PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A

MATHEMATICAL, PHYSICAL AND ENGINEERING SCIENCES

From Solar Sneezing to Killer Electrons: Outer Radiation Belt Response to Solar Eruptions

Journal:	*Philosophical Transactions A*
Manuscript ID	RSTA-2018-0097.R1
Article Type:	Review
Date Submitted by the Author:	19-Mar-2019
Complete List of Authors:	Daglis, Ioannis; National and Kapodistrian University of Athens, Department of Physics Katsavrias, Christos; National and Kapodistrian University of Athens, Department of Physics Georgiou, Marina; University College London, Mullard Space Science Laboratory, Department of Space and Climate Physics
Issue Code (this should have already been entered but please contact the Editorial Office if it is not present):	SPACE-WEATHER
Subject:	Astrophysics (10) < ASTRONOMY (1000), Solar system (169) < ASTRONOMY (1000), Space exploration (171) < ASTRONOMY (1000)
Keywords:	Space storms, Radiation belts, Wave-particle interactions, Energetic particles, Relativistic electrons
Note: The following files were submitted by the author for peer review, but cannot be converted to PDF. You must view these files (e.g. movies) online.	
Daglis Revised LaTeX.rar	

<u>Author-supplied statements</u>

Relevant information will appear here if provided.

Ethics

Does your article include research that required ethical approval or permits?:
This article does not present research with ethical considerations

Statement (if applicable):
CUST_IF_YES_ETHICS :No data available.

Data

It is a condition of publication that data, code and materials supporting your paper are made publicly available. Does your paper present new data?:
My paper has no data

Statement (if applicable):
CUST_IF_YES_DATA :No data available.

Conflict of interest

I/We declare we have no competing interests

Statement (if applicable):
CUST_STATE_CONFLICT :No data available.

Authors' contributions

This paper has multiple authors and our individual contributions were as below

Statement (if applicable):
IAD oversaw the writing of the entire manuscript, and led the writing of Sections 1, 2, and 6. MG led the writing of section 4. CK led the writing of sections 3 and 5. All authors contributed to the writing of all sections. All authors have read and approved the manuscript.

PROCEEDINGS A

rspa.royalsocietypublishing.org

Research

Article submitted to journal

Subject Areas:

xxxxx, xxxxx, xxxx

Keywords:

Radiation belts, trapped particles, plasma waves, wave–particle interactions, coronal mass ejections, stream interaction regions

Author for correspondence:

Ioannis A. Daglis

e-mail: iadaglis@phys.uoa.gr

From Solar Sneezing to Killer Electrons: Outer Radiation Belt Response to Solar Eruptions

Ioannis A. Daglis[1,2,3], Christos Katsavrias[1,2] and Marina Georgiou[4]

[1] Department of Physics, National and Kapodistrian University of Athens, GR-15487 Athens, Greece

[2] Institute of Accelerating Systems and Applications, National and Kapodistrian University of Athens, GR-15487 Athens, Greece

[3] Institute for Astronomy, Astrophysics, Space Applications and Remote Sensing, National Observatory of Athens, GR-15236 Penteli, Greece

[4] Mullard Space Science Laboratory, Department of Space and Climate Physics, University College London, Dorking, United Kingdom

Electrons in the outer Van Allen (radiation) belt occasionally reach relativistic energies, turning them into a potential hazard for spacecraft operating in geospace. Such electrons have secured the reputation of satellite killers and thus a prominent role in space weather. The flux of these electrons can vary over timescales of years (related to the solar cycle) to minutes (related to Sudden Storm Commencements). Electric fields and plasma waves are the main factors regulating the electron transport, acceleration and loss. Both the fields and the plasma waves are driven directly or indirectly by disturbances originating in the Sun, propagating through interplanetary space and impacting the Earth. This paper reviews our current understanding of the response of outer Van Allen belt electrons to solar eruptions and their interplanetary extensions, i.e. interplanetary coronal mass ejections (ICMEs) and high–speed solar wind streams (HSSs) and the associated stream interaction regions (SIRs).

THE ROYAL SOCIETY PUBLISHING

1. Introduction

Earth's radiation belts were the first major charged particle population that was discovered in space. The seminal discovery was made through the measurements of Geiger–Mueller tubes by Professor James Van Allen's group on-board the Explorer 1 and 3 spacecraft [1].

It is now widely accepted that the Van Allen radiation belts consist of two belts of energetic particles azimuthally drifting around the Earth: a stable inner belt in the region L < 2 composed of energetic electrons and ions (mainly protons) and a very dynamic outer belt in the region L > 3 that is composed predominantly of electrons with a "slot" region separating the two. Occasionally a third (electron) belt appears [2,3].

Radiation belt particles are distinguished by their high energies (100 keV to 20 MeV/200 MeV for electrons/protons) compared to the much lower energies of all other magnetospheric plasma populations. The first source proposed for the origin of the radiation belts was decay of neutrons produced by cosmic rays impacting the atmosphere. Balloon and rocket measurements, however, showed that the loss rates of radiation belt electrons through precipitation into the atmosphere would have demanded improbably high rates of replenishment if cosmic rays had been the source [4,5]. Cosmic ray neutron albedo is now widely accepted as the generation mechanism for the highly-energetic protons in the inner belt (e.g. [6]).

Outer belt electrons have been observed to reach ultra-relativistic energies well above 10 MeV (i.e., $\gamma > 20$, where γ is the Lorentz factor). Taking into account that the typical energy of electrons in the terrestrial ionosphere is less than 1 eV and the typical energy of solar wind electrons is about 10 eV, it is obvious that how these electrons come to be energized is a major theme of space research, with both astrophysical and societal significance.

Although the basic mechanisms driving the acceleration, transport and loss of charged particles are well understood, the relative importance, effectiveness, synergy and/or antagonism of the various physical mechanisms on the outer belt electron dynamics remain under substantial dispute. The Van Allen Probes mission [7] has contributed very significantly to radiation belt research through prolific and detailed measurements, covering all energies of radiation belt electrons and providing unprecedented measurements of ultra–relativistic electrons with energy coverage up to 20 MeV.

2. Outer Van Allen Belt Variability

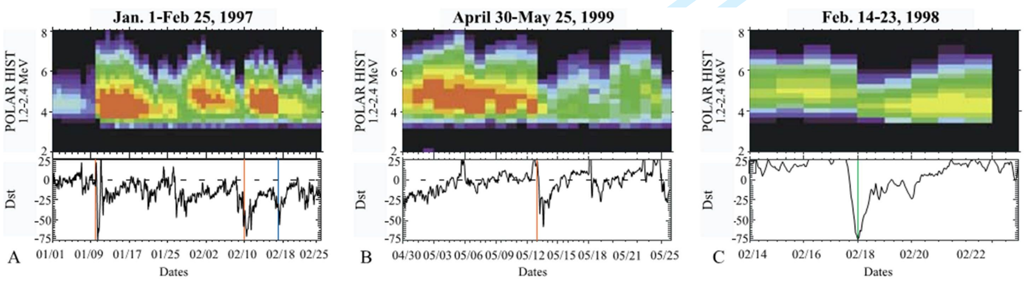

Figure 1. Representation of three different types of the outer electron belt response as measured from the POLAR/HIST instrument. Source: Reeves et al. [8].

Charged particles respond adiabatically to sufficiently slow geomagnetic field changes. This means that there are no permanent effects on radiation belt electrons due to slow changes (compared to typical gyro, bounce and drift timescales) in the magnetic field configuration during magnetic storms and when the field returns to its pre–storm state the radiation belt electrons also return to their pre–storm state. Accordingly, any other changes in the radiation belts have to be studied and interpreted in the context of such adiabatic changes. To fully understand radiation belt processes, we have to separate adiabatic and non-adiabatic storm-time processes, which usually occur simultaneously. All processes affecting radiation belt electrons (both adiabatically and non–adiabatically) are typically enhanced during magnetic storms. Therefore, it had been reasonable to assume that magnetic storms (especially intense ones) produce significant or large radiation belt enhancement events. Reeves et al. [9], made an effort to demonstrate this storm effect, but found instead that, although most radiation belt enhancements observed at geosynchronous orbit do occur during magnetic storms, the degree of radiation belt electron enhancements is not correlated with the Dst index (i.e., the storm intensity). Moreover, Onsager et al. [10] showed that magnetic storms do not only occasionally enhance the radiation belts, but also produce non-adiabatic, permanent loss of electrons from the radiation belts. In a seminal follow-on study Reeves et al. [8] investigated the influence of 276 moderate and intense magnetic storms from 1989 through 2000 (see also figure 1) and found out that there were storms increasing the fluxes of relativistic electrons in the outer radiation belt (53%), storms decreasing the fluxes (19%), and storms resulting in no net change in the fluxes (28%). Ten years later, Turner et al. [11], using a database of 53 events (December 2007–August 2012) and phase space density (PSD) calculations, derived from THEMIS satellites' data, showed that, 58% of the events resulted in relativistic electron PSD enhancement, 17% in depletion and 25% resulted in no significant change in the PSD.

