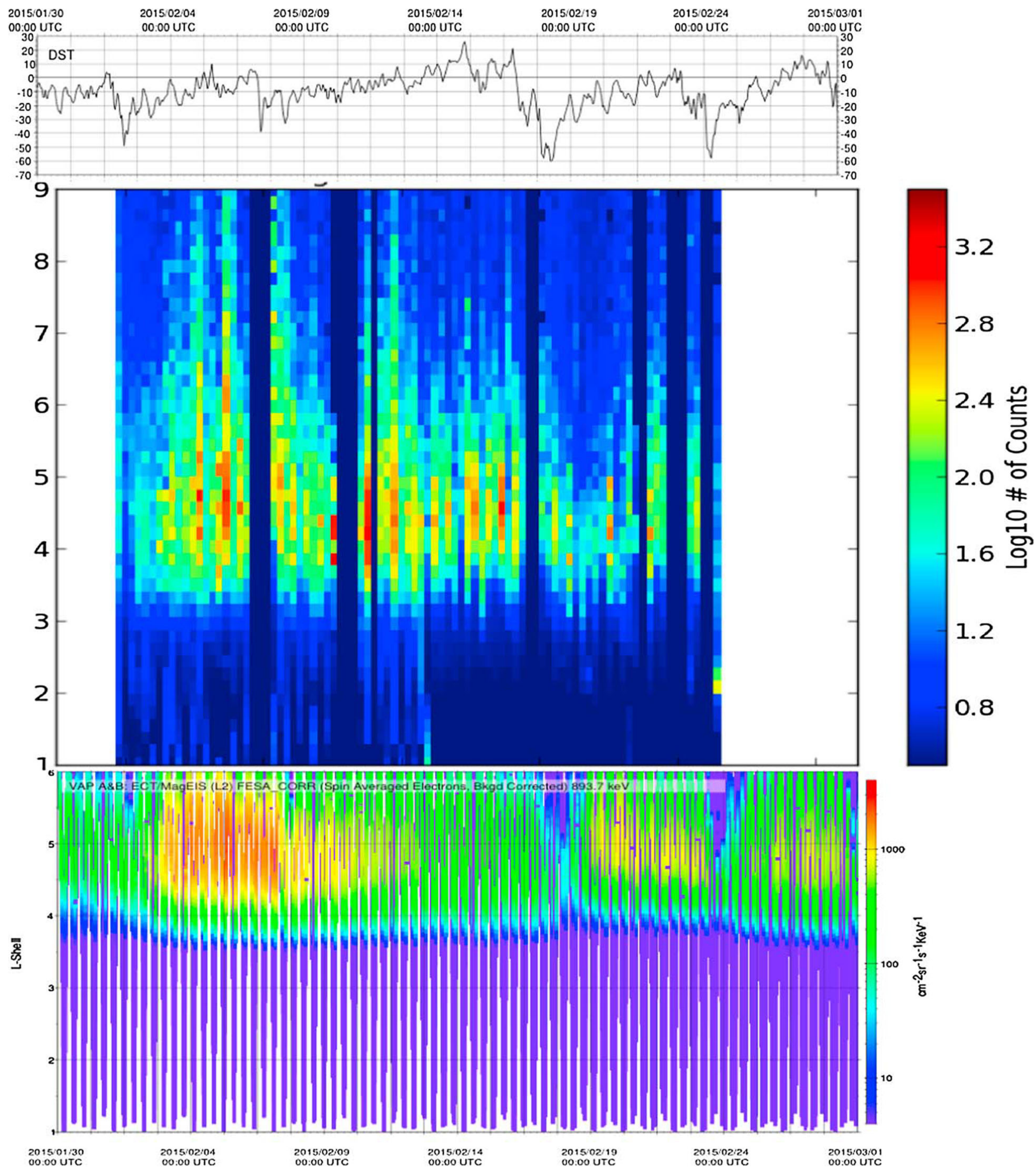

Fig. 7 Measurements of > 985 keV electrons by sensors onboard FireBird and differential flux by MagEIS for the 893 keV channel (reproduced from Crew et al. (2016). The top panel shows the Dst index, the middle panel FIREBIRD-integral counts, and the bottom panel MagEIS measurements

2.5.1 Electron energization processes

Radial transport Electrons moving radially inward gain energy due to the conservation of the first adiabatic invariant; this process is termed radial diffusion and has been established several decades ago (Falthammar 1965; Schulz and Lanzerotti 1974); similarly outward radial motion tends to decrease particle energy and more importantly to loss via escape through magnetopause. Radial diffusion is caused by magnetic and electric field perturbations (Falthammar 1965), and more recent work has shown that

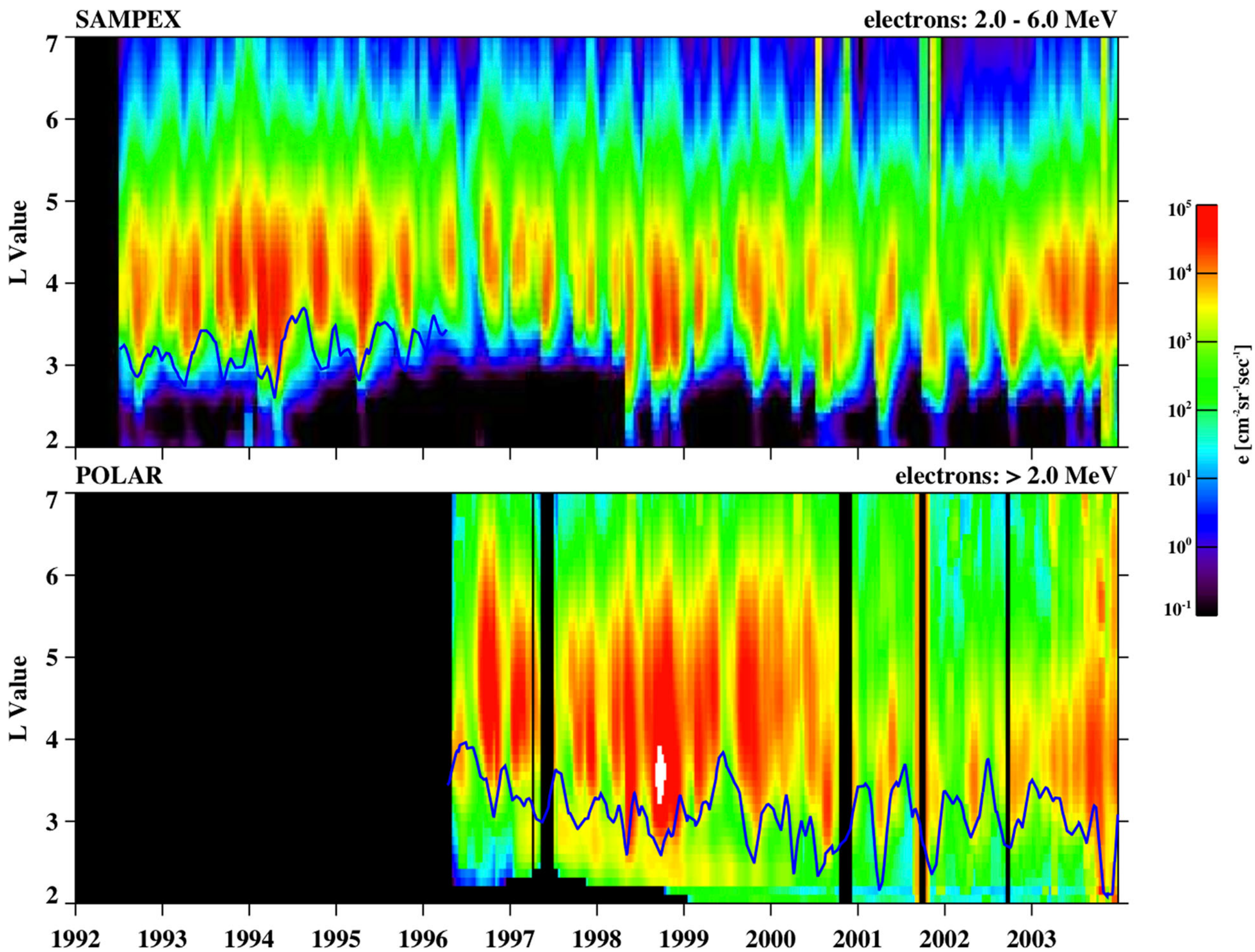

Fig. 8 Energetic electron intensities measured by instruments onboard SAMPEX (top) and Polar (bottom) satellites. Daily averaged fluxes spanning over a decade (1992 to 2003) are shown for 2.0 to 6.0 MeV and > 2.0 MeV electrons. The electron intensities are smoothed with a 30-day running box-car average. Also shown as a blue trace model calculated location of the plasmapause multiplied by a factor of 1.3. Figure is reproduced from Kanekal (2006)

enhanced ULF wave activity speeds up this process considerably (Elkington et al. 1999; Shprits et al. 2008; Su and et al. 2015). Jaynes et al. (2018) have used REPT observations of ultra-relativisitic electrons during the 17 March 2015 event to show that electrons are energized to as high as $\approx$ 8 MeV in energy on rather short time scales. Figure 10 shows measurements of 6.3 MeV electron fluxes by the REPT instrument for the month of March 2015. The top panel of the figure shows a clear inward motion on electrons, and Jaynes et al. (2018) calculate a diffusion rate D_{LL} of about 0.3 day^{-1} for these ultra-relativistic electrons. Another study by Zhao et al. (2018) demonstrated that inward radial diffusion was responsible for energizing electrons to ultra-relativistic energies, again using data from the REPT instrument.

Another study by Ozeke et al. (2020) used ground-based measurements of ULF waves to characterize the global distribution of the ULF wave power and simulated radial diffusion effects during March 2015 and March 2013 on electron fluxes in the outer zone. They compared their simulation results with observations made by the REPT instrument onboard Van Allen Probes and concluded that ULF wave-driven radial diffusion was an important mechanism for both energization and loss via magnetopause shadowing (see Fig. 4 of Ozeke et al. (2020)).

It is clear from these and other studies that enhanced radial diffusion plays an important role in radiation belt dynamics while energization and pitch angle scattering by wave particle are also an equally significant mechanism.

