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Kilpua, E.K.J.; Hietala, H.; Turner, D.L.; Koskinen, H.E.J.; Pulkkinen, Tuija I.; Rodriguez, J.V.; Reeves, G.D.; Claudepierre, S.G.; Spence, H.E. **Unraveling the drivers of the storm time radiation belt response**

Published in: Geophysical Research Letters

DOI: 10.1002/2015GL063542

Published: 01/01/2015

Document Version Publisher's PDF, also known as Version of record

Please cite the original version:

Kilpua, E. K. J., Hietala, H., Turner, D. L., Koskinen, H. E. J., Pulkkinen, T. I., Rodriguez, J. V., Reeves, G. D., Claudepierre, S. G., & Spence, H. E. (2015). Unraveling the drivers of the storm time radiation belt response. *Geophysical Research Letters*, *4*2(9), 3076-3084. https://doi.org/10.1002/2015GL063542

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Geophysical Research Letters

RESEARCH LETTER

10.1002/2015GL063542

Key Points:

- We superpose the different substructures of each solar wind storm driver
- During stream interface regions, CME ejecta and sheaths loss mechanisms dominate
- Enhancements occur during fast streams trailing the stream interface or the CME

Supporting Information:

- Figures S1 S3, Tables S1 S4, and Table S5 caption
- Table S5

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Citation:

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(2015), Unraveling the drivers of the storm time radiation belt response, *Geophys. Res. Lett.*, *42*, 3076–3084,
doi:10.1002/2015GL063542.

Received 18 FEB 2015 Accepted 25 MAR 2015 Accepted article online 29 MAR 2015 Published online 4 May 2015

Unraveling the drivers of the storm time radiation belt response

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Abstract We present a new framework to study the time evolution and dynamics of the outer Van Allen belt electron fluxes. The framework is entirely based on the large-scale solar wind storm drivers and their substructures. The Van Allen Probe observations, revealing the electron flux behavior throughout the outer belt, are combined with continuous, long-term (over 1.5 solar cycles) geosynchronous orbit data set from GOES and solar wind measurements A superposed epoch analysis, where we normalize the timescales for each substructure (sheath, ejecta, and interface region) allows us to avoid smearing effects and to distinguish the electron flux evolution during various driver structures. We show that the radiation belt response is not random: The electron flux variations are determined by the combined effect of the structured solar wind driver and prestorm electron flux levels. In particular, we find that loss mechanisms dominate during stream interface regions, coronal mass ejection (CME) ejecta, and sheaths while enhancements occur during fast streams trailing the stream interface or the CME.

1. Introduction

The outer Van Allen belt [e.g., Van Allen et al., 1958] is composed of high-energy (0.1 to several MeV) electrons encircling the Earth at altitudes from about 3 to 6 Earth radii (R_E). The belt is particularly dynamic during active periods known as geomagnetic storms [e.g., *Reeves et al.*, 2003] and poses a significant hazard to satellite technology operating in this region [*O'Brien*, 2009]. The electrons typically reach out to geostationary orbit (GEO; 5.6 R_E from the surface of the Earth), which is populated by several hundred communication, commercial, military, and scientific satellites, and is thereby also a significant source of long-term data of the space environment [*Onsager et al.*, 1996].

NASA's Van Allen Probes launched in August 2012 [*Mauk et al.*, 2012] have yielded significant new information on radiation belt dynamics especially by confirming the central role of local wave-particle processes in accelerating radiation belt electrons to ultrarelativistic energies [*Reeves et al.*, 2013; *Thorne et al.*, 2013]. However, even these results do not overcome the complexity of the competing acceleration, transport, and loss processes operating in time scales from a few seconds to several days [*Baker et al.*, 2013, 2014; *Turner et al.*, 2014], which makes a prediction of the electron fluxes challenging.

While under normal conditions, the solar wind is highly varying and appears almost random, drivers of geomagnetic storms arrive in characteristic sequences lasting from tens of hours to days. The most important drivers of geomagnetic storms are coronal mass ejections (CMEs) [e.g., *Gosling*, 1990] and the slow-fast stream interaction regions (SIRs) [e.g., *Gosling and Pizzo*, 1999]. The electron flux enhancements during SIR-driven storms [*Miyoshi and Kataoka*, 2005; *Borovsky and Denton*, 2006; *Bortnik et al.*, 2006; *Yuan and Zong*, 2012] have been linked to a combination of southward interplanetary magnetic field (IMF) and high-speed solar wind introducing electron acceleration via whistler waves [*Miyoshi et al.*, 2013]. However, the response of the electron fluxes to CMEs has been poorly understood, and the results connecting the radiation belt response to specific solar wind conditions have been controversial [e.g., *Paulikas and Blake*, 1979; *Onsager et al.*, 2007; *Li et al.*, 2011; *Reeves et al.*, 2011].