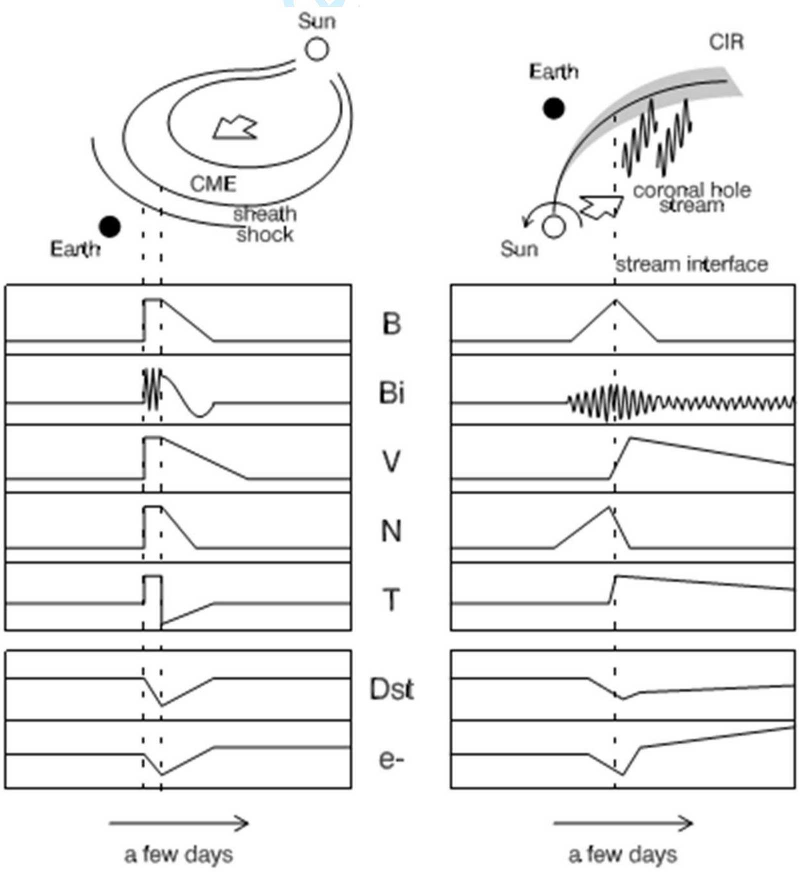

Figure 2. Representation of different evolution of solar wind parameters during an ICME and a SIR. Source: Kataoka and Miyoshi [12].

rspa.royalsocietypublishing.org Proc R Soc A 0000000

While under usual conditions, the solar wind is highly varying and appears almost random at the Earth's orbit, drivers of geomagnetic storms arrive in characteristic sequences lasting from tens of hours to days. The most important drivers of geomagnetic storms are Interplanetary Coronal Mass Ejections (ICMEs) and High–Speed Streams (HSSs) with associated Stream or Co-rotating Interaction Regions (SIRs/CIRs). Several studies have revealed that the dynamic outer zone electron radiation belt will evolve differently during storms driven by the two drivers, since they have different solar wind parameters (figure 2). For example, SIRs exhibit more fluctuating z component of the interplanetary magnetic field (IMF) than ICMEs, while, on the other hand ICMEs, exhibit a much more steep gradient of both solar wind speed and density than SIRs. Because of the aforementioned differences, Borovsky and Denton [13] have linked the 1.1–1.5 MeV electron flux enhancements at geosynchronous orbit, during SIR–driven storms, to a combination of southward interplanetary magnetic field (IMF) and high–speed solar wind. Li et al. [14] studied 72 CIR-driven storm periods and indicated that the phase space density of source electrons at $L^* < 7$, exhibited a remarkable consistency with the evolution of chorus waves and was highly dependent on the preceding interplanetary magnetic field z–component.

Interplanetary shocks that impact the terrestrial magnetosphere can occasionally be highly geoeffective. At the Earth orbit, most interplanetary shocks are forward shocks driven by CMEs. interplanetary shocks are also formed at leading/trailing edges of CIRs/SIRs, but typically far from the Earth, at 2–3 AU. Strong interplanetary shocks compress the magnetosphere suddenly and lead to rapid and pronounced enhancements of relativistic electrons within a few minutes. An outstanding example was the shock that triggered the sudden commencement of the March 24, 1991, storm and compressed the magnetopause inside the geosynchronous orbit. The shock impact resulted in the rapid formation of a new radiation belt in the slot region, at $L \approx 2.5$, with a peak in the electron energy spectrum at 15 MeV [15,16], observed by sensors on board the Combined Release and Radiation Effects Satellite (CRRES). A similar event was observed by the Van Allen Probes in March 2015 [17]. A statistical study of Van Allen Probes observations showed that about 25% of interplanetary shocks impacting the magnetosphere are are associated with prompt electron energization [18].

3. Acceleration and Loss Mechanisms

There are various theories of how electrons are accelerated to relativistic energies and how relativistic electrons decay; all of them have as basic condition the violation of one or more adiabatic invariants. These theories can be divided into 2 major categories: 1) inward radial diffusion and 2) *in situ* acceleration. A way to distinguish between acceleration by inward radial diffusion and local acceleration through wave–particle interactions is to calculate the electron PSD, which has distinct profiles for the two acceleration mechanisms (figure 3).

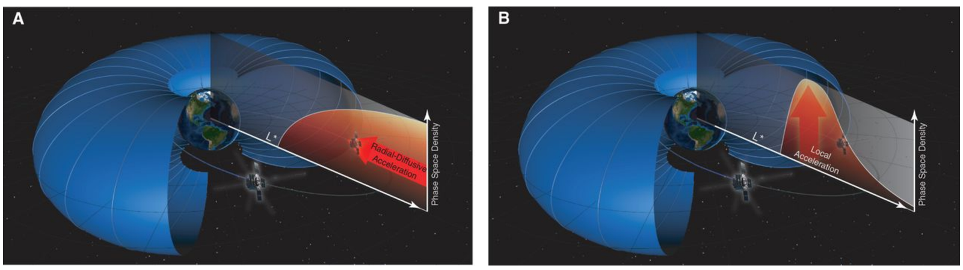

Figure 3. There is an ongoing debate on how electrons trapped in the Earth's radiation belts are accelerated to relativistic energies. Using electron PSD, we can differentiate between radial diffusion (positive monotonic gradients) and local acceleration (growing peaks). Source: Reeves et al. [19].

Inward radial diffusion is associated with the violation of the third adiabatic invariant, while the first and second adiabatic invariants are conserved. This allows particles to diffuse earthward whenever there are negative density gradients, and gain energy in the process [20]. Earthward radial diffusion can be further divided, mainly, into: a) substorm injections and b) transport from the plasma sheet [21,22].

In situ acceleration takes place when the first and/or the second adiabatic invariant are violated. Theory and observation suggest that the plasma waves responsible for these violations are whistler chorus mode waves [23]. Horne and Thorne [24] appointed an energy limit (some 100s keV), above which, such waves, tend to accelerate electrons and simultaneously lead to precipitation into the ionosphere through pitch angle scattering.

As in the case of enhancements, a decrease in electron flux can be caused by adiabatic effects (the so-called "Dst effect" [25,26]), but true losses of radiation belt electrons are believed to be dominated by one, or a combination, of two mechanisms: 1) scattering into the atmospheric loss cones (drift or bounce) via wave–particle interactions with plasmaspheric hiss, electromagnetic ion cyclotron (EMIC) or chorus waves [27–29] and 2) magnetopause shadowing combined with outward diffusion [30,31]. Magnetopause shadowing [32] is the term used for particles that are lost through drifting into the magnetopause, and this can become important even for lower L–shells whenever the magnetopause is compressed inwards due to high speed solar wind streams or high pressure pulses.