Wave-particle interactions Wave-particle interactions play an important role in energizing radiation belt electrons. There are two different processes in the wave-particle interactions: (1) drift resonance between drifted electrons and MHD fast mode waves and (2)

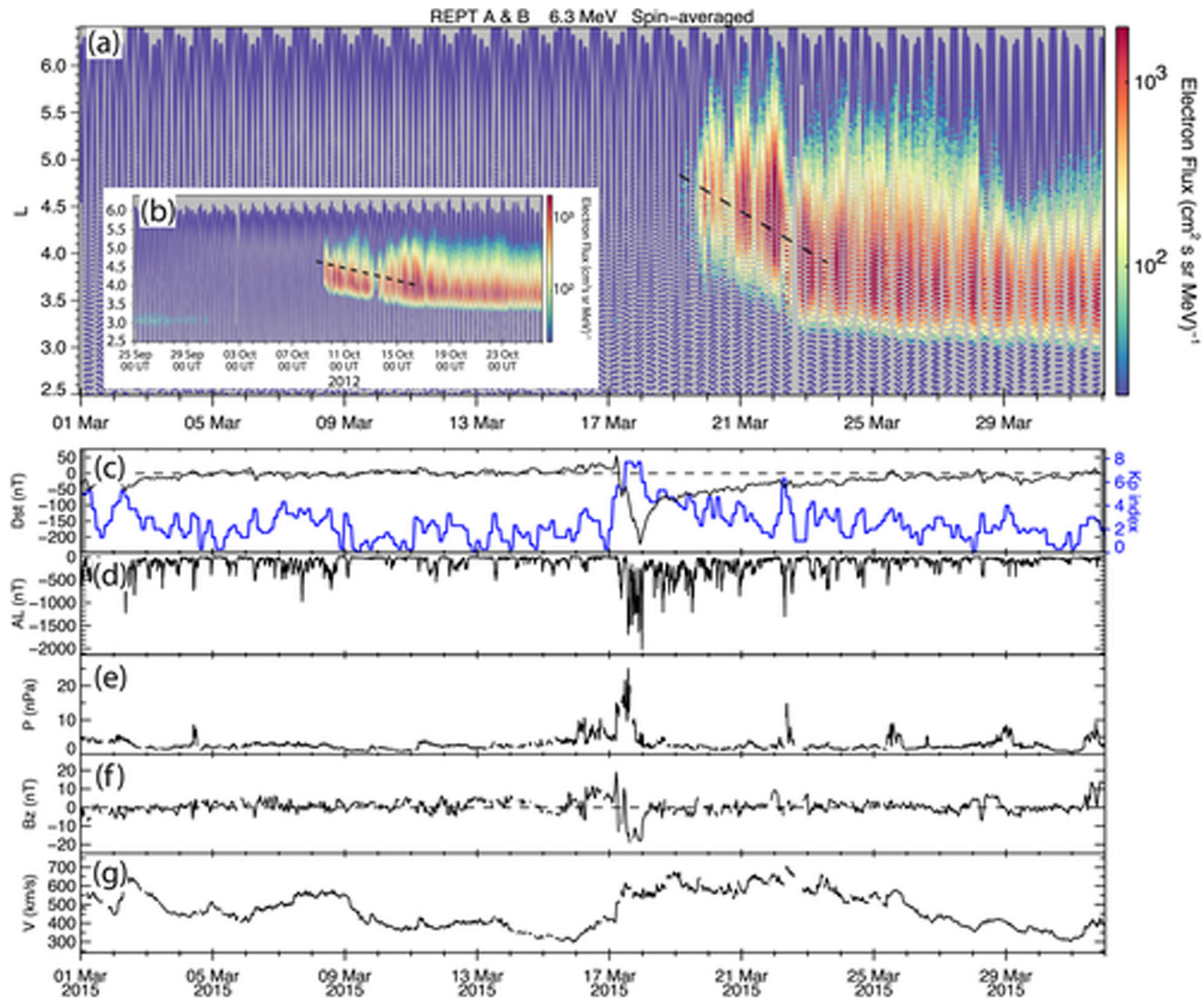

Fig. 9 Radial diffusion of ultra-reltivistic electrons (6.3 MeV) shown in the top panel. Also shown in the top panel is the comparatively slower radial diffusion during October 2012. Compare to much slower diffusion seen in previous strong storm in October 2012, black dashed lines show the slope of inward drift. The rest of the panels show Dst, Kp, AL, and solar wind parameters. Figure is reproduced from Jaynes et al. (2018)

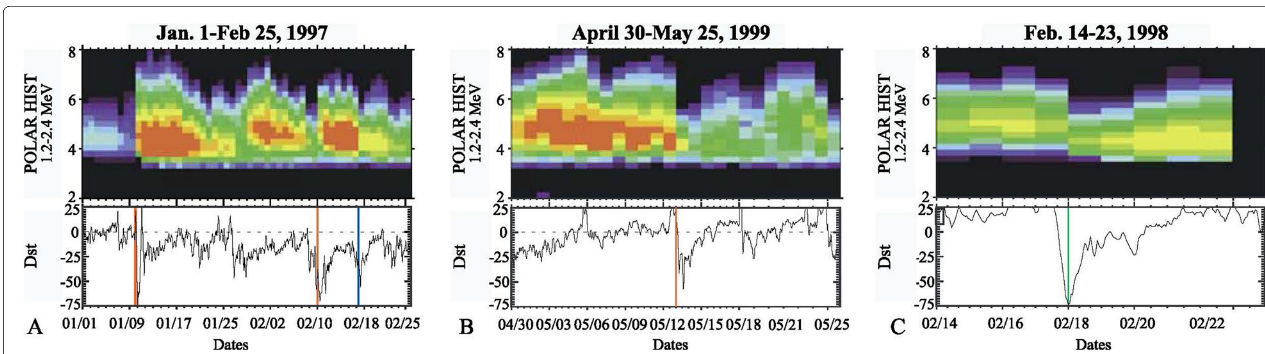

Fig. 10 Radiation belt response during geomagnetic storms of similar strength. The net flux of energetic electrons may increase, decrease, or stay the same between the main and recovery phase illustrating the important dynamic between energization and loss. Figure is reproduced from Reeves et al. (2013)

cyclotron resonance between gyrating electrons and Whistler mode/magnetosonic mode waves. The first process has been recognized as an adiabatic process due to conservation of the first and second invariants, while the second process has been recognized as non-adiabatic process through violation of all invariants.

Since the late 1990s, theories have suggested that interactions through cyclotron resonance causes accelerations of relativistic electrons (Summers et al. 1998), and several observational studies indicate that interactions with Whistler mode chorus contribute to flux enhancement of relativistic electrons. Measurements on the radial profile of the phase space density are essential to discriminate the processes (Green and Kivelson 2004). Several studies carried out prior to the Van Allen Probes mission reported on the observation of a peak in the phase space density inside the outer belt likely arising from internal electron energization. However, detailed and comprehensive observations by Van Allen Probes provided definitive evidence for local electron energization as distinct from energization due to radial transport (Reeves et al. 2013).

Reeves et al. (2013) showed growing peak of the phase space density, which indicates that generation of MeV electrons occur inside the outer belt. Thorne et al. (2013) showed variations of the plasma wave data and electron data from Van Allen Probes and compared with the quasi-linear simulation. They concluded that Whistler mode waves actually cause acceleration of MeV electrons.

During the Van Allen Probes era, there are a number of reports that whistler mode waves accelerate electrons and growing peak of the phase space density inside the outer belt (Reeves et al. 2013), and it has been established that internal acceleration through resonance with whistler mode waves should be a key process on the formation of MeV electrons of the outer belt. The elementary process of accelerations has also been identified by both Van Allen Probes and Arase (Fennell et al. 2014; Kurita et al. 2018).

Another important aspect of the wave-particle interactions is understanding the non-linear wave-particle interactions. Whistler mode chorus waves are generated through non-linear interactions with electrons through formation of the electron hole/hill in the phase space (Omura et al. 2009). Evidence of non-linear interactions has been reported by comparing theories (Foster et al. 2017; Kubota and Omura 2018).

Generation of chorus waves and acceleration of relativistic electrons are the result of an interplay among different plasma/particle populations via wave-particle interactions. Cross-energy coupling process (Miyoshi et al. 2018) is a key concept to understand enhancement of the outer belt electrons. Figure 11 (Jaynes et al. 2015) shows a schematic diagram of how different plasma/particle populations contribute to generate of plasma waves and subsequent enhancement of outer belt electrons. These processes occur associated with substorm activities. Sustained substorm activities for a few days driven by the small amplitude of southward IMF are essential to cause the large flux enhancement through this process (Miyoshi et al. 2013).

Rapid injection by IP shocks Interplanetary shocks can inject energetic electrons into the magnetosphere very rapidly on time scales of a few minutes, i.e., on electron time drift time scales; the most dramatic such an event was first observed by the CRRES spacecraft (Blake et al. 1992). The observations showed very high energy electrons with energies > 13 MeV were injected deep into the magnetospheric slot region ($\lessapprox 2 < L \lessapprox 3$). Blake et al. point out that the spectrum continues up to almost 50 MeV. The injected electrons were stably trapped in the

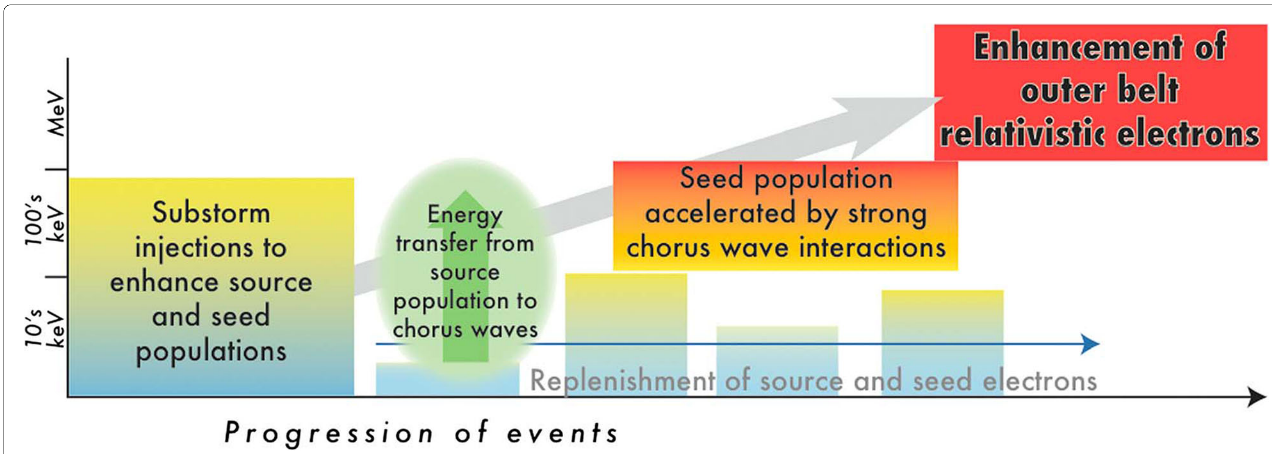

Fig. 11 Diagram illustrating the interplay and contribution of low-energy electrons (source) in generating plasma waves which act upon a seed population to energize electrons to relativistic energies (reproduced from Jaynes et al. (2015))

inner zone and lingered for many years as observed by the SAMPEX spacecraft (Looper et al. 1994). The process of injection is fairly well understood and has been modeled (Li et al. 1993); (Hudson et al. 1997); Wygant et al. (Wygant and et al. 1994)) and results from the electrons "surfing" a magnetosonic pulse electric field while conserving their first invariant.