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Figure 1. The structure of large-scale solar wind storm drivers and Earth's typical paths through them (dashed arrows) that lead to characteristic sequences (S1–S4). See text for details.

Previous studies have not typically considered the substructures within CMEs and SIRs (Figure 1). The core of the CME is the driving ejecta, and if the ejecta is sufficiently fast with respect to the ambient solar wind, a shock wave and a turbulent sheath forms ahead of the ejecta. An SIR consists of a slower stream followed by an interface region and a faster stream. A stream interface (SI) is embedded within the interface region. As such substructures (sheaths, ejecta, interface regions, and fast streams) have distinct solar wind conditions as well as different magnetospheric and ionospheric responses [e.g., *Huttunen and Koskinen*, 2004; *Yermolaev et al.*, 2010], it can be expected that they also have distinct effects on the radiation belt electron dynamics [e.g., *Hietala et al.*, 2014]. Furthermore, previous studies have typically taken the storm peak (the *Dst* minimum) as the reference time and have used a very extended, 4–5 days intervals for calculating the prestorm and poststorm electron fluxes. Such approaches cannot distinguish the effects of the structured storm drivers, the interference of preceding/following solar wind structures, nor the effect of the preevent radiation belt population.

Here we present a new framework to study the radiation belt electron response, which is entirely based on solar wind storm driver sequences. We perform a superposed epoch analysis which uses multiple reference times (based on the driver substructures) and we normalize the timescales for each substructure [*Kilpua et al.*, 2013; *Hietala et al.*, 2014]. This approach allows us to determine the evolution of the electron fluxes during each substructure and consequently to determine the overall radiation belt response (depletion, no change, or enhancement) during the typical large-scale storm drivers. Furthermore, we calculate the flux levels at fixed times before and after the structure and take care to avoid the interference from preceding/following solar wind structures. The statistical part of this study uses the nearly continuous solar wind and electron flux observation at GEO from GOES, spanning more than 1.5 solar cycles (1995–2013), while the Van Allen Probe data provide us detailed information on the energy and the *L* shell dependent electron flux behavior in the context of our storm driver sequences.

2. Data Sets and Methods

We define geomagnetic storms in terms of the 1 h *Dst* index (< -50 nT). *Dst* measures low-latitude global variations in the horizontal component of the geomagnetic field and roughly represents the strength of the equatorial ring current. We examine only isolated storms. Hence, our study excludes interacting CMEs, i.e., events featuring multiple shocks and ejecta, and SIRs following each other in a relatively rapid sequence. From the initial set of 398 geomagnetic storms we excluded 71 events due to two storms being too close to each other (another storm *Dst* minimum within 48 h), 25 events due to unclear solar wind structure, 18 due to a data gap (in GOES or solar wind measurements), and three events due to a contamination of the GOES data by a Solar Proton Event (SPEs). The final set includes 193 isolated geomagnetic storms (Table S5 in the supporting information).

CMEs and SIRs were identified using the existing online catalogs and by inspection of the typical IMF and solar wind plasma signatures [e.g., Jian et al., 2006a, 2006b]. The crossing distance from the CME

center (i.e., central/near-central cut or edge encounter) was estimated from the profiles of the total pressure perpendicular to the magnetic field (P_t) [*Jian et al.*, 2006b].

Storm drivers are categorized into three CME- and one SIR-related sequences, illustrated schematically in Figure 1. Sequence 1 (S1) presents the cases where a shock and a sheath are observed, but only the edge of the CME is encountered (*Sheath only*). In S1 P_t increases rapidly at the shock and then decays gradually over hours or even days. S2 includes the cases where only a CME ejecta is identified (*Ejecta only*); i.e., the ejecta was too slow with to drive a shock. In S3 a shock and a sheath are detected, followed by an ejecta that is encountered close to the center (*Sheath* + *Ejecta*). S4 comprises SIRs (see section 1). S2 and S3 are further divided into events where the ejecta is trailed by a slow or a fast solar wind stream. For a fast stream we require that the solar wind speed exceeds 500 km/s at least 25% of the 48 h period after the ejecta.