4. Role of ULF and VLF Waves

A large number of different plasma waves, generated by a broad variety of physical mechanisms, appear in different region of the Earth's magnetosphere [33]. Field-line Resonances (FLRs) represent a class of ultra–low frequency (ULF) pulsations observed in electric and magnetic field measurements in space and on the ground. Quasi-sinusoidal waveforms are classified as continuous and are further broken down into five categories (Pc1 to Pc5), depending on their frequency [34]. A simple mathematical description of ULF waves was developed by Dungey [35] and is based on the idea of standing Alfvén waves on magnetic field lines. The broader class of ULF quasi-sinusoidal and broad-band variations may be excited in response to velocity shear instabilities at the magnetopause flanks [36–38] or compressive variations in the solar wind dynamic pressure [39–41]. Such solar wind-driven waves, typically of low azimuthal wave number, m, respond almost directly to changing solar wind conditions when compared to waves with internal sources. Internal plasma instabilities with high m-number can be excited by ring current ions injected towards the dusk sector of the magnetosphere [42,43].

Large–scale ULF waves were observed concurrently with a rapid increase in relativistic electron fluxes during the 10-11 January 1997 magnetic storm [44]. The observation of these largely monochromatic waves with dominant toroidal polarization led to the conclusion that electrons could be accelerated via drift-resonant interaction with low-m number toroidal waves. Electrons drifting with a frequency ω_d that satisfies the equation $\omega = (m \pm 1) \cdot \omega_d$, where m and ω is the wave mode number and frequency, will experience continuous acceleration throughout their motion in a compressed dipole field, which will be dependent on its noon-midnight asymmetry. In this case of violation of the third adiabatic invariant of electrons motion, while the first and second invariants are conserved, the resulting radial motion will lead to a change in their energy. Interaction of electrons drifting in dipole magnetic field with the azimuthal electric field of toroidal–mode FLRs is governed by the resonance condition $\omega = m \cdot \omega_d$, while there also asymmetric resonance for the poloidal component of such ULF fluctuations. Electrons drifting in an asymmetric magnetic field will be subject to the combined effects of each resonance described above, with the degree of interaction depending on wave power at frequencies corresponding to the resonance conditions.

Radial transport is most often described as a stochastic process whereby a source population of electrons, for example, from the plasma sheet [45,46] is transported Earthwards, from regions of weaker to regions of stronger geomagnetic field, and thereby increase their energy. The

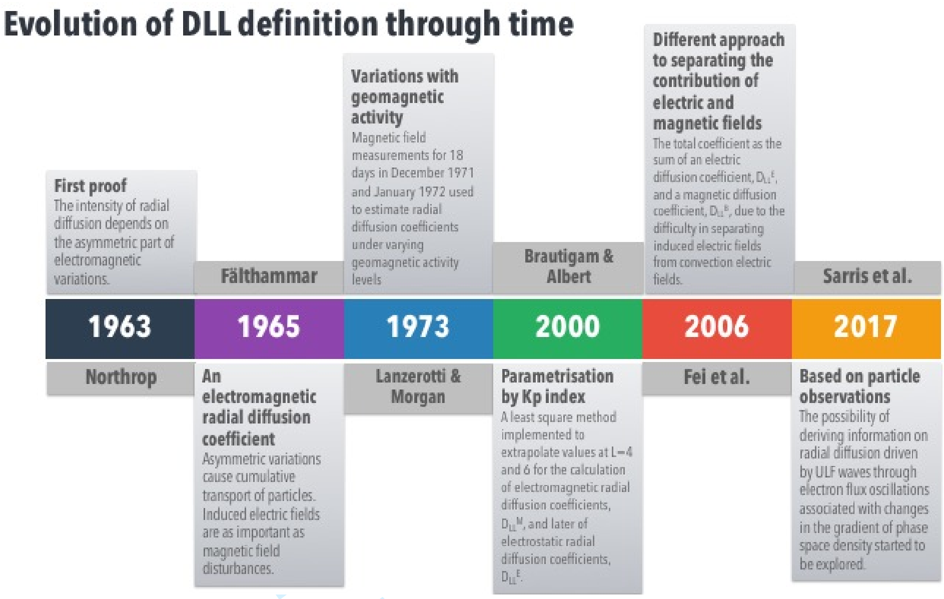

Figure 4. The evolution of radial diffusion coefficients definition, starting from the first years of radiation belt research.

diffusion rate is proportional to power spectral density of stochastic fluctuations of the Earth's magnetic field and induced electric fields, as well as fluctuations in convection electric fields in the ULF frequency range [15]. Since the first derivation of a radial diffusion coefficient from electromagnetic field variation effects on the dynamics of electrons [47], different approaches have been introduced to characterize the radial diffusion process (figure 4). In the theoretical approach preferred in recent works to quantify the diffusion rate [48–50], the total radial diffusion coefficient is defined as the sum of an electric diffusion coefficient, due to azimuthal electric field perturbations, and a magnetic coefficient, due to compressional magnetic field perturbations, $D_{LL}^{tot} = D_{LL}^{E} + D_{LL}^{B}$, because of the difficulty in separating convective and inductive terms in electric field measurements. Since no correlation between the magnetic field fluctuations and induced electric fields through Faraday's law is assumed, there are uncertainties introduced in this derivation of radial diffusion coefficients that have not yet been quantified [51].

The most important – in terms of space weather – VLF waves are the whistler chorus mode waves. These waves have a range of frequencies $0.05\ |\Omega_e| < \Omega < 0.8|\Omega_e|$ (where $|\Omega_e|$ the electron gyro–frequency), and are observed outside the plasmasphere, over a broad range of MLT extending from the nightside through dawn to the dayside, with peak wave intensities generally found near the Equator on the nightside [52–54]. Lower band chorus waves ($0.1\ |\Omega_e| < \Omega < 0.5|\Omega_e|$) are generated due to anisotropic angular distributions of electrons with few to tens of keV's energy (typically referred as source population) which are injected near midnight from the plasma sheet due to substorm injections thus their emission strongly depends on substorm activity [55–57]. Such chorus waves can, in turn, interact resonantly with higher energy (30–300 keV typically referred as seed population) electrons also injected by substorms, and can very efficiently accelerate them to multi–MeV energies [58–62]. Figure 5, shows a schematic of the combined role of substorms and chorus waves in producing the initial energetic electron population which, then, can be pumped up in energy by large factors on characteristic time scales of minutes to hours.

Observational evidence, supporting the aforementioned scenario has been provided by several studies. Summers at al. [23], showed that a source population of a few 100 keV energy can be effectively accelerated through wave–particle interactions with chorus waves. Brautigam and Albert [64], studied the September 9, 1990, event and found that radial diffusion by itself cannot

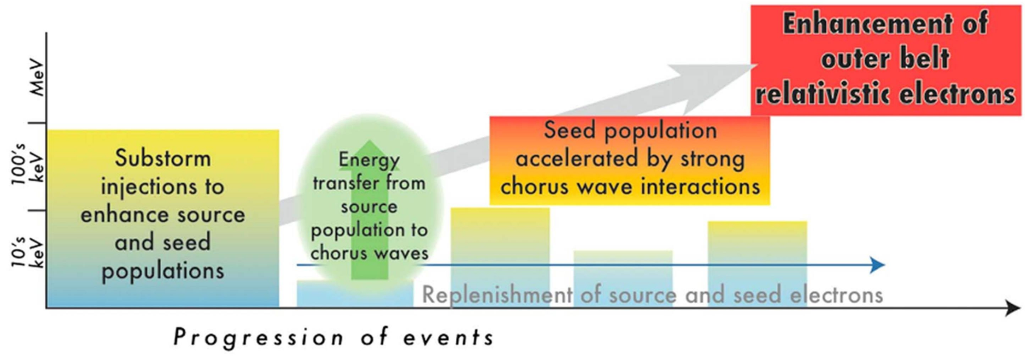

Figure 5. Schematic of the ideal setup and sequence for the enhancement of relativistic (>1 MeV) outer belt electrons [63].

explain the increment of electrons with energies higher than 1 MeV. Instead they proposed that such phenomena can be effectively explained by interactions with whistler chorus mode waves. At the same extent, Iles et al. [66], examined the September 11-16, 1990, time period (which was characterized by enhanced substorm activity without magnetic storm occurrence) and suggested that peaks in relativistic electron PSD at $4.0 < L^* < 5.5$, were in good correlation with the prolonged substorm activity and increased chorus wave activity.