During the VarSITI era, multiple IP shocks have resulted in rapid injections of electrons energized during their transport from outer regions of the magnetosphere (Foster et al. 2015; Kanekal and et al. 2016; Schiller et al. 2016). The injected electrons often lead to enhanced bunches electrons as they drift around (drift echos). Figure 12 shows the radiation belt electron response to the IP shock event of March 2015 (Kanekal and et al. 2016). The figure shows pitch angle-resolved electrons of several energies as measured by the REPT instrument. Rapid injection followed by velocity dispersed drift echos are seen, with the arrival of the shock indicated by a vertical black line. Electron enhancements are seen to occur within about 5 min of the shock arrival. Due largely to the paucity of measurements, studies relating various shock properties to characteristics of electron injections have not been well established. For example, the March 2015 shock event showed a more harder spectrum (as compared to electron spectrum just prior to injection) than the September 2017

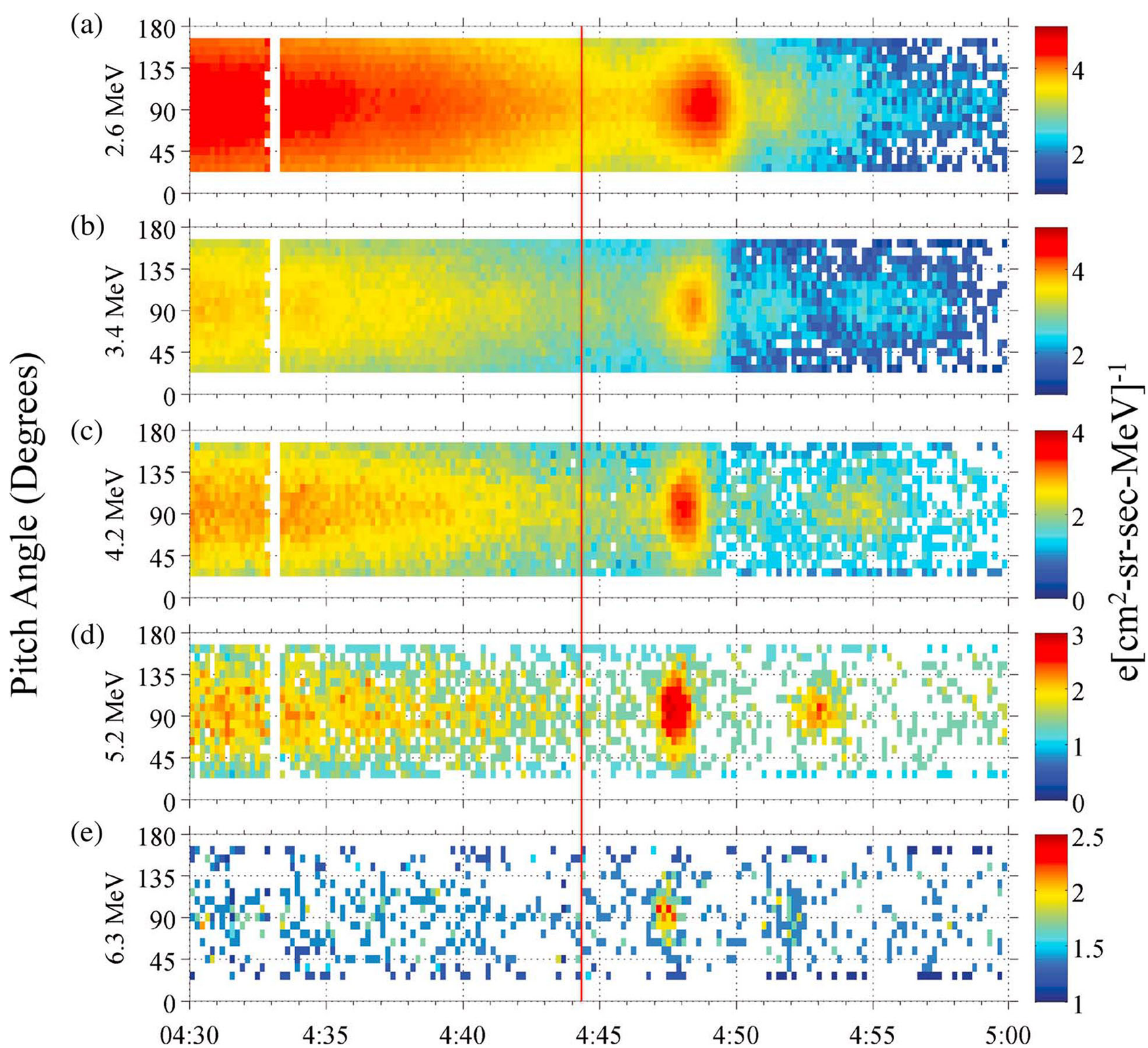

Fig. 12 REPT measurements (Van Allen Probe A) of pitch angle-resolved energetic electrons. Relativistic electron intensities at energies of 2.6, 3.4, 4.2, and 6.3 MeV are shown from the top to bottom panels, respectively. The red vertical line shows the IP shock arrival time (reproduced from Kanekal and et al. (2016))

event which was a much stronger shock (Kanekal 2020). A study by Schiller et al. (2016) studied the relationship between shock characteristics and the highest energy of the injected electrons and found that shock mach number correlated best and suggest that shock strength plays an important role. The studies mentioned in the previous paragraph have established underlying physical processes that result in these injections; however, we emphasize no conclusive relationship between IP shock parameters and electron properties such as spectral hardness has been established.

The space weather implications of rapid energization due to IP shocks are significant, since, as the March 1991 event demonstrated, very high-energy electrons can be injected deep unto the magnetosphere and persist for several years. Persistent high fluxes of electrons pose a critical threat to spacecraft.

Solar driver dependence Relativistic electrons of the outer belt show different responses associated with the solar wind disturbances. As mentioned previously, large-scale solar wind structures such as CMEs and CIRs cause geomagnetic storms, and the outer belt electron flux and spatial distributions also change during the period. For geomagnetic storms, intense southward IMF is essential to cause severe magnetic storm through the enhancement of the cross-polar cap potential. On the other hand, magnetic storms do not always cause large flux enhancement of the outer belt electrons (Reeves et al. 2013). Several studies showed some cases of strong outer belt relativistic electron enhancements during non-storm times (Schiller et al. 2014), and these studies pointed out increasing of chorus wave power during the flux enhancement event. It has been indicated that the high-speed coronal hole stream following CIR is more effective for the large flux enhancement at GEO rather than CME-driven storms and the southward IMF embedd in the high-speed coronal hole stream is important for the large flux enhancement (Miyoshi and Kataoka (2005), (2008); Kilpua et al. 2015). Li et al. (2011) has shown that the solar wind speed is not a necessary condition for the flux enhancements at GEO. These studies indicate the importance of the southward IMF besides the solar wind speed that has been considered as a primary parameter for the outer belt electrons, and prolonged substorm activities are essential to cause the flux enhancement.

From the analysis of 200 stream interface events in solar cycle 23, Miyoshi et al. (2013) have shown that the southward IMF in the high-speed stream that is controlled by the Russell-McPherron effect (Russell and McPherron 1973) affects key parameters of electron acceleration by chorus waves. These parameters include source electron population, thermal plasma density, and chorus wave activity itself. They showed that prolonged substorm activity is essential for the large flux enhancement. Their model as depicted in Fig. 13 (Miyoshi et al. 2013) shows how solar wind speed and the prolonged southward IMF control relativistic electron flux enhancement through wave-particle interactions. More recently, Zhao et al. (2017) showed increase of electron PSD associated with solar wind/geomagnetic parameters as well as the important role played by substorms.

It is generally accepted that CMEs predominantly occur during the ascending phase and CIRS during the descending phase of the solar cycle; however, that is not always the case. Kanekal et al. (2015) studied an interesting period during November 2013 when the radiation belts were driven concurrently by weak CMEs during an ongoing HSS event. They used Van Allen Probes measurements of electron intensities to calculate phase space densities (PSD) and found that the lower-energy electrons were accelerated by radial diffusion while the higher-energy electrons were energized by wave-particle interactions. Figure 14 shows the radial profile of PSD obtained using MagEIS and REPT measurements onboard Van Allen Probe A (similar results were found for Probe B). The profiles for two values of K, the second adiabatic invariant and for multiple values of the first, i.e., μ show that at lower values of the latter, the profiles are monotonic whereas at higher values exhibit a peak.

Another recent study by Pandya et al. (2019) compared radiation belt responses to 28(27) CME(CIR) events. They examined the dependence of electron flux variability upon interplanetary parameters such as solar wind speed, IMF B_Z. Their findings emphasize the different nature of electron responses to these two types of solar drivers. The distinct response of the radiation belts to solar drivers has also been demonstrated by Baker and et al. (2014c) who studied an event during March 2013 when a high-speed stream was followed by a coronal mass ejection. They showed that this resulted in energization due to prolonged gradual radial diffusion which was followed by a much more rapid enhancement. More recently, Baker et al. (2019) used relativistic electron measurements spanning 6 years from the REPT instrument onboard Van Allen Probes. Their long-term study confirmed the important role played by solar wind speed in energizing electrons, specifically a threshold speed of 500 km/s being required to enhance relativistic electron intensities. Long periods when the solar wind speed did not exceed the threshold showed no detectable high-energy electrons. As the authors point, this fact, despite being known for decades (see, for example, Baker et al. 1979; Paulikas and Blake 1979), still remains unexplained as to the physical processes leading to the existence of such a threshold value.

From these studies, prolonged southward IMF, high-speed solar wind, and low solar wind dynamic pressure