We use primarily data from the ACE spacecraft but have complemented those with data from the Wind spacecraft. The data were obtained through the Coordinated Data Analysis Web (CDAWeb). The analysis uses 16 s magnetic field data from the MAG/ACE instrument and 64 s plasma data from Solar Wind Experiment (SWE)/ACE instrument, and 1 min magnetic field data from the Magnetic Fields Investigation/Wind and 90 s plasma data from SWE/Wind. We employed the geocentric solar magnetospheric (GSM) coordinate system. We time shifted the data from the Wind or ACE location using the average solar wind speed during the driver sequence. A wavelet analysis was performed on the IMF north-south component (B_Z) and dynamic pressure (P_{dyn}) to calculate the wave power in the ultralow frequency (ULF) range from 3 to 10 min. The 1 h *Dst* index and 5 min *AE* index (substorm activity) were obtained from the OMNI data set through CDAWeb. The magnetopause subsolar distance was calculated from the *Shue et al.* [1998] model, which depends on P_{dyn} and B_Z .

For the superposed epoch analysis we interpolated all data to a 5 min cadence. Naturally, the durations of sheath regions, ejecta, and interface regions vary from event to event. The mean durations of these substructures are given in Table S3. To avoid smearing effects, we have normalized the timescales for sheath, ejecta, and interface region for sequences S2–S4 to this mean duration [*Kilpua et al.*, 2013; *Hietala et al.*, 2014]. Note that for the interface regions we renormalized the data separately from the start of the interface region to the SI and from the SI to end of the interface region.

The radiation belt response at GEO was determined using > 2 MeV and 5 min averaged electron observations from the GOES Energetic Particle Sensor (EPS). A 24 h sliding window average was applied to the log10 of the electron fluxes to remove diurnal variations [e.g., *Reeves et al.*, 2003]. The radiation belt response was determined by calculating the ratio of 24 h averaged preevent and postevent fluxes (R_{RB}) [e.g., *Reeves et al.*, 2003; *Turner et al.*, 2013]. The radiation belt (RB) responses were then categorized based on the R_{RB} values to depletion ($R_{RB} < 0.5$), no change ($0.5 < R_{RB} < 2$), and enhancement ($R_{RB} > 2$).

The preevent fluxes were calculated 24 h before the shock for S1 and S3, 24 h before the ejecta leading edge for S2, and 24 h before the start of the interface region for S4. The postevent fluxes were calculated 48 h after the shocks for S1 and 48 h after the end of the interface region for S4. For S2 and S3, the time interval selection varied depending on the speed of the solar wind trailing the ejecta. If the ejecta was followed by a slow (fast) stream, the postevent flux was calculated 24 h (48 h) after the ejecta trailing edge.

3. Results

3.1. Statistical Analysis of the GOES Observations

Figure 2 shows the distribution of storm drivers for each type of radiation belt response based on the ratio of preevent and postevent GOES > 2 MeV electron fluxes. The detailed information used to compile Figure 2 is given in Table S4. All CME-related sequences (S1 – S3) have more depleting than enhancing events. Ejecta only (S2) are the most likely to deplete the belts (71%). In contrast, a clear majority (73%) of the *SIR* sequences (S4) enhance electron fluxes. When we further divide events in S2 and S3 according to the speed of the trailing solar wind, the association with the radiation belt response becomes even more distinct: 82% of S2, where the ejecta is followed by slow wind, cause a depletion, while depletion occurs only in 43% of the cases where a fast stream follows. For Sheath + Ejecta the corresponding percentages are 57% and 31%, respectively.