5. Recent Studies and New Insights

Recent statistical studies on the electron fluxes in the outer belt [67,68] or the total electron content [?], which aimed at determining the effect of geomagnetic storms on radiation belt electrons, had similar results with the older studies by Reeves and Turner [8,9,11,22]. Reeves et al. [69], further showed that the net effect of each storm is both energy and L–shell dependent.

Several research efforts have been directed towards understanding how different solar wind drivers produce different types of responses both in geomagnetic activity and in radiation belt dynamics. It has been shown that the result of each driver type can be, statistically, completely different [70,71] and also energy and L–shell dependent (see figure 6). In a recent study, Horne et al. [72] suggested that high–speed solar wind streams may be more effective in enhancing relativistic and ultra–relativistic electrons than a major geomagnetic storm, due to high values of solar wind speed that are known to correlate well with enhanced Pc5 activity [73].

The effects of ICMEs, on the other hand, can be quite diverse because of their rather complex structure. Hietala et al. [74] have shown that ICME sheath regions can cause substantial, long–term depletions of the outer radiation belt electrons, while Kilpua et al. [70] have argued that following ICME impact, the radiation belt fluxes increase mainly in cases where both the sheath and the ejecta substructures have high values of solar wind speed.

Especially regarding acceleration, the greatest dispute still refers to the dominant mechanism: inward radial diffusion driven by ULF waves versus local acceleration by VLF chorus waves. Georgiou et al. [75,76] demonstrated a remarkable association between the enhancement of ULF Pc5 wave activity and outer radiation belt electron flux enhancements during magnetic storms that occurred during the time period between January 1998 and April 2004. In addition, the earthward penetration depth of Pc5 waves was found to be correlated with the storm intensity, similarly to penetration of the outer radiation belt within the slot region. The response of the outer electron radiation belt to the selected storms suggested ULF wave power-correlated acceleration processes that operate by inward radial transport. On the other hand, Boyd et al. [77], examined electron PSD radial profiles (relativistic electrons with μ=700 MeV/G) during 80 distinct events and showed that that local acceleration is the dominant acceleration mechanism for the 87% of them. Nevertheless, they pointed out that the rest 13% of the events had features consistent with

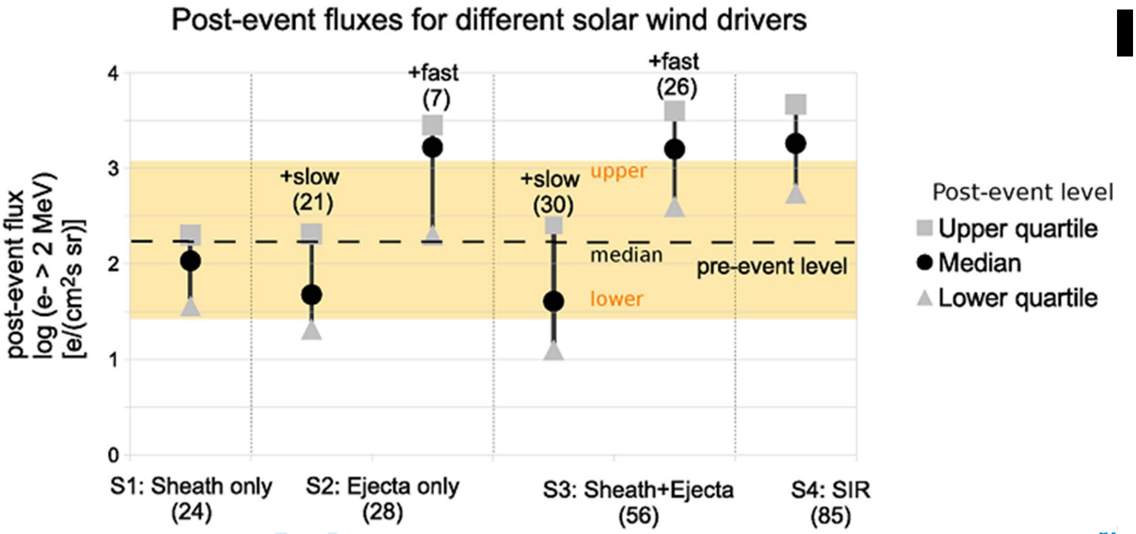

Figure 6. Post-event radiation belt electron fluxes from GOES measurements for different storm driver sequences. Source: Kilpua et al. [70].

inward radial transport. In addition, Li et al. [78], examined the extreme storm of March 2015 (St. Patrick's event) and suggested that radial diffusion alone was unable to produce the rising peak at the right location. Yet, argued that further acceleration of these electrons to even higher energies could be achieved by radial diffusion via Pc5–ULF waves. The latter is in agreement with the work by Jaynes et al. [63]. Both presented observational indications that enhanced inward radial diffusion of relativistic electrons (1–2 MeV) was able to produce further acceleration up to multi–MeV energies during two separate events. Ma et al. [79], combined observations from RBSP with simulation results to demonstrate that, during the March 1 – 5, 2013 event, chorus waves caused a relativistic electron flux increase by more than 1 order of magnitude during the first 18 h, while during the recovery phase the coupled radial diffusion and the pitch angle scattering by EMIC waves and plasmaspheric hiss controlled electron dynamics. Along the same line, Katsavrias et al. [80], suggested that during the March 2013 intense storm the chorus–driven acceleration of relativistic electrons exceeded the Pc5–driven losses. Finally, Kanekal et al. [81], indicated that the combined effects of local acceleration and radial diffusion are even more complex during events with overlapping drives, as these mechanisms act differently on population with different μ and K values.

Regardless which one is the dominant acceleration or loss mechanism, the fact that they are not necessarily defined by geomagnetic activity adds more complexity to the response of the outer belt. Schiller et al. [82], showed that during a period of weak geomagnetic disturbances there was an enhancement of approximately 2.5 orders of magnitude for 0.6 – 1.3 MeV electrons in less than 13 h. Along the same line, Katsavrias et al. [83], showed that during a period of continuously positive Sym-H index, outward radial diffusion via ULF waves combined with magnetopause shadowing, resulted in a relativistic electron PSD dropout of 2 orders of magnitude.

6. Summary and Discussion

After more than two decades of renewed interest and detailed research on the Earth's outer radiation belt, its exact response to solar eruptions and to their subsequent interplanetary and geospace disturbances is still under debate.

Solar eruptions that find their way through interplanetary space to the Earth's magnetosphere, can lead, by driving various acceleration mechanisms, to the creation of killer electrons, i.e. relativistic electrons in the outer Van Allen belt.

Numerous studies over the past two decades have significantly revised our perception of how electrons with initial energies of only a few eV can reach energies of several MeVs. From the somewhat simplistic view of relativistic electrons being just the plain, recurrent result of magnetic storms, we have come to the realization of the much more complex ways the flux of relativistic electrons is influenced by different plasma waves, which in turn are driven in variable ways by different interplanetary disturbances.

It has become clear that the eventual effect of the various interplanetary drivers on the radiation belts depends on the synergy/antagonism of internal magnetospheric processes (storm/substorm occurrence and growth of various plasma wave modes) resulting from different combinations of IMF and solar wind parameters.

The southward IMF orientation is a pre–requisite for the occurrence of dynamic magnetospheric phenomena that dissipate energy stored in the magnetic field as a result of reconnection at the dayside magnetopause. Prolonged duration (i.e., many hours) of southward IMF leads to magnetic storms, while shorter periods of southward IMF are sufficient to drive magnetospheric substorms. High–speed solar wind increases the coupling efficiency and energy transfer from the solar wind to the magnetosphere, at the same time driving the growth of Kelvin–Helmholtz instabilities, which lead to the appearance of ULF waves. ULF waves are also favored by the impact of high–speed ICMEs.