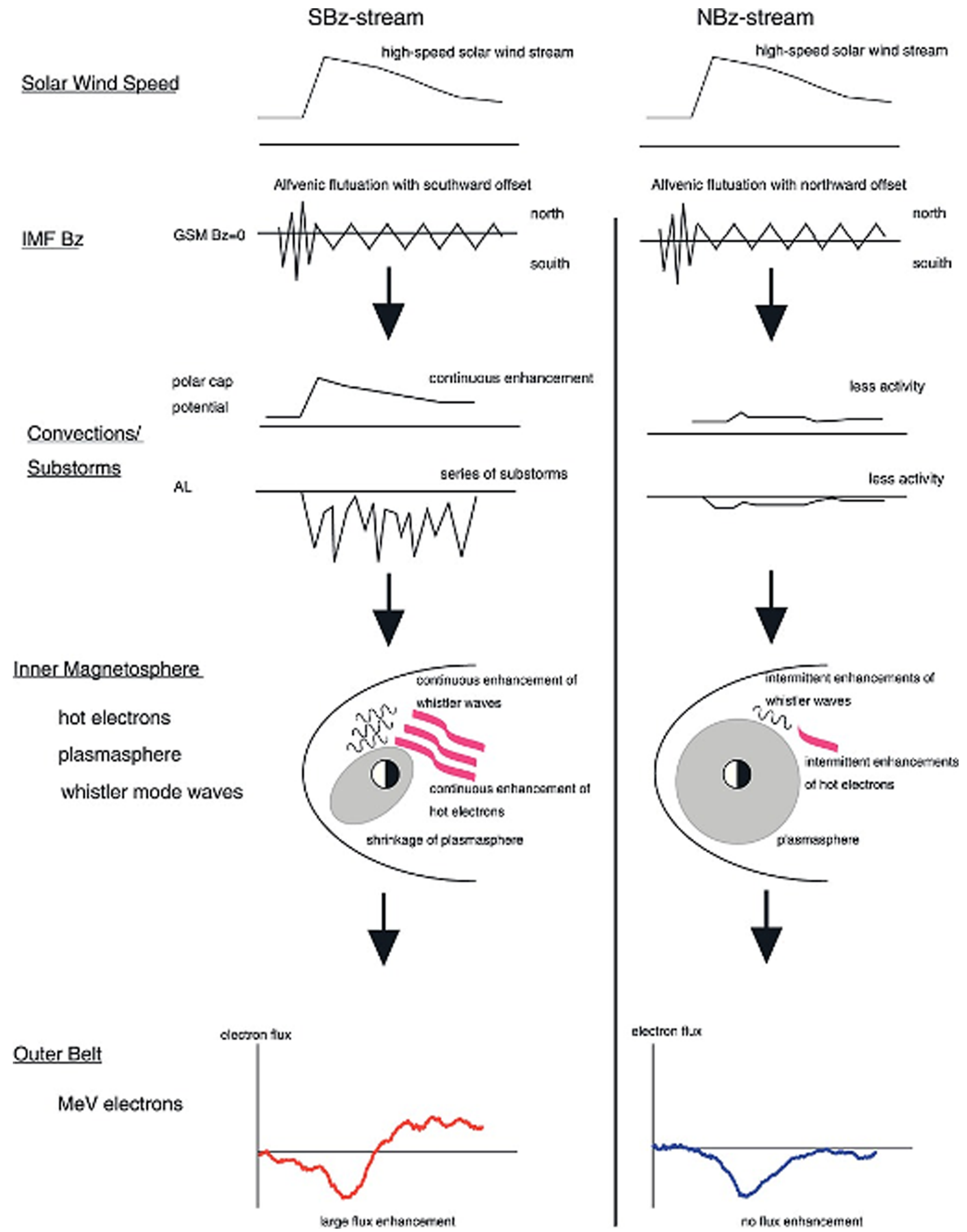

Fig. 13 Schematic of the ideal setup and sequence for strong enhancement of outer belt electrons through chorus wave-particle interactions in the high-speed streams (Miyoshi et al. 2013)

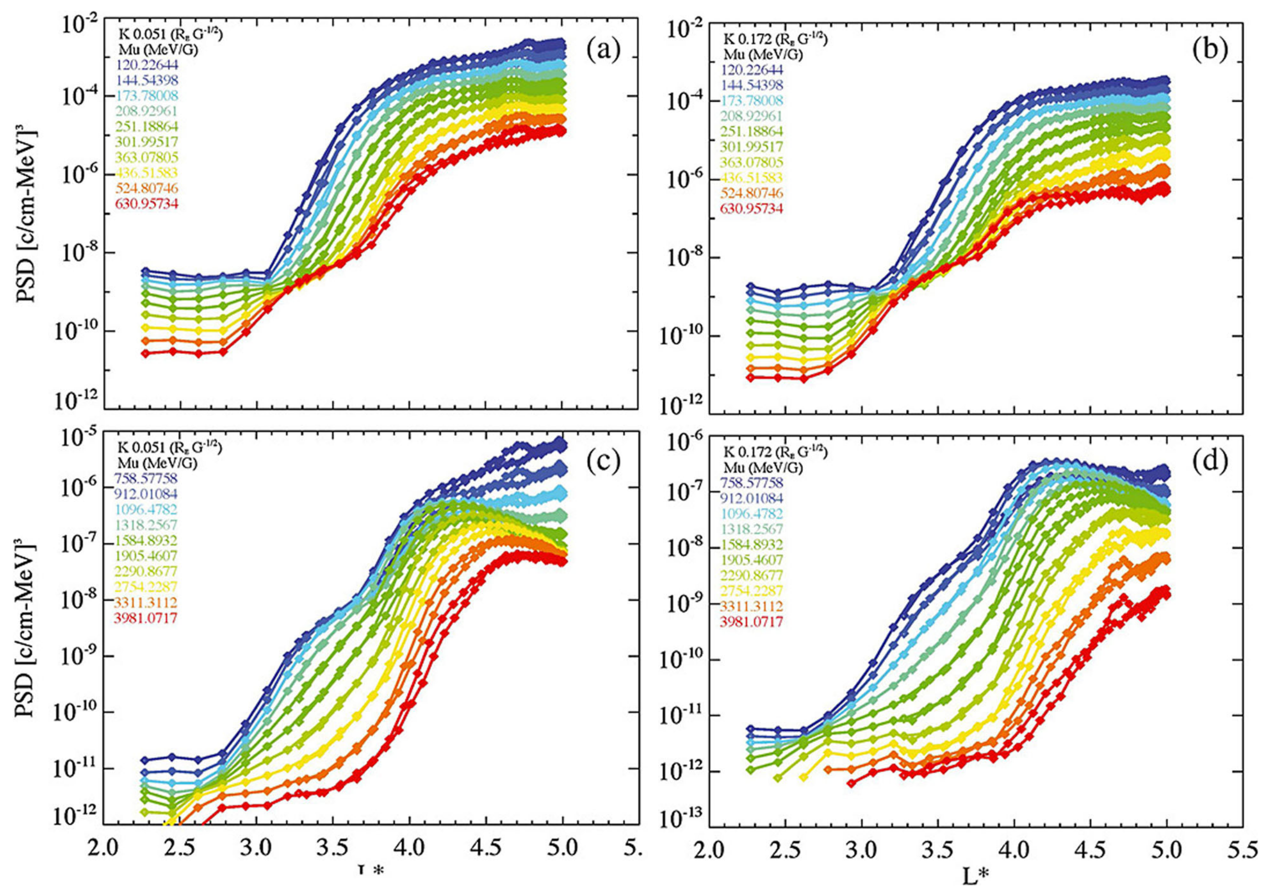

Fig. 14 Radial profiles of electron phase space density obtained from measurements by Van Allen Probe A of pitch angle-resolved energetic electrons. The panels show for two values of the second adiabatic invariant, *K* multiple values of PSD for μ, the first invariant as color coded lines. The numerical values are listed in the legend accompanying the figures (reproduced from Kanekal et al. (2015)

have been recognized as the main contributions to cause the large flux enhancement. These situations are readily found in trailing edge of the stream interface with the toward/away sector polarities in spring/fall through Russell-McPherron effect. During the period, intense chorus waves are observed (Miyoshi et al. 2013; Li et al. 2014). It is important to note that prolonged substorm activities with/without magnetic storms are essential to cause the large flux enhancements. This is an important paradigm to indicate the need for more accurate space weather forecasting models.

2.5.2 Electron loss processes

Magnetopause shadowing An important mechanism of loss of electrons from the radiation belts is the so-called magnetopause shadowing, where drifting electrons are on trajectories that encounter the magnetopause, and as a consequence, they escape the magnetosphere into interplanetary space. During disturbed times, as for example when a CME compresses the magnetosphere, the magnetopause moves inward and electrons which were on closed drift shells now encounter the magnetopause and escape. Studies suggest electron loss occurs associated with enhancements of the solar wind dynamic pressure, suggesting that the magnetopause shadowing leads to electron loss (Turner and Ukhorskiy 2020).

If the phase space density of electrons in the outer part of the outer belt decreases, negative spatial gradient of the phase space density is expected, and subsequent outward radial diffusion takes place (Miyoshi et al. 2003; Shprits et al. 2006), which contributes to electron loss of the whole outer belt. Simulations using the Fokker-Planck equation have assumed that electron phase space density decreases if the last-closed drift *L*-shell is larger than the dayside magnetopause.

On the other hand, actual trajectories of electrons in the dayside magnetopause are complicated, and drift-shell bifurcation causes the pitch angle scattering. Several test particle simulations have investigated these electron trajectories in detail (Kim et al. 2008, 2010, Saito et al. 2010). As mentioned by Kim and Lee (2014) and Mauk et al. (2016), it is difficult for electrons to cross the field line of the dayside magnetopause because gyro-radius of electrons are too small, and further detailed analysis lb considering actual structure of the dayside magnetopause is necessary.

Particle precipitation Pitch angle scattering is another important process to cause loss of relativistic electrons from the outer belt. Whistler mode waves and EMIC waves are important for the pitch angle scattering of relativistic electrons (Millan and Thorne 2007). From late of the 2000s, observational evidence has shown that EMIC waves actually cause the pitch angle scattering of MeV electrons (Miyoshi et al. 2008; Rodger et al. 2015; Usanova et al. 2014), which has been theoretically predicted in 1971 (Thorne and Kennel 1971). Since EMIC waves are generated by a temperature anisotropy of hot ions, ring current ions affect MeV electrons through wave-particle interactions. Several studies (Kubota and Omura 2017) indicated that rapid precipitations are possible through non-linear interactions between EMIC waves and MeV electrons.

Whistler mode waves also contribute to the loss of electrons. Hiss waves cause the pitch angle scattering of MeV electrons, and the flux of MeV electrons gradually decreases. Interactions with hiss waves are a primary loss process of MeV electrons in the slot region. Recent studies (Zhao et al. 2019) showed that interactions with hiss waves produce reversed energy spectra in the slot region.

Chorus waves also cause precipitation of electrons. The Arase observations identified for the first time that flux enhancements of tens keV electrons inside loss cone correspond to enhancement of chorus waves (Kasahara et al. 2018), which is definite evidence that pitch angle scattering and subsequent precipitation by wave-particle interactions actually occur. Figure 15 reproduced from Kasahara et al. (2018) illustrates schematically the interaction between chorus waves at the equator and bouncing electrons which are pitch angle scattered ultimately into the loss cone and precipitate. Figure 16 also reproduced from Kasahara et al. (2018) shows ERG/Arase measurements illustrating the simultaneous enhancement of wave power (top panel) and increased intensities of nearly field-aligned electrons clearly indicating the causal connection between the waves and precipitation of these electrons. If chorus waves propagate to higher latitudes, chorus waves can resonate with high-energy electrons and cause the pitch angle scattering of sub-relativistic/relativistic electrons (Miyoshi et al. 2015; Miyoshi et al. 2020), which may contribute tothe loss of MeV electrons. One of the significant phenomena about particle precipitation is the microbursts of relativistic electrons. Combined observations by balloon, FIREBIRD-II, AC-6 Cubesat identified the spatial and temporal evolution of a microburst region (Anderson et al. 2017). The relationship between microbursts and chorus waves as observed by FIREBIRD-II and Van Allen Probes (Breneman et al. 2017) indicates that microbursts of MeV electrons result from non-linear wave-particle interactions between electrons and chorus waves (Horne and Thorne 2003; Saito et al. 2012; Wang and Shprits; Miyoshi et al. 2020).

While it has been confirmed that both Whistler mode waves and EMIC waves cause significant precipitation of energetic electrons from the outer belt, quantitative estimation to discriminate dominant loss process of the outer belt has still been open problem.