The superposed epoch analysis (Figure 3) reveals the characteristic time evolution of radiation belt electron fluxes at GEO, solar wind conditions during the driver substructures, and the related magnetospheric responses. The four panels show the results for each of the driver sequences, separated into enhancing and



S1: Sheath only S2: Ejecta only S3: Sheath+ejecta S4: SIR

Figure 2. (top) Distribution of storm drivers for each type of radiation belt response. (middle) Distribution of radiation belt responses for each storm driver category. (bottom) Same as Figure 2 (middle) for Ejecta only (S2) and Sheath + Ejecta (S3) but now separated between the ejecta followed by slow and fast streams.

depleting radiation belt responses (red and blue curves, respectively). It is seen that depleting events have clearly higher preevent fluxes than enhancing events. If the flux levels are already low, they cannot decrease much further, and if the storm driver increases the fluxes, the overall enhancement easily follows. In turn, if the starting level is high, the fluxes can considerably decrease. Even though the driver increases the fluxes, return close to the preevent level is more likely than an increase significantly above the starting level. Hence, the resulting overall radiation belt response depends both on the preevent electron flux population and the characteristics of the driver sequence.

To eliminate the effect of the prestorm flux level, we also calculate the median responses for the subset of enhancing and depleting events with similar preevent flux levels (pink and light blue curves, respectively, in Figure 3). Such subsets are obtained by calculating the medians for the events where the prestorm flux level was below the median for all enhancing events (of a given sequence) and above the median for all depleting events. Figures S1-S3 provided in the supporting information show the black, red/blue, and pink/light blue curves of Figure 3 separately. In addition, Figure 4 shows the medians and the upper and lower quartiles of the postevent flux levels for different driver sequences.



Figure 3. (top left) Panels show (A) GOES > 2 MeV electron flux at GEO, (B) solar wind speed, (C) IMF north-south component in GSM, (D) solar wind P_{dyn} , ULF wave power (3–10 min) in (E) B_Z and (F) P_{dyn} , (G) subsolar magnetopause position, (H) Dst, and (I) AE. For sequences S2-S4 we have rescaled the data during the (top right) ejecta, (bottom left) sheath, and (bottom right) interface region (from start to SI and from SI to end) to the same duration. The black curves show the medians of all events. The medians for the subsets that enhanced (number of events S1: 9, S2: 6, S3: 17, S4: 62), and depleted (S1: 13, S2: 20, S3: 25, S4: 11) electron fluxes are denoted by red and blue curves, respectively. The pink (S1: 4, S2: 4, S3: 9, S4: 29) and light blue (S1: 7, S2: 9, S3: 13, S4: 6) dashed curves show the subsets of enhancing and depleting events starting from more similar preevent flux levels (see also Figures S1-S3 in the supporting information). The data shown here are smoothed by applying a least squares polynomial smoothing filter.



Post-event fluxes for different solar wind drivers

Figure 4. Postevent radiation belt electron fluxes for different storm driver sequences (see section 2 for definitions). The gray triangles give the lower quartiles, black circles the medians, and the gray squares the upper quartiles. The dashed horizontal line shows the median, and the orange-shaded area shows the range from the lower to upper quartile of the preevent flux level for all sequences.

3.1.1. Electron Flux Response to Solar Wind Substructures

The sheaths (part of S1 and S3) and interface regions (in S4) generally decrease electron fluxes (Figure 3). This decrease is associated with the strong inward motion of the magnetopause and high solar wind ULF fluctuation power. The sheaths that pertain to the overall enhancing sequences (red and pink curves) have considerably higher *AE* activity than the sheaths that pertain to depleting sequences (blue and light blue curves). However, the fluxes generally decrease after the shock also during the sheaths that later on result in enhanced fluxes.

For depleting SIRs the fluxes decrease throughout the interface region, while for enhancing SIRs the fluxes start to increase during the trailing part of the interface region (from SI to end). It is seen from Figure 3 that the trailing part of the interface region for enhancing SIRs is faster and has higher *AE* than for depleting SIRs. Note also that the sheaths and interface regions cause true losses of electrons from the system: The fluxes decrease even when there is no enhancement of the ring current (compare the light blue curves for *Dst* and electron fluxes during the sheaths in S3 or the first part of the interface region in S4).

During the ejecta (part of S2 and S3) the electron fluxes primarily decrease. The ejecta are associated with prolonged southward B_Z , relatively low P_{dyn} and low solar wind ULF power. The ejecta that pertain to enhancing sequences are clearly faster and have stronger southward B_Z and higher AE and Dst activity than the ejecta that pertain to depleting sequences, in particular in S3. For enhancing Ejecta only (S2) the fluxes stay relatively unchanged during the ejecta, while for enhancing Sheath + Ejecta (S3) the fluxes start to increase considerably already during the ejecta.