It is obvious that distinct types of solar eruptions and associated interplanetary disturbances result in different effects in the inner magnetosphere. High–speed streams mainly to the occurrence of prolonged and intense magnetospheric substorms, while ICMEs lead to the occurrence of magnetic storms and occasionally to the growth of ULF waves (ICME sheaths).

Substorm acceleration and earthward injection of low–energy plasma sheet electrons provide the source and seed population, from which the relativistic and ultra–relativistic killer electrons will be born, if certain plasma waves will grow and act on them. The growth of different plasma waves is favored – as mentioned above – by pressure pulses and/or high–speed solar wind (ULF waves), as well as substorm–injected electrons (VLF waves) and storm–time ring current asymmetric ion distributions (ULF waves). As both ULF and VLF waves can lead to both acceleration and loss of electrons, the final net effect on the outer Van Allen belt depends on the interplay of the various mechanisms and the balance between acceleration and loss of energetic electrons.

With regard to acceleration, it has not yet been established whether the dominant mechanism is inward radial diffusion driven by ULF waves or local acceleration by VLF chorus waves. A way to distinguish between the two mechanisms is to calculate the electron PSD, which has different profiles for the two acceleration mechanisms. However, nothing precludes, in principle, simultaneous action of the two mechanisms.

With regard to relativistic electron losses, although the sinks are just two (the atmosphere and the magnetopause), the prevailing mechanism is not clear as a multitude of mechanisms may act in parallel: outward diffusion by ULF waves and pitch–angle scattering by chorus waves, EMIC waves and plasmaspheric hiss.

How can we improve our understanding of killer electrons genesis and, more broadly, of the dynamics of the outer Van Allen belt electrons? The scientifically intriguing and societally relevant (because of spacecraft vulnerability to energetic electrons) endeavour of electron enhancement forecasting, requires detailed knowledge of the prevailing acceleration, transport and loss mechanisms for variable solar sneezing, i.e., for different types of solar eruptions and associated interplanetary disturbances impacting geospace.

To achieve this, the community needs:

- further exhaustive case and statistical studies of detailed particle and wave observations in the inner magnetosphere

- combination of observational studies with modeling of wave–particle interactions, in order to confirm or discard the significance of wave effects, which in principle exist, but may not be of practical importance
- large–scale modeling, incorporating the propagation and arrival of interplanetary disturbances and the resulting magnetospheric effects (storm/substorm occurrence and wave growth)

Currently, NASA's Van Allen Probes and JAXA's Arase satellite are providing unprecedented insight into the physical processes that drive the outer radiation belt variability. However, the two missions are expected to retire in the next years. To continue gathering measurements of the Van Allen belts' environment, CubeSat missions serve as pathfinders for new miniaturized technologies that could help scientists realize a long-sought dream: deploying a constellation of satellites to gather simultaneous, multi-point measurements of Earth's ever-changing Van Allen belts. Among them, the Colorado Student Space Weather Experiment (CSSWE) [84] was launched in 2012, the Focused Investigations of Relativistic Electron Intensity Range and Dynamics (FIREBIRD) CubeSat in 2013 [85] and was followed by FIREBIRD II in 2016 [86], while a series of new CubeSat missions are already or scheduled to be put in orbit, including the Compact Radiation Belt Explorer (CeRES).

Ethics. To the authors' best knowledge, there are no ethics implications triggered by this review.

Data Accessibility. This review does not contain any supporting data.

Authors' Contributions. IAD oversaw the writing of the entire manuscript, and led the writing of Sections 1, 2, and 6. MG led the writing of section 4. CK led the writing of sections 3 and 5. All authors contributed to the writing of all sections. All authors have read and approved the manuscript.

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

Funding. MG was supported by the Natural Environment Research Council (NERC) Highlight Topic Grant #NE/P017185/1 (Rad-Sat).

Acknowledgements. We thank the referees for their constructive comments and suggestions.

References

1. Van Allen J. A., 1958, Observation of high intensity radiation by satellites, *Alpha and Gamma, Jet Propulsion*, **28**, pp 588–592, doi:10.2514/8.7396.
2. Baker, D. N., S. G. Kanekal, V. C. Hoxie, M. G. Henderson, X. Li, H. E. Spence, S. R. Elkington, R. H. W. Friedel, J. Goldstein, M. K. Hudson, G. D. Reeves, R. M. Thorne, C. A. Kletzing, and S. G. Claudepierre, 2013, A long–lived relativistic electron storage ring embedded in Earth's outer Van Allen belt, *Science*, **340**, pp 186–190, doi:10.1126/science.1233518.
3. Mann, I. R., L. G. Ozeke, K. R. Murphy, S. G. Claudepierre, D. L. Turner, D. N. Baker, I. J. Rae, A. Kale, D. K. Milling, A. J. Boyd, H. E. Spence, G. D. Reeves, H. J. Singer, S. Dimitrakoudis, I. A. Daglis, and F. Honary, 2016, Explaining the dynamics of the ultra–relativistic third Van Allen radiation belt, *Nature Physics*, **12**, pp 978–983, doi: 10.1038/NPHYS.
4. Singer, S.F., 1958, Trapped albedo theory of the radiation belt, *Physical Review Letters*, **1**, pp 181–183, doi:10.1103/Physrevlett.1.181.
5. Winckler, J.R., P. D. Bhavsar, and K. A. Anderson, 1962, A study of the precipitation of energetic electrons from the geomagnetic field during magnetic storms, *Journal of Geophysical Research*, **67**, pp 3717–3736, doi:10.1029/JZ067i010p03717.
6. Selesnick, R.S., M. D. Looper, and R. A. Mewaldt, 2007, A theoretical model of the inner proton radiation belt, *Space Weather*, **5**, S04003, doi:10.1029/2006SW000275.
7. Mauk, B. H., N. J. Fox, S. G. Kanekal, R. L. Kessel, D. G. Sibeck, and A. Ukhorskiy, 2013, Science objectives and rationale for the Radiation Belt Storm Probes mission, *Space Sci. Rev.*, **179**, pp 3–27, doi:10.1007/s11214-012-9908-y.
8. Reeves, G. D., K. L. McAdams, R. H. W. Friedel, and T. P. O'Brien, 2003, Acceleration and loss of relativistic electrons during geomagnetic storms, *Geophysical Research Letters*, **30**, 1529, doi:10.1029/2002gl016513.