2.6 Ground-based observations and conjunction studies

During solar cycle 24, multi-spacecraft have observed Geospace, which enable us to realize multi-point coordinated observations. Many conjunction studies among Van Allen Probes, Arase, THEMIS, MMS, and other satellites are achieved. One of the coordinated observations from multi-spacecraft is the radial profile of the phase space density. Boyd et al. (2018) investigated the phase space density profile up to L = 7.5 using both Van Allen Probes and THEMIS satellite, and they showed the peak of PSD beyond apogee altitude of Van Allen Probes. Multi-spacecraft observations could discriminate spatial-temporal variations of particle and field/waves. For example, Kurita et al. (2018) showed loss of MeV electron flux on timescales 30 min using both Van Allen Probes and Arase satellites and argued that EMIC waves cause the pitch angle scattering. Teramoto et al. (2019) identified modulations of MeV electrons by the MHD-fast mode waves occurring over the limited azimuthal longitudes using Van Allen Probes and Arase satellite.

Another great advantage for the inner magnetosphere research is the development of ground-based network observations. Several multi-point network observations have been developed, SuperDARN radars, magnetometers, optical imagers, riometers, and VLF/LF radio wave receivers. There have been many opportunities for conjugate observations between satellites and ground-based observations, which identified latitudinal/local time distributions.

2.7 Open questions and future directions

During the VarSITI era, new discoveries (e.g., multiple belt structure) and new observations (e.g., direct observations of wave-particle interactions) advanced the current understanding of the dynamics of the inner magnetosphere, in particular, that of energization and loss of radiation belt electrons. This was made possible by improved instrumentation and dedicated missions such as Arase, Van Allen Probes, MMS, and THEMIS. For example, Arase and van Allen Probes carried comprehensive instrument suites that characterized electric and magnetic fields, plasma waves, and energetic particles.

Nevertheless, many open questions remain, and indeed, some of the recent discoveries may have opened up new frontiers. For example, while the role of wave-particle

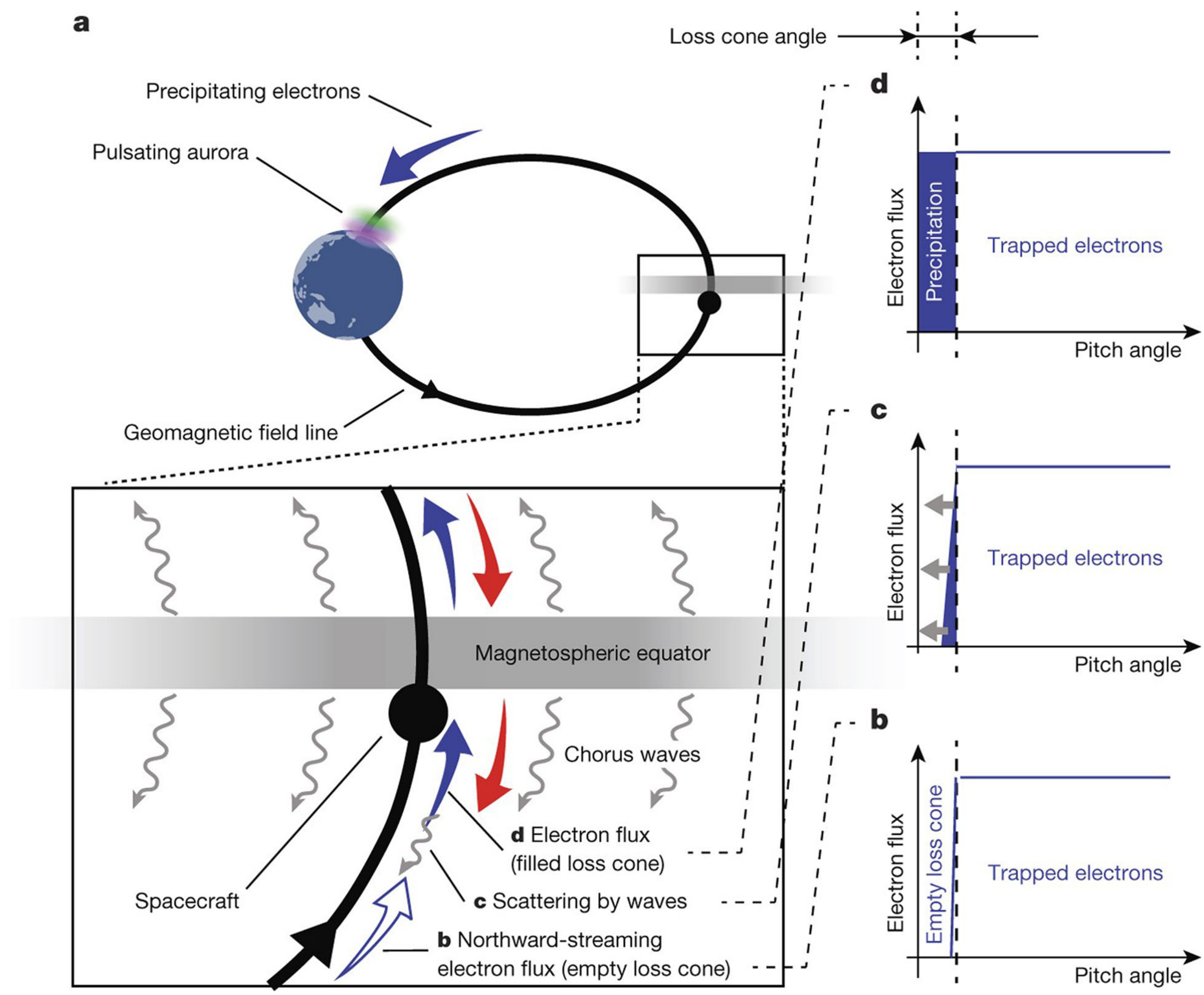

Fig. 15 Interaction of electrons with Chorus waves leading to their precipitation Figure reproduced from Kasahara et al. (2018)

interactions in energization and loss has long been recognized (for a review see for example Thorne (2010)), the importance of non-linear wave-wave and wave-particle interactions remains an open question. Recent theoretical and modeling (e.g., see Omura et al. 2015) suggest that they play a crucial role. Another important open question is in regard to electron loss from the radiation belts, viz., the relative importance of magnetopause shadowing and wave-particle precipitation (Turner et al. 2012). Of critical importance is the role of energetic particle precipitation in affecting the chemistry of the upper atmosphere (Turunen et al. 2016), an important open question that needs to be answered regarding climate change. The discovery of the so-called impenetrable barrier (Baker et al. 2014a) raises the question of its possible anthropic origin via ground-based VLF transmitters. Another open question is regarding the immediate injections resulting from IP shocks, i.e., what are the IP shock properties and internal magnetospheric conditions that result in the most intense injections? An event similar to the March 1991 (Blake et al. 1992) could pose a serious hazard for spacecraft and space weather consequences such as induced currents in power grids. Quantitative understanding of the origin of the highest energy electrons also remains an important open question, despite some recent progress (Zhao et al. 2019).

The need for multi-point measurements in advancing our quantitative understanding of the inner magnetospheric dynamics has long been recognized. This is a key direction in future scientific endeavors. The advent of CubeSats has made this a real and tangible goal. Innovations in space instrumentation and low-cost access to space have further spurred interest in the community, and proposed missions include constellations of CubeSats to study radiation belts, ring current, and plasma waves that drive particle dynamics (Kanekal et al. 2018,

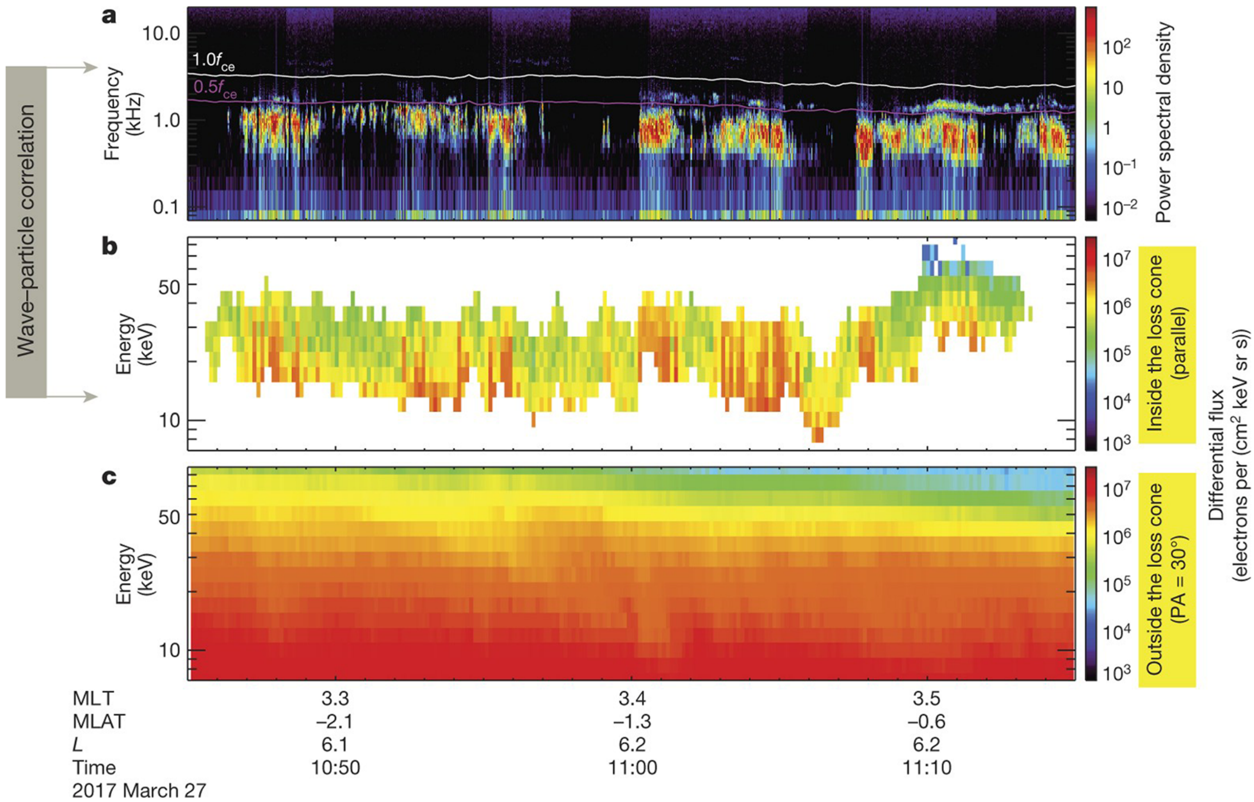

Fig. 16 Figure reproduced from Kasahara et al. (2018)

2019; Li et al. 2013). These CubeSat missions also play a complementary role to major "flag ship" type missions as the latter often have capabilities that are comprehensive (Fox and Burch; Miyoshi et al. 2018). Increasing societal reliance upon space-based assets for communication, Earth observation, and global climate issues are also driving the need for future mission to comprehensively understand the near-Earth environment. Flagship type missions that address the Sun-Earth, inner heliosphere as an integrated system are another important future trend that is being recognized as necessary to understand not only the system-as-a-whole but also the constituent parts such as the radiation belts and ring current.