Fast streams, which are an integral part of SIRs, but may occur also trailing CMEs, increase the electron fluxes. Fast streams are associated with low solar wind ULF power and prolonged and moderate level *AE* activity. Due to generally low P_{dyn} and fluctuating and weak IMF the magnetopause remains at its nominal location and does not contribute to electron losses.

3.1.2. Response to Characteristic Driver Sequences

We can now merge the electron responses during these substructures to combine the characteristic radiation belt response during the identified driver sequences. Sheaths only (S1) effectively deplete the electrons. If modest increases occur, they are caused by high-speed wind with southward IMF. The tendency of Ejecta only (S2) and Sheath + Ejecta (S3) to deplete radiation belts is associated with the depleting effect of the sheath and ejecta substructures. This is illustrated also in Figure 4, which shows that the postevent flux levels were the lowest (median and lower quartile) for those S3 events where the ejecta was trailed by the slow stream. Flux enhancements in S2 and S3 occur mainly later, in cases where the ejecta is followed by a fast stream (more common for S3 than for S2). Figure 4 shows that the postevent flux levels are clearly higher for S3 and S2 when the ejecta is trailed by the fast stream; the levels are, in fact, similar to the SIR sequences.

In SIRs (S4), the fluxes decrease during the first part of the interface region. There is a modest increase during the latter part of the interface region for enhancing SIRs, but the primary flux increase occurs during the fast stream. Note that for SIR the postevent fluxes have the highest levels of all investigate sequences (Figure 4).

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Figure 5. Electron fluxes from Van Allen Probes RBSP-ECT/Mag-ElS instrument as a function of energy and *L* shell (*L* is the radial distance in R_E from the center of the Earth to the equatorial crossing points of dipole field lines). The plots merge data from both Van Allen Probes binned in time (t = 5.5 h) and *L* shell (L = 0.1) for 7 days around the storm peak. (left) SIR-driven storm, (middle) Ejecta only-driven storm, and (right) Sheath + Ejecta-driven storm (fast stream follows). The magenta dash-dotted lines indicate the start and end times of the interface region and the SI time for the SIR storm (Event 1) and the start and end times of the ejecta for Ejecta only (Event 2) and Sheath + Ejecta-driven (Event 3) storms.

For depleting SIRs, both the interface region and the following stream are considerably slower and the AE activity weaker than for enhancing SIRs.

3.2. Van Allen Probe Analysis

While the electron flux data at GEO are immensely valuable due to the long time series allowing extensive statistical studies, the orbit is at the outer fringes of the outer Van Allen belt, and thus, these observations at a single energy and radial distance may not necessary reflect the behavior of the rest of the outer belt electrons at different *L* shells or energies [e.g., *Yuan and Zong*, 2012]. We examined the Van Allen Probes observations for the 14 events for which both GOES and Van Allen Probe data are available (October 2012 to December 2013). For all these events, we confirmed that measurements of > 2 MeV electrons at GEO from GOES were consistent with > 1.5 MeV electron flux measurements from the Van Allen Probes at L = 6 (nearest to the apogee).

Figure 5 presents Van Allen Probe measurements for three events representing (1) SIR-driven storms (S4), (2) Ejecta only-driven storms (S2), and (3) Sheath + Ejecta-driven storms (S3) followed by fast solar wind. These three events highlight the complexity of the responses: The *energy dependence* of the response is evident in Events 1 and 2: The low-energy electron fluxes during Event 1 increased shortly after the interface region arrival at all *L* shells, with the delay in the flux enhancement growing with increasing energy. During Event 2, fluxes of MeV electrons decreased throughout the belt, while the lower energy electron fluxes enhanced only at the heart of the belt (~ 3 < L <~ 6). The *location dependence* is demonstrated during Event 3: The sheath and ejecta efficiently wiped out the MeV electrons at high *L* shells. While the flux depletion at high *L* shells lasted throughout the postevent period, the fluxes were enhanced at lower *L* shells during the end part of the ejecta.