9. Reeves, G. D., 1998, Relativistic electrons and magnetic storms: 1992-1995, *Geophysical Research Letters*, **25**, pp 1817–1820, doi:10.1029/98gl01398.
10. Onsager, T. G., G. Rostoker, H.âĂŘJ. Kim, G. D. Reeves, T. Obara, H. J. Singer, and C. Smithtro, 2002, Radiation belt electron flux dropouts: Local time, radial, and particle–energy dependence, *Journal of Geophysical Research*, **107**, pp SMP 21-1-SMP 21-11, doi: 10.1029/2001ja000187.
11. Turner, D. L., V. Angelopoulos, W. Li, M. D. Hartinger, M. Usanova, I. R. Mann, J. Bortnik and Y. Shprits, 2013, On the storm-time evolution of relativistic electron phase space density in Earth's outer radiation belt, *Journal of Geophysical Research*, **118**, pp 2196–2212, doi:10.1002/jgra.50151.
12. Kataoka, R., and Y. Miyoshi, 2006, Flux enhancement of radiation belt electrons during geomagnetic storms driven by coronal mass ejections and corotating interaction regions, *Space Weather*, **4**, S09004, doi:10.1029/2005SW000211.
13. Borovsky, J. E., and M. H. Denton, 2006, Differences between CME–driven storms and CIR–driven storms, *Journal of Geophysical Research*, **111**, A07S08, doi:10.1029/2005JA011447.
14. Li, W., R. Thorne, J. Bortnik, R. McPherron, Y. Nishimura, V. Angelopoulos, and I. G. Richardson, 2012, Evolution of chorus waves and their source electrons during storms driven by corotating interaction regions, *Journal of Geophysical Research*, **117**, A08209, doi: 10.1029/2012ja017797.
15. Blake, J. B., W. A., Kolasinski, R. W. Fillius, and E. G. Mullen, 1992, Injection of electrons and protons with energies of tens of MeV into L<3 on 24 March 1991, *Geophysical Research Letters*, **19**, 821–824, doi:10.1029/92GL00624.
16. Li, X., I. Roth, M. Temerin, J. R. Wygant, M. K. Hudson, and J. B. Blake, 1993, Simulation of the prompt energization and transport of radiation belt particles during the March 24, 1991 SSC, *Geophysical Research Letters*, **20**, 2423–2426, doi:10.1029/93GL02701.
17. Kanekal, S. G., D. N. Baker, J. F. Fennell, A. Jones, Q. Schiller, I. G. Richardson, X. Li, D. L. Turner, S. Califf, S. G. Claudepierre, L. B. Wilson III, A. Jaynes, J. B. Blake, G. D. Reeves, H. E. Spence, C. A. Kletzing, and J. R. Wygant, 2016, Prompt acceleration of magnetospheric electrons to ultrarelativistic energies by the 17 March 2015 interplanetary shock, *Journal of Geophysical Research*, **121**, pp 7622 – 7635, doi:10.1002/2016JA022596.
18. Q. Schiller, S. G. Kanekal, L. K. Jian, X. Li, A. Jones, D. N. Baker, A. Jaynes, and H. E. Spence, 2016, Prompt injections of highly relativistic electrons induced by interplanetary shocks: A statistical study of Van Allen Probes observations, *Geophysical Research Letters*, **43**, pp 12,317–12,324, doi:10.1002/2016GL071628.
19. Reeves G. D., H. E. Spence, M. G. Henderson, S. K. Morley, R. H. W. Friedel, H. O. Funsten, D. N. Baker, S. G. Kanekal, J. B. Blake, J. F. Fennell, S. G. Claudepierre, R. M. Thorne, D. L. Turner, C. A. Kletzing, W. S. Kurth, B. A. Larsen, and J. T. Niehof, 2003, Electron acceleration in the heart of the Van Allen radiation belts, *Science*, **341**, pp 991–994, doi: 10.1126/science.1237743.
20. Schulz, M., and L. J. Lanzerotti, 1974, *Particle diffusion in the radiation belts*, Springer, Heidelberg.
21. Taylor, M. G. G. T., R. H. W. Friedel, G. D. Reeves, M. W. Dunlop, T. A. Fritz, P. W. Daly and A. Balogh, 2004, Multisatellite measurements of electron phase space density gradients in the Earth's inner and outer magnetosphere, *Journal of Geophysical Research*, **109**, A05220, doi:10.1029/2003JA010294.
22. Turner, D. L., V. Angelopoulos, Y. Shprits, A. Kellerman, P. Cruce, and D. Larson, 2012, Radial distributions of equatorial phase space density for outer radiation belt electrons, *Geophysical Research Letters*, **39**, L09101, doi:10.1029/2012GL051722.
23. Summers, D., R. M. Thorne, F. and Xiao, 1998, Relativistic theory of wave–particle resonant diffusion with application to electron acceleration in the magnetosphere, *Journal of Geophysical Research*, **103**, pp 20,487–20,500, doi:10.1029/98JA01740.
24. Horne, R. B., and R. M. Thorne, Potential waves for relativistic electron scattering and stochastic acceleration during magnetic storms, 1998, *Journal of Geophysical Research*, **25**, pp 3011–3014, doi: 10.1029/98GL01002.
25. Kim, H. J., and A. A. Chan, 1997, Fully adiabatic changes in storm-time relativistic electron fluxes, *Journal of Geophysical Research*, **102**, pp 22,107–22,116, doi:10.1029/97ja01814.
26. Reeves, G. D., and I. A. Daglis, 2016, Geospace magnetic storms and the Van Allen radiation belts, in *Waves, Particles, and Storms in Geospace: A Complex Interplay*, edited by G. Balasis, I. A. Daglis, and I. R. Mann, pp 51–79, *Oxford University Press*, ISBN:9780198705246.

27. Jaynes, A. N., X. Li, Q. G. Schiller, L. W. Blum, W. Tu, D. L. Turner, B. Ni, J. Bortnik, D. N. Baker, S. G. Kanekal, J. B. Blake and J. Wygant, 2014, Evolution of relativistic outer belt electrons during an extended quiescent period, *Journal of Geophysical Research*, **119**, pp 9558–9566, doi:10.1002/2014JA020125.
28. Usanova, M. E., A. Drozdov, K. Orlova, I. R. Mann, Y. Shprits, M. T. Robertson, D. L. Turner, D. K. Milling, A. Kale, D. N. Baker, S. A. Thaller, G. D. Reeves, H. E. Spence, C. Kletzing, and J. Wygant, 2014, Effect of EMIC waves on relativistic and ultrarelativistic electron populations: Ground–based and Van Allen Probes observations, *Geophysical Research Letters*, **41**, pp 1375–1381, doi:10.1002/2013GL059024.
29. Bortnik, J., R. M. Thorne, W. Li, and X. Tao, 2016, Chorus waves in geospace and their influence on radiation belt dynamics, in *Waves, Particles, and Storms in Geospace: A Complex Interplay*, edited by G. Balasis, I. A. Daglis, and I. R. Mann, pp 192–216, *Oxford University Press*, ISBN:9780198705246.
30. Shprits, Y. Y., R. M. Thorne, R. Friedel, G. D. Reeves, J. Fennell, D. N. Baker, and S. G. Kanekal, 2006, Outward radial diffusion driven by losses at magnetopause, *Journal of Geophysical Research*, **111**, A11214, doi:10.1029/2006JA011657.
31. Turner, D. L., Y. Shprits, M. Hartinger, and V. Angelopoulos, 2012, Explaining sudden losses of outer radiation belt electrons during geomagnetic storms, *Nature Physics*, **8**, pp 208–212, doi:10.1038/nphys2185.
32. Kim, K. C., and D. Y. Lee, 2014, Magnetopause structure favorable for radiation belt electron loss, *Journal of Geophysical Research*, **119**, pp 5495–5508, doi:10.1002/2014JA019880.
33. Shawhan, S. D., 1985, The menagerie of geospace plasma waves, *Space Science Reviews*, **42**, pp. 257–274, doi: 10.1007/BF00218235.
34. Jacobs, J. A., Y. Kato, S. Matsuhita, and V. A. Troitskaya, 1964, Classification of geomagnetic micropulsations, *Journal of Geophysical Research*, **69**, pp 180–181, doi: 10.1029/JZ069i001p00180.
35. Dungey, J. W., 1967, Hydromagnetic waves and the ionosphere, *Academic Press*, New York, USA.
36. Miura A., 1992, Kelvin–Helmholtz instability at the magnetospheric boundary: Dependence on the magnetosheath sonic Mach number, *Journal of Geophysical Research*, **97**, pp 10,655–10,675, doi:10.1029/92JA00791.
37. Mann I. R., A. N. Wright, K. J. Mills, and V. M. Nakariakov, 1999, Excitation of magnetospheric waveguide modes by magnetosheath flows, *Journal of Geophysical Research*, **104**, pp 333-354, doi:10.1029/1998JA900026.
38. Claudepierre, S. G., S. R. Elkington, and M. Wiltberger, 2008, Solar wind driving of magnetospheric ULF waves: Pulsations driven by velocity shear at the magnetopause, *Journal of Geophysical Research*, **113**, A05218, doi:10.1029/2007JA012890.
39. Sibeck, D. G., W. Baumjohann, R. C. Elphic, D. H. Fairfield, and J. F. Fennell, 1989, The magnetospheric response to 8–minute period strong–amplitude upstream pressure variations, *Journal of Geophysical Research*, **94**, pp 2505-2519, doi:10.1029/JA094iA03p02505.
40. Kepko, L., H. E. Spence, and H. J. Singer, 2002, ULF waves in the solar wind as direct drivers of magnetospheric pulsations, *Geophysical Research Letters*, **29**, pp 39-1-39-4, doi:10.1029/2001GL014405.
41. Kepko, L., and H. E. Spence, 2003, Observations of discrete, global magnetospheric oscillations directly driven by solar wind density variations, *Journal of Geophysical Research*, **108**, 1257, doi:10.1029/2002JA009676.
42. Sarris, T. E., W. Liu, X. Li, K. Kabin, E. R. Talaat, R. Rankin, V. Angelopoulos, J. Bonnell, and K. H. Glassmeier, 2010, THEMIS observations of the spatial extent and pressure-pulse excitation of field line resonances, *Geophysical Research Letters*, **37**, L15104, doi:10.1029/2010GL044125.
43. Takahashi, K., C. T. Russell, and R. R. Anderson, 1985, ISEE 1 and 2 observations of the spatial structure of a compressional Pc 5 wave, *Geophysical Research Letters*, **12**, pp 613-616, doi:10.1029/GL012i009p00613.
44. Hudson, M. K., S. R. Elkington, J. G. Lyon, C. C. Goodrich, and T. J. Rosenberg, 1999, Simulation of radiation belt dynamics driven by solar wind variations, in *Sun-Earth Plasma Connections*, edited by J. L. Burch, R. L. Carovillano, S. K. Antiochos, Geophysical Monograph 109, American Geophysical Union, Washington DC.
45. Borovsky, J. E., and T. E. Cayton, 2011, Entropy mapping of the outer electron radiation belt between the magnetotail and geosynchronous orbit, *Journal of Geophysical Research*, **116**, A06216, doi:10.1029/2011JA016470.