3 Conclusions

During the varSITI era, much progress has been made in understanding the dynamics of the inner magnetosphere, and this review has focused particularly on the dynamics of the outer zone electrons. Major missions such as Arase, THEMIS, Van Allen Probes, and CubeSats and high-altitude balloons have contributed to the progress. New discoveries, such a multi-belt morphology, existence of a putative prevention of continued inward motion of energetic electrons (so-called impenetrable barrier mentioned earlier), and direct observation of wave-particle interactions, are some of the significant observational findings during the VarSITI era. In addition, our understanding of the underlying physical processes of electron energization and loss has also advanced considerably, e.g., in delineation of the importance of source, seed populations that lead to energization. Other areas of advances in understanding electron energization include the complementary role played by wave-particle and radial diffusion in producing ultra-relativistic electrons. Conjunctions between spacecraft and ground-based observations have been used to understand particle precipitation and the role of various plasma waves in general in regard to electron energization as well as loss. Contribution to space weather aspects, such as detailed observations of rapid injection of multi-MeV electrons by interplanetary shocks, has re-emphasized the need for continuous monitoring of radiation in geospace.

Yet, despite the impressive achievements during the VarSITI era, not unexpectedly, the new findings and advancements have opened up new vistas with many new scientific questions. This era has also seen the coming-of-age of CubeSats and advances in the miniaturization of space instrumentation, which have for the first time made multi-point in situ measurements possible. We believe that the future is bright for further progress in our understanding of the inner magnetosphere, especially in the light of technological innovations regarding space platforms such as CubeSats, low-cost launches and sophisticated instrumentation.

Abbreviations
CeREs: Compact Radiation belt Explorer; CME: coronal mass ejections; CIR: co-rotating interaction regions; CRRES: Combined Release and Radiation Effects Satellite; CSSWE: Colorado Student Space Weather Experiment CubeSat; EMIC: Electromagnetic Ion Cylcotron Waves; FIREBIRD: Focused Investigations of Relativistic Electron Burst Intensity, Range, and Dynamics; GEO: Gysynchronous Earth Orbit; IMF: interplanetary magnetic field; JAXA: Japan Aerospace eXploration Agency; MagEIS: Magnetic Electron Ion Spectrometer; MMS: Magnetospheric Multi Scale mission; RBSP: Radiation Belt Storm Probes; REPT: Relativistic Electron Proton Telescope; SAMPEX: Solar Anomalous Magnetic Explorer; SPeCIMEN: Specification and Prediction of the Coupled Inner-Magnetospheric Environment; THEMIS: Time History of Events and Macroscale Interactions during Substorms; VarSITI: The Variability of the Sun and Its Terrestrial Impact

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Authors' contributions
SK has contributed toward reviewing the results from Van Allen Probes. YM is chiefly responsible for the results from Arase. Both authors have read all sections and approved the final manuscript.

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Competing interests
The authors declare that they have no competing interest.

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References
Angelopoulos V (2008) The THEMIS Mission. Space Sci Rev 141(1):5. https://doi.org/10.1007/s11214-008-9336-1
Anderson BR, Shekhar S, Millan RM, Crew AB, Spence HE, Klumpar DM, Blake JB, O'Brien TP, Turner DL (2017) Spatial scale and duration of one microburst region on 13 August 2015. J Geophys Res Space Phys 122:5949–5964. https://doi.org/10.1002/2016JA023752
Baker DN, Blake JB, Callis LB, Belian RD, Cayton TE (1989) Relativistic electrons near geostationary orbit: evidence for internal magnetospheric acceleration. Geophys Res Lett 16(6):559–562
Baker DN, Blake JB, Callis LB, Cummings JR, Hovestadt D, Kanekal S, Klecker B, Mewaldt RA, Zwickl RD (1994) Relativistic electron acceleration and decay time scales in the inner and outer radiation belts: SAMPEX. Geophys Res Lett 21(6):409–412
Baker DN, et al. (2014c) Gradual diffusion and punctuated phase space density enhancements of highly relativistic electrons: Van Allen Probes observations. Geophys Res Lett 41:1351–1358. https://doi.org/10.1002/2013GL058942
Baker DN, Higbie PR, Belian RD, Hones EW (1979) Do Jovian electrons influence the terrestrial outer radiation zone? Geophys Res Lett 6:531–534. https://doi.org/10.1029/GL006i006p00531
Baker DN, Hoxie V, Zhao H, Jaynes AN, Kanekal S, Li X, Elkington S (2019) Multiyear measurements of radiation belt electrons: acceleration, transport, and loss. J Geophys Res Space Phys 124:2588–2602. https://doi.org/10.1029/2018JA026259
Baker DN, Jaynes AN, Hoxie VC, Thorne RM, Foster JC, Li X, et al. (2014a) An impenetrable barrier to ultrarelativistic electrons in the Van Allen radiation belts. Nature 515(7528):531–534. https://doi.org/10.1038/nature13956
Baker DN, Kanekal SG (2008) Solar cycle changes, geomagnetic variations, and energetic particle properties in the inner magnetosphere. J Atmos Solar-Terr Phys 70(2):195–206. https://doi.org/https://doi.org/10.1016/j.jastp.2007.08.031
Baker DN, Kanekal SG, Hoxie VC, Henderson MG, Li X, Spence HE, et al. (2013) A long-lived relativistic electron storage ring embedded in Earth's outer Van Allen belt. Science 340(6129):186–190. https://doi.org/https://doi.org/10.1126/science.1233518
Balasis G, Daglis IA, Mann IR (2016) Waves, particles, and storms in Geospace: a complex interplay. Oxford University Press, Oxford
Blake JB, Baker DN, Turner N, Ogilvie KW, Lepping RP (1997) Correlation of changes in the outer-zone relativistic-electron population with upstream solar wind and magnetic field measurements. Geophys Res Lett 24:927–929
Blake JB, et al. (2013) The Magnetic Electron Ion Spectrometer (MagEIS) Instruments aboard the Radiation Belt Storm Probes (RBSP) Spacecraft. Space Sci Rev. https://doi.org/10.1007/s11214-013-9991-8
Blake JB, Kolasinski WA, Fillius RW, Mullen EG (1992) Injection of electrons and protons with energies of tens of MeV into $L < 3$ on March 24, 1991. Geophys Res Lett 19:821–824. https://doi.org/10.1029/92GL00624
Blake JB, O'Brien TP (2016) Observations of small-scale latitudinal structure in energetic electron precipitation. J Geophys Res Space Phys 121(4):3031–3035. https://doi.org/10.1002/2015JA021815
Boyd AJ, Turner DL, Reeves GD, Spence HE, Baker DN, Blake JB (2018) What causes radiation belt enhancements: a survey of the Van Allen Probes era. Geophys Res Lett 45:5253–5259. https://doi.org/10.1029/2018GL077699
Breneman AW, Crew A, Sample J, Klumpar D, Johnson A, Agapitov O, Kletzing CA (2017) Observations directly linking relativistic electron microbursts to whistler mode chorus: Van Allen Probes and FIREBIRD II. Geophys Res Lett 44:11,265–11,272. https://doi.org/10.1002/2017GL075001
Burch JL, Moore TE, Torbert RB, Giles BL (2016) Magnetospheric multiscale overview and science objectives. Space Sci Rev 199(1):5–21. https://doi.org/10.1007/s11214-015-0164-9
Crew AB, Spence HE, Blake JB, Klumpar DM, Larsen BA, O'Brien TP, et al. (2016) First multipoint in situ observations of electron microbursts: initial results from the NSF FIREBIRD II mission. J Geophys Res Space Phys:5272–5283. https://doi.org/10.1002/2016JA022485@10.1002/(ISSN)2169-9402.EEL15
Cummings JR, Cummings AC, Mewaldt RA, Selesnick RS, Stone EC, Rosen-vinge TTvon (1993) New evidence for geomagnetically trapped anomalous cosmic rays. Geophys Res Lett 20(18):2003–2006. https://doi.org/10.1029/93GL01961