4. Discussion

The depleting effect of the sheath regions found in this study is consistent with a smaller statistical study of 31 sheath regions by *Hietala et al.* [2014]. The decrease is associated with the "magnetopause shadowing," i.e., the paths of the particles that were previously on the closed drift shells cross the magnetopause and they are lost. The magnetopause shadowing in sheath regions is the combination of a strongly compressed magnetosphere due to high *P*_{dyn} and high ULF activity, which scatters electrons to larger distances and increases the loss rates [*Turner et al.*, 2012]. The decreasing geomagnetic field in the storm main phase ("*Dst* effect," *Kim and Chan* [1997]) adds to the effect by expanding the electron drift shells outward in the magnetosphere. The generally depleting effect of the ejecta is also primarily due to the magnetopause shadowing: During prolonged southward IMF, the drift shells expand (the *Dst* effect) and magnetic reconnection erodes the magnetopause (stand-off distance decreases; Figure 3, top right, (G)). Electrons can quickly escape when

there is a magnetic connection through the magnetopause [Kim and Lee, 2014], e.g., along the reconnected field lines.

Substorms are known to inject lower energy seed particles to GEO and accelerate them locally due to induced electric fields and via whistler waves [e.g., *Thorne et al.*, 2013; *Gabrielse et al.*, 2014; *Boyd et al.*, 2014]. We found that the electron fluxes decreased even in those sheaths that were related to intense substorm activity (high *AE*), implying the strong dominance of the above described loss mechanisms. We found that during the enhancing Sheath + Ejecta events, the electron fluxes tend to increase already during the ejecta substructure. In such cases both the sheath and the ejecta cause high substorm activity. This implies prolonged transport of seed electrons via enhanced convection and/or substorm injections and their acceleration. The Sheath + Ejecta associated Van Allen Probe Event 3 (Figure 5 and section 3.2) also highlights the importance of transporting the lower energy seed population into the inner magnetosphere. It should be noted that the ejecta that are pushed from behind by a fast stream are generally faster than the ejecta trailed by the slow wind. This adds to their tendency to increase the fluxes.

The fast streams lack properties associated with electron depletion, such as compressed magnetopause due to high P_{dyn} and prolonged southward B_Z while, as discussed above, the prolonged substorm activity efficiently injects and accelerates electrons. Note also that the energy-dependent local acceleration of lower energy seed population during the trailing part of the interface region was showcased by the Van Allen Probe data (Figure 5, Event 1, and section 3.2). Our results pertaining to SIRs are consistent with earlier studies [*Miyoshi et al.*, 2013], but we distinguish with higher detail the electron flux evolution within the SIR sequence, in particular the depleting effect of the leading part of the interface region.

5. Conclusions

Our analysis demonstrates that the storm time response of the outer Van Allen belt electrons is not random but depends on the properties of the solar wind driver and on the preevent level of relativistic electrons in the belt itself. By constructing our analysis carefully on the solar wind drivers, we have been able to distinguish these independent effects on the relativistic electron fluxes at the geostationary orbit. We find that the electrons are depleted during stream interface regions, CME ejecta, and sheath regions, probably due to effective magnetopause shadowing, while increases occur primarily during fast streams trailing the interface region or the CME. During CMEs the fluxes increase mainly in cases where both the sheath and the ejecta substructures have a high speed and cause prolonged electron injection. Three case studies of detailed Van Allen Probe measurements revealed the complexity of the energy and location-dependent response of the electron fluxes. Continued Van Allen Probe observations are expected to provide further details on the internal magnetospheric acceleration, transport, and loss processes occurring within the outer belt during storms, all of which can now be put into better context using the storm driver sequences presented here.

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Acknowledgments

The GOES data were processed by NOAA Space Weather Prediction Center and archived and made available to the public by NOAA National Geophysical Data Center. This work was supported by RBSP-ECT funding provided by JHU/APL contract 967399 under NASA's prime contract NAS5-01072, Work at JHU/APL was supported by NASA grant NNX10AK93G. D.L.T. is thankful for funding from NASA's THEMIS mission (contract NAS5-02099) and the Van Allen Probes RBSP-ECT (provided by JHU/APL contract 967399). The work of E.K. is funded by Academy of Finland projects 1218152 and 1267087. The work of H.H. is funded by the UK Science and Technology Facilities Council (STFC) grant ST/K001051/1. The Väisälä foundation and the Alfred Kordelin foundation are also thanked for financial support. To identify interplanetary CMEs and SIRs, we have used the UCLA and Richardson and Cane lists found at http://www.srl.caltech.edu/ACE/ASC/ DATA/level3/icmetable2.htm, and http://www-ssc.igpp.ucla.edu/forms/ stereo/stereo_level_3.html, respectively.

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