46. Boyd, A. J., H. E. Spence, S. G. Claudepierre, J. F. Fennell, J. B. Blake, D. N. Baker, G. D. Reeves, and D. L. Turner, 2014, Quantifying the radiation belt seed population in the 17 March 2013 electron acceleration event, *Geophysical Research Letters*, **41**, pp 2275–2281, doi:10.1002/2014GL059626.
47. Fälthammar C. G., 1965, Effects of time-dependent electric fields on geomagnetically trapped radiation, *Journal of Geophysical Research*, **70**, pp 2503–2516, doi:10.1029/JZ070i011p02503.
48. Fei, Y., A. A. Chan, S. R. Elkington, and M. J. Wiltberger, 2006, Radial diffusion and MHD particle simulations of relativistic electron transport by ULF waves in the September 1998 storm, *Journal of Geophysical Research*, **111**, A12209, doi:10.1029/2005JA011211.
49. Ozeke, L. G., I. R. Mann, K. R. Murphy, I. J. Rae, D. K. Milling, S. R. Elkington, A. A. Chan, and H. Singer, 2012, ULF wave derived radiation belt radial diffusion coefficients, *Journal of Geophysical Research*, **117**, A04222, doi:10.1029/2011JA017463.
50. Ozeke, L. G., I. R. Mann, K. R. Murphy, I. J. Rae, and D. K. Milling, 2014, Analytic expressions for ULF wave radiation belt radial diffusion coefficients, *Journal of Geophysical Research*, **119**, pp 1587–1605, doi:10.1002/2013JA019204.
51. Lejosne, S., D. Boscher, V. Maget, and G. Rolland, 2013, Deriving electromagnetic radial diffusion coefficients of radiation belt equatorial particles for different levels of magnetic activity based on magnetic field measurements at geostationary orbit, *Journal of Geophysical Research*, **118**, pp 3147–3156, doi:10.1002/jgra.50361.
52. Santolik, O., D. A. Gurnett, J. S. Pickett, M. Parrot, and N. Cornilleau–Wehrlin, 2003, Spatio–temporal structure of storm–time chorus, *Journal of Geophysical Research*, **108**, 1278, doi: 10.1029/2002JA009791.
53. Li, W., R. M. Thorne, V. Angelopoulos, J. Bortnik, C. M. Cully, B. Ni, O. LeContel, A. Roux, U. Auster, and W. Magnes, 2009, Global distribution of whistler–mode chorus waves observed on the THEMIS spacecraft, *Geophysical Research Letters*, **36**, L09104, doi: 10.1029/2009GL037595.
54. Meredith, N. P., R. B. Horne, A. Sicard–Piet, D. Boscher, K. H. Yearby, W. Li, and R. M. Thorne (2012), Global model of lower band and upper band chorus from multiple satellite observations, *Journal of Geophysical Research*, **117**, A10225, doi: 10.1029/2012JA017978.
55. Meredith, N. P., Horne, R. B., and Anderson, R. R., 2001, Substorm dependence of chorus amplitudes: Implications for the acceleration of electrons to relativistic energies, *Journal of Geophysical Research*, **106**, pp 13,165–13,178, doi:10.1029/2000JA900156.
56. Li, W., R. M. Thorne, J. Bortnik, D. N. Baker, G. D. Reeves, S. G. Kanekal, H. E. Spence, and J. C. Green, 2015, Solar wind conditions leading to efficient radiation belt electron acceleration: A superposed epoch analysis, *Geophysical Research Letters*, **42**, pp 6906–6915, doi:10.1002/2015GL065342.
57. Boynton, R. J., H. Aryan, S. N. Walker, V. Krasnoselskikh, and M. A. Balikhin, 2018, The influence of solar wind and geomagnetic indices on Lower Band Chorus emissions in the inner magnetosphere, *Journal of Geophysical Research*, **123**, pp 9022–9034, doi:10.1029/2018JA025704.
58. O'Brien, T. P., K. R. Lorentzen, I. R. Mann, N. P. Meredith, J. B. Blake, J. F. Fennell, M. D. Looper, D. K. Milling, and R. R. Anderson, 2003, Energization of relativistic electrons in the presence of ULF power and MeV microbursts: Evidence for dual ULF and VLF acceleration, *Journal of Geophysical Research*, **108(A8)**, 1329, doi:10.1029/2002JA009784.
59. Meredith, N. P., M. Cain, R. B. Horne, R. M. Thorne, D. Summers and R. R. Anderson, 2003, Evidence for chorus-driven electron acceleration to relativistic energies from a survey of geomagnetically disturbed periods, *Geophysical Monograph Series*, **108**, 1248, doi:10.1029/2002JA009764.
60. Horne, R. B., R. M. Thorne, S. A. Glauert, J. M. Albert, N. P. Meredith, and R. R. Anderson, 2005, Timescale for radiation belt electron acceleration by whistler mode chorus waves, *Journal of Geophysical Research*, **110**, A03225, doi:10.1029/2004JA010811.
61. Baker, D. N., and I. A. Daglis, 2007, Radiation belts and ring current, in *Space Weather - Physics and Effects*, edited by V. Bothmer and I. A. Daglis, pp 173–202, Springer Verlag, Berlin.
62. Thorne, R. M., Li, W., Ni, B., Ma, Q., Bortnik, J., Chen, L., Baker, D. N., Spence, H. E., Reeves, G. D., Henderson, M. G., Kletzing, C. A., Kurth, W. S., Hospodarsky, G. B., Blake, J. B., Fennell, J. F., Claudepierre, S. G., and Kanekal, S. G., 2013, Rapid local acceleration of relativistic radiation-belt electrons by magnetospheric chorus, in *Nature*, **504**, pp 411–414, doi:10.1038/nature12889.
63. Jaynes, A. N., D. N. Baker, H. J. Singer, J. V. Rodriguez, T. M. Loto'aniu, A. F. Ali, S. R. Elkington, X. Li, S. G. Kanekal, S. G. Claudepierre, J. F. Fennell, W. Li, R. M. Thorne,

C. A. Kletzing, H. E. Spence, and G. D. Reeves, 2015, Source and seed populations for relativistic electrons: Their roles in radiation belt changes, *Journal of Geophysical Research*, **120**, pp 7240–7254, doi:10.1002/2015JA021234.