Desai MI, Allegrini F, Ebert RW, Ogasawara K, Epperly ME, George DE, et al. (2019) The CubeSat mission to study solar particles. IEEE Aerosp Electron Syst Mag 34(4):16–28. https://doi.org/10.1109/MAES.2019.2917802
Desai M, Giacalone J (2016) Large gradual solar energetic particle events. Living Rev Solar Phys 13(1):3. https://doi.org/10.1007/s41116-016-0002-5
Elkington SR, Hudson MK, Chan AA (1999) Acceleration of relativistic electrons via drift resonant interactions with toroidal-mode Pc-5 ULF oscillations. Geophys Res Lett 26:3273–3276
Falthammar C-G (1965) Effects of time dependent electric fields on geomagnetically trapped radiation. J Geophys Res 70:2503–2516
Fennell JF, Roeder JL, Kurth WS, Henderson MG, Larsen BA, Hospodarsky G, et al. (2014) Van Allen Probes observations of direct wave-particle interactions. Geophys Res Lett 41(6):1869–1875. https://doi.org/10.1002/2013GL059165
Foster JC, Erickson PJ, Omura Y, Baker DN, Kletzing CA, Claudepierre SG (2017) Van Allen Probes observations of prompt MeV radiation belt electron acceleration in nonlinear interactions with VLF chorus. J Geophys Res Space Phys 122:324–339. https://doi.org/10.1002/2016JA023429
Foster JC, Wygant JR, Hudson MK, Boyd AJ, Baker DN, Erickson PJ, Spence HE (2015) Shock-induced prompt relativistic electron acceleration in the inner magnetosphere. J Geophys Res Space Phys 120:1661–1674. https://doi.org/10.1002/2014JA020642
Fox N, Burch JL (eds) Van Allen Probes Mission. Springer US, Boston. https://doi.org/10.1007/978-1-4899-7433-4-2
Gold T (1959) Motions in the magnetosphere of the Earth. J Geophys Res (1896-1977) 64(9):1219–1224. https://doi.org/10.1029/JZ064i009p01219
Gopalswamy N (2016) History and development of coronal mass ejections as a key player in solar terrestrial relationship. Geosci Lett 3(1):8. https://doi.org/10.1186/s40562-016-0039-2
Green JC, Kivelson MG (2004) Relativistic electrons in the outer radiation belt: differentiating between acceleration mechanisms. J Geophys Res Space Phys 109(A3). https://doi.org/10.1029/2003JA010153
Hess WN (1959) Van Allen belt protons from cosmic-ray neutron leakage. Phys Rev Lett 3(1):11–13. https://doi.org/10.1103/PhysRevLett.3.11
Horne RB, Thorne RM (2003) Relativistic electron acceleration and precipitation during resonant interactions with Whistler-mode chorus. Geophys Res Lett 30(10):1527. https://doi.org/10.1029/2003GL016973
Hudson MK, Elkington SR, Lyon JG, Marchenko VA, Roth I, Temerin M, Blake JB, Gussenhoven MS, Wygant JR (1997) Simulations of radiation belt formation during storm sudden commencements. J Geophys Res 102(A7):14,087–14,102. https://doi.org/10.1029/97JA03995
Jaynes AN, Ali AF, Elkington SR, Malaspina DM, Baker DN, Li X, et al. (2018) Fast diffusion of ultrarelativistic electrons in the outer radiation belt: 17 March 2015 storm event. Geophys Res Lett 45(10):882. https://doi.org/10.1029/2018GL079786
Jaynes AN, Baker DN, Singer HJ, Rodriguez JV, Loto'aniu TM, Ali AF, et al. (2015) Source and seed populations for relativistic electrons: their roles in radiation belt changes. J Geophys Res Space Phys 120(9):7240–7254. https://doi.org/10.1002/2015JA021234
Jones FC, Ellison DC (1991) The plasma physics of shock acceleration. Space Sci Rev 58(1):259–346. https://doi.org/10.1007/BF01206003
Kanekal SG (2006) A review of recent observations of relativistic electron energization in the Earth's outer Van Allen radiation belt. In: Proceedings of the ILWS Workshop on Solar Influence on the Heliosphere and Earth's Environment, Goa, India, 19-24 Feb. 2006, edited by N. Gopalswamy and A. Bhattacharyya. Quest Publications, Goa. pp 274–279
Kanekal, SG (2020) Private communication
Kanekal SG, Baker DN, Blake JB (2001) Multisatellite measurements of relativistic electrons: global coherence. Journal of Geophysical Research: Space Physics 106(A12):29721–29732. https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2001JA000070. https://doi.org/10.1029/2001JA000070
Kanekal SG, Blum L, Christian ER, Crum G, Desai M, Dumonthier J, et al. (2019) The MERiT onboard the CeREs: a novel instrument to study energetic particles in the Earth's radiation belts. J Geophys Res Space Phys 124:5734–5760. https://doi.org/10.1029/2018JA026304
Kanekal S, Blum L, Christian E, Crum G, Dumonthier J, Evans A, et al. (2018) CeREs: the Compact Radiation belt Explorer. CeREs:2018. https://digitalcommons.usu.edu/smallsat/2018/all2018/259/
Kanekal SG, et al. (2016) Prompt acceleration of magnetospheric electrons to ultrarelativistic energies by the 17 March 2015 interplanetary shock. J Geophys Res Space Phys 121:7622–7635. https://doi.org/10.1002/2016JA022596
Kanekal SG, Baker DN, Henderson MG, Li W, Fennell JF, Zheng Y, Richardson IG, Jones A, Ali AF, Elkington SR, et al. (2015) Relativistic electron response to the combined magnetospheric impact of a coronal mass ejection overlapping with a high-speed stream: Van Allen Probes observations. J Geophys Res Space Physics 120:7629–7641. https://doi.org/10.1002/2015JA021395
Kasahara S, Miyoshi Y, Yokota S, Mitani T, Kasahara Y, Matsuda S, et al. (2018) Pulsating aurora from electron scattering by chorus waves. Nature 554(7692):337–340. https://doi.org/10.1038/nature25505
Kilpua EKJ, Hietala H, Turner DL, Koskinen HEJ, Pulkkinen TI, Rodriguez JV, Reeves GD, Claudepierre SG, Spence HE (2015) Unraveling the drivers of the storm time radiation belt response. Geophys Res Lett 42:3076–3084. https://doi.org/10.1002/2015GL063542
Kim K-C, Lee D-Y (2014) Magnetopause structure favorable for radiation belt electron loss. J Geophys Res Space Phys 119:5495–5508. https://doi.org/10.1002/2014JA019880
Kim KC, Lee D-Y, Kim H-J, Lyons LR, Lee ES, Ozturk MK, Choi CR (2008) Numerical calculations of relativistic electron drift loss effect. J. Geophys. Res A09212. https://doi.org/10.1029/2007JA013011
Klein LW, Burlaga LF (1982) Interplanetary magnetic clouds At 1 AU. J Geophys Res Space Phys 87(A2):613–624. https://doi.org/10.1029/JA087iA02p00613
Kubota Y, Omura Y (2017) Rapid precipitation of radiation belt electrons induced by EMIC rising tone emissions localized in longitude inside and outside the plasmapause. J Geophys Res Space Phys 122:293–309. https://doi.org/10.1002/2016ja023267
Kubota Y, Omura Y (2018) Nonlinear dynamics of radiation belt electrons interacting with chorus emissions localized in longitude. J Geophys Res Space Phys 123:4835–4857. https://doi.org/10.1029/2017JA025050
Kurita S, Miyoshi Y, Kasahara S, Yokota S, Kasahara Y, Matsuda S, et al. (2018) Deformation of electron pitch angle distributions caused by upper band chorus observed by the Arase satellite. Geophys Res Lett 45(16):7996–8004. https://doi.org/10.1029/2018GL079104
Li X, et al. (2013) First results from CSSWE CubeSat: characteristics of relativistic electrons in the near-Earth environment during the October 2012 magnetic storms. J Geophys Res Space Phys 118:6489–6499. https://doi.org/10.1002/2013JA019342
Li W, et al. (2014) Radiation belt electron acceleration by chorus waves during the 17 March 2013 storm. J Geophys Res Space Phys 119:4681–4693. https://doi.org/10.1002/2014JA019945
Li X, Roth I, Temerin M, Wygant JR, Hudson MK, Blake JB (1993) Simulation of the prompt energization and transport of radiation belt particles during the March 24, 1991 SSC. Geophys Res Lett 20(22):2423–2426. https://doi.org/10.1029/93GL02701
Li X, Roth I, Temerin M, Wygant JR, Hudson MK, Blake JB (2018) Simulation of the prompt energization and transport of radiation belt particles during the March 24, 1991 SSC. J Geophys Res Space Phys:2423–2426. https://doi.org/10.1029/93GL02701@10.1002/(ISSN)2169-9402.RADBELTS
Li X, Selesnick R, Schiller Q, Zhang K, Zhao H, Baker DN, Temerin MA (2017) Measurement of electrons from albedo neutron decay and neutron density in near-Earth space. Nature 552(7685):382–385. https://doi.org/10.1038/nature24642
Li X, Temerin M, Baker DN, Reeves GD (2011) Behavior of MeV electrons at geosynchronous orbit during last two solar cycles. J Geophys Res 116:A11207. https://doi.org/10.1029/2011JA016934
Looper MD, Blake JB, Mewaldt RA, Cummings JR, Baker DN (1994) Observations of the remnants of the ultrarelativistic electrons injected by the strong SSC of 24 March 1991. Geophys Res Lett 21:2079–2082. https://doi.org/10.1029/94GL01586
Mann IR, Ozeke LG, Murphy KR, Claudepierre SG, Turner DL, Baker DN, et al. (2016) Explaining the dynamics of the ultra-relativistic third Van Allen radiation belt. Nat Phys 12(10):978–983. https://doi.org/10.1038/nphys3799
Mauk BH, Cohen IJ, Westlake JH, Anderson BJ (2016) Modeling magnetospheric energetic particle escape across Earth's magnetopause as observed by the MMS mission. Geophys Res Lett 43:4081–4088. https://doi.org/10.1002/2016GL068856
Mauk BH, Fox NJ, Kanekal SG, Kessel RL, Sibeck DG, Ukhorskiy A (2014) Science Objectives and Rationale for the Radiation Belt Storm Probes Mission. In: Fox N, Burch JL (eds). The Van Allen Probes Mission. Springer US, Boston. pp 3–27. https://doi.org/10.1007/978-1-4899-7433-4-2

Millan RM, Thorne RM (2007) Review of radiation belt relativistic electron losses. J Atmos Solar-Terr Phys 69(3):362–377. https://doi.org/10.1016/j.jastp.2006.06.019
Miyoshi YS, Jordanova VK, Morioka A, Evans DS (2018) Solar cycle variations of the electron radiation belts: observations and radial diffusion simulation. Space Weather 2:S10S02. https://doi.org/10.1029/2004SW000070
Miyoshi Y, Kataoka R (2005) Ring current ions and radiation belt electrons during geomagnetic storms driven by coronal mass ejections and corotating interaction regions. Geophys Res Lett 32:L21105. https://doi.org/10.1029/2005GL024590
Miyoshi Y, Kataoka R (2008) Flux enhancement of the outer radiation belt electrons after the arrival of stream interaction regions. J Geophys Res 113:A03S09. https://doi.org/10.1029/2007JA012506
Miyoshi Y, Kataoka R, Kasahara Y, Kumamoto A, Nagai T, Thomsen MF (2013) High-speed solar wind with southward interplanetary magnetic field causes relativistic electron flux enhancement of the outer radiation belt via enhanced condition of whistler waves. Geophys Res Lett 40:4520–4525. https://doi.org/10.1002/grl.50916
Miyoshi Y, Morioka A, Obara T, Misawa T, Nagai T, Kasahara Y (2003) Rebuilding process of the outer radiation belt during the 3 November 1993 magnetic storm: NOAA and Exos'D observations. J Geophys Res 108(A1):1004. https://doi.org/10.1029/2001JA007542
Miyoshi Y, Sakaguchi K, Shiokawa K, Evans D, Albert J, Connors M, Jordanova V (2008) Precipitation of radiation belt electrons by EMIC waves, observed from ground and space. Geophys Res Lett 35:L23101. https://doi.org/10.1029/2008GL035727
Miyoshi Y, Saito S, Seki K, Nishiyama T, Kataoka R, Asamura K, Katoh Y, Ebihara Y, Sakanoi T, Hirahara M, et al. (2015) Relation between fine structure of energy spectra for pulsating aurora electrons and frequency spectra of whistler mode chorus waves. J Geophys Res Space Phys 120:7728–7736. https://doi.org/10.1002/2015JA021562
Miyoshi Y, Saito S, Kurita S, Asamura K, Hosokawa K, Sakanoi T, Mitani T, Ogawa Y, Oyama S, Tsuchiya F, Jones SL, Jaynes AN, Blake JB (2020) Relativistic electron microbursts as high energy tail of pulsating aurora electrons. Geophys Res Lett 47. https://doi.org/10.1029/2020GL090360
Miyoshi Y, Shinohara I, Takashima T, Asamura K, Higashio N, Mitani T, et al. (2018) Geospace exploration project ERG. Earth, Planets and Space 70(1):101. https://doi.org/10.1186/s40623-018-0862-0
Omura Y, Hikishima M, Katoh Y, Summers D, Yagitani S (2009) Nonlinear mechanisms of lower-band and upper-band VLF chorus emissions in the magnetosphere. J Geophys Res 114:A07217. https://doi.org/10.1029/2009JA014206
Omura Y, Miyashita Y, Yoshikawa M, Summers D, Hikishima M, Ebihara Y, Kubota Y (2015) Formation process of relativistic electron flux through interaction with chorus emissions in the Earth's inner magnetosphere. J Geophys Res Space Phys 120:9545–9562. https://doi.org/10.1002/2015JA021563
Owens MJ, Forsyth RJ (2013) The heliospheric magnetic field. Living Rev Solar Phys 10(1):5. https://doi.org/10.12942/lrsp-2013-5
Ozeke LG, Mann IR, Dufresne SKY, Olifer L, Morley SK, Claudepierre SG, et al. (2020) Rapid outer radiation belt flux dropouts and fast acceleration during the March 2015 and 2013 storms: the role of ULF wave transport from a dynamic outer boundary. J Geophys Res Space Phys 125:e2019JA027179. https://doi.org/10.1029/2019JA027179
Pandya M, Veenadhari B, Ebihara Y, Kanekal SG, Baker DN (2019) Variation of radiation belt electron flux during CME- and CIR-driven geomagnetic storms: Van Allen Probes observations. J Geophys Res Space Phys 124:6524–6540. https://doi.org/10.1029/2019JA026771
Parker EN (1958) Dynamics of the interplanetary gas and magnetic fields. Astrophys J 128:664. https://doi.org/10.1086/146579
Paulikas GA, Blake JB (1979) Effects of the solar wind on magnetospheric dynamics: energetic electrons at the synchronous orbit, in Quantitative Modeling of Magnetospheric Processes, Geophys. monogr. Ser., Vol. 21, edited by W. P. Olson. AGU, Washington DC
Reeves GD, Spence HE, Henderson MG, Morley SK, Friedel RHW, Funsten HO, et al. (2013) Electron acceleration in the heart of the Van Allen radiation belts. Science 341(6149):991–994. https://doi.org/10.1126/science.1237743
Rodger CJ, Hendry AT, Clilverd MA, Kletzing CA, Brundell JB, Reeves GD (2015) High-resolution in situ observations of electron precipitation-causing EMIC waves. Geophys Res Lett 42:9633–9641. https://doi.org/10.1002/2015gl066581
Roederer JG, Lejosne S (2018) Coordinates for representing radiation belt particle flux. Journal of GeophysicalResearch: Space Physics 123:1381–1387. https://doi.org/10.1002/2017JA025053
Russell CT, McPherron RL (1973) Semiannual variation of geomagnetic activity. J Geophys Res 78(1):92–108. https://doi.org/10.1029/JA078i001p00092
Saito S, Miyoshi Y, Seki K (2010) A split in the outer radiation belt by magnetopause shadowing: test particle simulations. J Geophys Res 115:A08210. https://doi.org/10.1029/2009JA014738
Saito S, Miyoshi Y, Seki K (2012) Relativistic electron microbursts associated with Whistler chorus rising tone elements: GEMSIS-RBW simulations. J Geophys Res 117:A10206. https://doi.org/10.1029/2012JA018020
Schiller Q, Gerhardt D, Blum L, Li X, Palo S (2014) Design and scientific return of a miniaturized particle telescope onboard the Colorado Student Space Weather Experiment (CSSWE) CubeSat. In: 2014 IEEE Aerospace Conference. pp 1–14. https://doi.org/10.1109/AERO.2014.6836372
Schiller Q, Kanekal SG, Jian LK, Li X, Jones A, Baker DN, Jaynes A, Spence HE (2016) Prompt injections of highly relativistic electrons induced by interplanetary shocks: a statistical study of Van Allen Probes observations. Geophys Res Lett 43:12,317–12,324. https://doi.org/10.1002/2016GL071628
Schiller Q, Li X, Blum L, Tu W, Turner DL, Blake JB (2014) A nonstorm time enhancement of relativistic electrons in the outer radiation belt. Geophys Res Lett 41:7–12. https://doi.org/10.1002/2013GL058485
Schulz M, Lanzerotti LJ (1974) Particle diffusion in the radiation belts. Springer, New York
Shiokawa K, Georgieva K (2020) A review of the SCOSTEP's 5-year Scientific program VarSITI - variability of the sun and its terrestrial impact. submitted to Progress in Earth and Planetary Sciences. https://doi.org/10.1186/s40645-021-00410-1
Shprits YY, Angelopoulos V, Russell CT, Strangeway RJ, Runov A, Turner D, et al. (2017) Scientific objectives of Electron Losses and Fields INvestigation Onboard Lomonosov Satellite. Space Sci Rev 214(1):25. https://doi.org/10.1007/s11214-017-0455-4
Shprits YY, Elkington S, Meredith NP, Subbotin DA (2008) Review of modeling of losses and sources of relativistic electrons in the outer radiation belt I: radial transport. J Atmos Solar-Terr Phys. https://doi.org/10.1016/j.jastp.2008.06.008
Shprits YY, Subbotin D, Drozdov A, Usanova ME, Kellerman A, Orlova K, et al. (2013) Unusual stable trapping of the ultrarelativistic electrons in the Van Allen radiation belts. Nat Phys 9(11):699–703. https://doi.org/10.1038/nphys2760
Shprits YY, Thorne RM, Friedel R, Reeves GD, Fennell J, Baker DN, Kanekal SG (2006) Outward radial diffusion driven by losses at magnetopause. J Geophys Res 111:A11214. https://doi.org/10.1029/2006JA011657
Sibeck D, Kanekal S, Kessel R, Fox N, Mauk B (2012) The Radiation Belt Storm Probes Mission: advancing our understanding of the Earth's radiation belts
Spence HE, Blake JB, Crew AB, Driscoll S, Klumpar DM, Larsen BA, et al. (2012) Focusing on size and energy dependence of electron microbursts from the Van Allen radiation belts. Space Weather 10(11). https://doi.org/10.1029/2012SW000869
Su Z, et al. (2015) Ultra-low-frequency wave-driven diffusion of radiation belt relativistic electrons. Nat. Commun 6:10096. https://doi.org/10.1038/ncomms10096
Summers D, Thorne RM, Xiao F (1998) Relativistic theory of wave-particle resonant diffusion with application to electron acceleration in the magnetosphere. J Geophys Res Space Phys 103(A9):7–20500. https://doi.org/10.1029/98JA01740
Teramoto M, Hori T, Saito S, Miyoshi Y, Kurita S, Higashio N, et al. (2019) Remote detection of drift resonance between energetic electrons and ultralow frequency waves: multisatellite coordinated observation by Arase and Van Allen Probes. Geophys Res Lett 46:11642–11651. https://doi.org/10.1029/2019GL084379
Thaller SA, Wygant JR, Cattell CA, Breneman AW, Tyler E, Tian S, et al. (2019) Solar rotation period driven modulations of plasmaspheric density and convective electric field in the inner magnetosphere. J Geophys Res Space Phys 124(3):1726–1737. https://doi.org/10.1029/2018JA026365
Thorne RM (2010) Radiation belt dynamics: the importance of wave-particle interactions. Geophys Res Lett 37:L22107. https://doi.org/10.1029/2010GL044990
Thorne RM, Bortnik J, Li W, Chen L, Ni B, Ma Q (2016) How Whistler-mode waves and thermal plasma density control the global distribution of the diffuse aurora and the dynamical evolution of radiation belt electrons. In:

Magnetosphere-Ionosphere Coupling in the Solar System (eds C.R. Chappell, R.W. Schunk, P.M. Banks, J.L. Burch and R.M. Thorne). https://doi.org/10.1002/9781119066880.ch9
Thorne RM, Kennel CF (1971) Relativistic electron precipitation during magnetic storm main phase. J Geophys Res 76(19):4446–4453. https://doi.org/10.1029/JA076i019p04446
Thorne RM, Li W, Ni B, Ma Q, Bortnik J, Baker DN, et al. (2018) Evolution and slow decay of an unusual narrow ring of relativistic electrons near L~3.2 following the September 2012 magnetic storm. Geophys Res Lett:3507–3511. https://doi.org/10.1002/grl.50627@10.1002/(ISSN)1944-8007.VAPROBES1
Thorne RM, Li W, Ni B, Ma Q, Bortnik J, Chen L, et al. (2013) Rapid local acceleration of relativistic radiation-belt electrons by magnetospheric chorus. Nature 504(7480):411–414. https://doi.org/10.1038/nature12889
Turner DL, Morley SK, Miyoshi Y, Ni B, Huang C-L (2012) Outer radiation belt flux dropouts: current understanding and unresolved questions. In: Dynamics of the Earth's radiation belts and inner magnetosphere, edited by D. Summers et al. AGU, Washington, D.C. https://doi.org/10.1029/2012GM001310
Turner DL, Ukhorskiy AY (2020) Outer radiation belt losses by magnetopause incursions and outward radial transport: new insight and outstanding questions from the Van Allen Probes era. In: Loss in the magnetosphere to particle precipitation in the atmosphere. pp 1–28. https://doi.org/10.1016/B978-0-12-813371-2.00001-9
Turunen E, Kero A, Verronen PT, Miyoshi Y, Oyama S-I, Saito S (2016) Mesospheric ozone destruction by high-energy electron precipitation associated with pulsating aurora. J Geophys Res Atmos:121. https://doi.org/10.1002/2016JD025015
Usanova ME, Drozdov A, Orlova K, Mann IR, Shprits Y, Robertson MT, et al. (2014) Effect of EMIC waves on relativistic and ultrarelativistic electron populations: ground-based and Van Allen Probes observations. Geophys Res Lett 41:1375–1381. https://doi.org/10.1002/2013gl059024
Van Allen J, McIlwain CE, Ludwig GH (1959) Radiation observations with satellite 1958. J Geophys Res (1896-1977) 64(3):271–286. https://doi.org/10.1029/JZ064i003p00271
Wang, Shprits On how high-latitude chorus waves tip the balance between acceleration and loss of relativistic electrons. Geophys Res Lett 46:7945–7954. https://doi.org/10.1029/2019GL082681
Wygant J, et al. (1994) Large amplitude electric and magnetic field signatures in the inner magnetosphere during injection of >15 MeV electron drift echoes. Geophys Res Lett 21:1739–1742. https://doi.org/10.1029/94GL00375
Zhao H, Baker DN, Jaynes AN, Li X, Elkington SR, Kanekal SG, Spence HE, Boyd AJ, Huang C-L, Forsyth C (2017) On the relation between radiation belt electrons and solar wind parameters geomagnetic indices: dependence on the first adiabatic invariant and L*. J Geophys Res Space Phys 122:1624–1642. https://doi.org/10.1002/2016JA023658
Zhao H, Baker DN, Li X, Jaynes AN, Kanekal SG (2018) The acceleration of ultrarelativistic electrons during a small to moderate storm of 21 April 2017. Geophys Res Lett 45:5818–5825. https://doi.org/10.1029/2018GL078582
Zhao H, Baker DN, Li X, Jaynes AN, Kanekal SG (2019) The effects of geomagnetic storms and solar wind conditions on the ultrarelativistic electron flux enhancements. J Geophys Res Space Physs 124:1948–1965. https://doi.org/10.1029/2018JA026257
Zhao H, Ni B, Li X, et al. (2019) Plasmaspheric hiss waves generate a reversed energy spectrum of radiation belt electrons. Nat. Phys 15:367–372. https://doi.org/10.1038/s41567-018-0391-6
Zurbuchen TH, Richardson IG (2006) In-situ solar wind and magnetic field signatures of interplanetary coronal mass ejections. In: Kunow H, Crooker NU, Linker JA, Schwenn R, Von Steiger R (eds). Coronal Mass Ejections. Springer, New York. pp 31–43. https://doi.org/10.1007/978-0-387-45088-9-3

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