64. Brautigam, D. H., and J. M. Albert, 2000, Radial diffusion analysis of outer radiation belt electrons during the October 9, 1990, magnetic storm, *Journal of Geophysical Research*, **105(A1)**, pp 291–309, doi: 10.1029/1999JA900344.
65. Iles, R. H. A., N. P. Meredith, A. N. Fazakerley, and R. B. Horne, 2006, Phase space density analysis of the outer radiation belt energetic electron dynamics, *Journal of Geophysical Research*, **111**, A03204, doi: 10.1029/2005JA011206.
66. Turner, D. L., T. P. O'Brien, J. F. Fennell, S. G. Claudepierre, J. B. Blake, E. K. J. Kilpua, and H. Hietala, 2015, The effects of geomagnetic storms on electrons in Earth's radiation belts, *Geophysical Research Letters*, **42**, pp 9176–9184, doi:10.1002/2015GL064747.
67. Moya, P. S., V. A. Pinto, D. G. Sibeck, S. G. Kanekal, and D. N. Baker, 2017, On the effect of geomagnetic storms on relativistic electrons in the outer radiation belt: Van Allen Probes observations, *Journal of Geophysical Research*, **122**, pp 11,100–11,108, doi:/10.1002/2017JA024735.
68. Murphy, K. R., C. E. J. Watt, I. R. Mann, I. J. Rae, D. G. Sibeck, A. J. Boyd, C. F. Forsyth, D. L. Turner, S. G. Claudepierre, D. N. Baker, H. E. Spence, G. D. Reeves, J. B. Blake, and J. Fennell, 2017, The global statistical response of the outer radiation belt during geomagnetic storms, *Geophysical Research Letters*, **45**, pp 3783–3792, doi:10.1002/2017GL076674.
69. Reeves, G.D., R. H. W. Friedel, B. A. Larsen, R. M. Skoug, H. O. Funsten, S. G. Claudepierre, J. F. Fennell, D. L. Turner, M. H. Denton, H. E. Spence, J. B. Blake, and D. N. Baker, 2016, Energy dependent dynamics of keV to MeV electrons in the inner zone, outer zone, and slot regions, *Journal of Geophysical Research*, **121**, pp 397–412, doi:10.1002/2015JA021569.
70. Kilpua, E. K. J., H. Hietala, D. L. Turner, H. E. J. Koskinen, T. I. Pulkkinen, J. V. Rodriguez, G. D. Reeves, S. G. Claudepierre, and H. E. Spence, 2015, Unraveling the drivers of the storm time radiation belt response, *Geophysical Research Letters*, **42**, pp 3076–3084, doi:10.1002/2015GL063542.
71. Shen, X. C., M. K. Hudson, A. Jaynes, Q. Shi, A. Tian, S. Claudepierre, M. R. Qin, Q. G. Zong, and W. J. Sun, 2017, Statistical study of the storm time radiation belt evolution during Van Allen Probes era: CME– versus CIR–driven storms, *Journal of Geophysical Research*, **122**, pp 8327–8339, doi:10.1002/2017JA024100.
72. Horne, R. B., M. W. Phillips, S. A. Glauert, N. P. Meredith, A. D. P. Hands, K. Ryden, and W. Li, 2018, Realistic worst case for a severe space weather event driven by a fast solar wind stream, *Space Weather*, **16**, pp 1202–1215, doi:10.1029/2018SW001948.
73. Simms, L. E., V. A. Pilipenko, and M. J. Engebretson, 2010, Determining the key drivers of magnetospheric Pc5 wave power, *Journal of Geophysical Research*, **115**, A10241, doi:10.1029/2009JA015025.
74. Hietala, H., E. K. J. Kilpua, D. L. Turner, and V. Angelopoulos, 2014, Depleting effects of ICME–driven sheath regions on the outer electron radiation belt, *Geophysical Research Letters*, **41**, pp 2258–2265, doi:10.1002/2014GL059551.
75. Georgiou, M., I. A. Daglis, E. Zesta, G. Balasis, I. R. Mann, C. Katsavrias, and K. Tsinganos, 2015, Association of radiation belt electron enhancements with earthward penetration of Pc5 ULF waves: A case study of intense 2001 magnetic storms, *Annales Geophysicae*, **33**, pp 1431–1442, doi:10.5194/angeo-33-1431-2015.
76. Georgiou, M., I. A. Daglis, I. J. Rae, E. Zesta, D. G. Sibeck, I. R. Mann, G. Balasis, and K. Tsinganos, 2018, Ultralow frequency waves as an intermediary for solar wind energy input into the radiation belts, *Journal of Geophysical Research*, **123**, pp 10,090–10,108, doi:10.1029/2018JA025355.
77. Boyd, A. J., D. L. Turner, G. D. Reeves, H. E. Spence, D. N. Baker, and J. B. Blake, 2018, What causes radiation belt enhancements: A survey of the Van Allen Probes Era, *Geophysical Research Letters*, **45**, pp 5253–5259, doi:10.1029/2018GL077699.
78. Li, W., Q. Ma, R. M. Thorne, J. Bortnik, X.âĂŘJ. Zhang, J. Li, D. N. Baker, G. D. Reeves, H. E. Spence, C. A. Kletzing, W. S. Kurth, G. B. Hospodarsky, J. B. Blake, J. F. Fennell, S. G. Kanekal, V. Angelopoulos, J. C. Green, and J. Goldstein, 2016, Radiation belt electron acceleration during the 17 March 2015 geomagnetic storm: Observations and simulations, *Journal of Geophysical Research*, **121**, pp 5520–5536, doi:10.1002/2016JA022400.
79. Ma, Q., W. Li, R. M. Thorne, Y. Nishimura, X.âĂŘJ. Zhang, G. D. Reeves, C. A. Kletzing, W. S. Kurth, G. B. Hospodarsky, M. G. Henderson, H. E. Spence, D. N. Baker, J. B. Blake,

J. F. Fennell, V. Angelopoulos, 2016, Simulation of energy–dependent electron diffusion processes in the Earth's outer radiation belt, *Journal of Geophysical Research*, **121**, pp 4217–4231, doi:10.1002/2016JA022507.

80. Katsavrias, C., I. A. Daglis, W. Li, S. Dimitrakoudis, M. Georgiou, D. L. Turner, and C. Papadimitriou, 2015a, Combined effects of concurrent Pc5 and chorus waves on relativistic electron dynamics, *Annales Geosphysicae*, **33**, pp 1173–1181, doi:10.5194/angeo-33-1173-2015.
81. Kanekal, S. G., D. N. Baker, M. G. Henderson, W. Li, J. F. Fennell, Y. Zheng, I. G. Richardson, A. Jones, A. F. Ali, S. R. Elkington, A. Jaynes, X. Li, J. B. Blake, G. D. Reeves, H. E. Spence, and C. A. Kletzing, 2015, Relativistic electron response to the combined magnetospheric impact of a coronal mass ejection overlapping with a high–speed stream: Van Allen Probes observations, *Journal of Geophysical Research*, **120**, pp 7629–7641, doi:10.1002/2015JA021395.
82. Schiller, Q., X. Li, L. Blum, W. Tu, D. L. Turner, and J. B. Blake, 2014, A nonstorm time enhancement of relativistic electrons in the outer radiation belt, *Geophysical Research Letters*, **41**, pp 7–12, doi:10.1002/2013GL058485.
83. Katsavrias, C., I. A. Daglis, D. L. Turner, I. Sandberg, C. Papadimitriou, M. Georgiou, and G. Balasis, 2015b, Nonstorm loss of relativistic electrons in the outer radiation belt, *Geophysical Research Letters*, **42**, pp 521–530, doi:10.1002/2015GL066773.
84. Li, X., Q. Schiller, L. Blum, S. Califf, H. Zhao, W. Tu, D. L. Turner, D. Gerhardt, S. Palo, S. Kanekal, D. N. Baker, J. Fennell, J. B. Blake, M. Looper, G. D. Reeves, and H. Spence, 2013b, First results from CSSWE CubeSat: Characteristics of relativistic electrons in the near-Earth environment during the October 2012 magnetic storms, *Journal of Geophysical Research*, **118**, pp 6489–6499, doi:10.1002/2013JA019342.
85. Spence, H. E., J. B. Blake, A. B. Crew, S. Driscoll, D. M. Klumpar, B. A. Larsen, J. Legere, S. Longworth, E. Mosleh, T. P. O'Brien, S. Smith, L. Springer, and M. Widholm, 2012, Focusing on size and energy dependence of electron microbursts from the Van Allen radiation belts, *Space Weather*, **10**, S11004, doi:10.1029/2012SW000869.
86. Klumpar, D., L. Springer, E. Mosleh, K. Mashburn, S. Berardinelli, A. Gunderson, M. Handley, N. Ryhajlo, H. Spence, S. Smith, J. Legere, M. Widholm, S. Longworth, A. Crew, B. Larsen, J. B. Blake, and N. Walmsley, 2015. Flight system technologies enabling the twin-CubeSat FIREBIRD-II scientific mission, in *Proceedings of the 29th Annual AIAA*, USU Conference on Small Satellites, at Logan Utan, doi:10.13140/RG.2.1.3368.4562.