

1 **Phase Space Density Analysis of Outer Radiation Belt**
2 **Electron Energization and Loss during Geoeffective and**
3 **Nongeoeffective Sheath Regions**

4 **Milla M. H. Kalliokoski¹, Emilia K. J. Kilpua¹, Adnane Osmane¹, Allison N.**
5 **Jaynes², Drew L. Turner³, Harriet George¹, Lucile Turc¹, Minna Palmroth^{1,4}**

6 ¹Department of Physics, University of Helsinki, Helsinki, Finland

7 ²Department of Physics and Astronomy, University of Iowa, Iowa City, Iowa, USA

8 ³Johns Hopkins University Applied Physics Laboratory, Laurel, Maryland, USA

9 ⁴Space and Earth Observation Centre, Finnish Meteorological Institute, Helsinki, Finland

10 **Key Points:**

- 11 • Opposite outer belt response to geoeffective and nongeoeffective sheaths, and phys-
12 ical mechanisms leading to these responses are revealed
- 13 • Understanding the immediate response of electron fluxes to different solar wind
14 drivers is crucial for forecasting overall belt dynamics
- 15 • The phase space density analysis was conducted for electrons at relativistic and
16 ultrarelativistic energies

Corresponding author: M. M. H. Kalliokoski, milla.kalliokoski@helsinki.fi

17 **Abstract**

18 Coronal mass ejection driven sheath regions are one of the key drivers of drastic
 19 outer radiation belt responses. The response can however be significantly different based
 20 on the sheath properties and associated inner magnetospheric wave activity. We performed
 21 here two case studies on the effects of sheaths on outer belt electrons of various energies
 22 using data from the Van Allen Probes. One sheath caused a major geomagnetic distur-
 23 bance and the other one had only a minor impact. We especially investigated phase space
 24 density of high-energy electrons to determine the dominant energization and loss pro-
 25 cesses taking place during the events. Both sheaths produced substantial variation in the
 26 electron fluxes from tens of kiloelectronvolts up to ultrarelativistic energies. The responses
 27 were however almost the opposite: the geoeffective sheath led to enhancement, while the
 28 nongeoeffective one caused a depletion throughout most of the outer belt. The case stud-
 29 ies highlight that both inward and outward radial transport driven by ultra-low frequency
 30 waves, combined with compression of the magnetopause, played an important role in gov-
 31 erning electron dynamics during these sheaths. Chorus waves also likely caused a local
 32 peak in phase space density, leading to the energization of the ultrarelativistic popula-
 33 tion during the geoeffective event. The occurrence of chorus waves was based on mea-
 34 surements of precipitating and trapped fluxes by low-altitude Polar Operational Envi-
 35 ronmental Satellites. The distinct responses and different mechanisms in action during
 36 these events are related to differing levels of substorm activity and timing of the peaked
 37 solar wind dynamic pressure in the sheaths.

38 **1 Introduction**

39 The outer Van Allen radiation belt in the Earth’s inner magnetosphere hosts elec-
 40 trons over a wide range of energies. These electrons experience significant variations over
 41 both short and long timescales driven by various acceleration, transport and loss pro-
 42 cesses. Adiabatic processes can lead to reversible changes in fluxes (the *Dst* effect, see,
 43 e.g., Kim & Chan, 1997) when electrons move radially inward or outward conserving all
 44 three adiabatic invariants. Irreversible changes occur when the conservation of one or
 45 more adiabatic invariants is violated. Different waves in the inner magnetosphere play
 46 a key role in such electron dynamics (see Thorne, 2010). For example, electromagnetic
 47 ion cyclotron (EMIC) waves scatter relativistic electrons into the loss cone leading to pre-
 48 cipitation loss into the upper atmosphere (e.g., Summers & Thorne, 2003; Kurita et al.,
 49 2018). Whistler mode chorus waves can also cause precipitation loss but are rather the
 50 dominant cause of local acceleration in the heart of the outer radiation belt (e.g., Bort-
 51 nik & Thorne, 2007; Thorne et al., 2013; Jaynes et al., 2015). Ultra-Low Frequency (ULF)
 52 wave driven radial transport can act to energize outer belt electrons (e.g., Su et al., 2015)
 53 or contribute to losses at the magnetopause (e.g., Shprits et al., 2006; Turner, Shprits,
 54 et al., 2012). Understanding which mechanisms govern the outer belt electron dynam-
 55 ics and response under observed solar wind conditions is important for maintaining safe
 56 operation of spacecraft travelling through or residing in the belt. This is especially paramount
 57 for the increasingly common nanosatellites whose small size limits the amount of shield-
 58 ing making them more vulnerable to anomalies induced by intense electron fluxes.

59 The key drivers of magnetospheric disturbances are interplanetary coronal mass
 60 ejections (ICMEs), slow-fast stream interaction regions (SIRs) and the following fast wind
 61 (e.g., Kilpua, Balogh, et al., 2017). Since these large-scale structures generally have dif-
 62 ferent solar wind conditions, the response of the outer radiation belt electron popula-
 63 tions to them varies (e.g., Kataoka & Miyoshi, 2006; Kilpua et al., 2015; Turner et al.,
 64 2019). A typical ICME is composed of a leading shock, a sheath region and the ejecta.
 65 Similarly, these regions have distinct magnetospheric impact (Kilpua, Koskinen, & Pulkki-
 66 nen, 2017). Statistical studies of solar wind properties and geomagnetic activity during
 67 ICME sheaths indicate that sheaths are associated with elevated interplanetary magnetic

68 field magnitude, solar wind speed, density and dynamic pressure and that their geof-
 69fectiveness depends on the ejecta properties (Yermolaev et al., 2015, 2017, 2018; Lugaz
 70et al., 2016; Masías-Meza et al., 2016; Kilpua et al., 2019; Kalliokoski et al., 2020). Sheaths
 71contain a high level of turbulent fluctuations in the magnetic field (e.g., Moissard et al.,
 722019). As detailed in previous studies (Kilpua et al., 2013, 2015; Hietala et al., 2014; Kalliokoski
 73et al., 2020), sheaths tend to cause intense wave activity in the inner magnetosphere, in
 74particular EMIC and ULF Pc5 waves, as well as strong compression of the magnetosphere.
 75The response of electron populations in the outer radiation belt can also be different dur-
 76ing sheaths and ejecta. In particular, the turbulent and compressed sheaths can cause
 77deep and sustained depletion of MeV electrons (Hietala et al., 2014; Kilpua et al., 2015;
 78Alves et al., 2016; Da Silva et al., 2020; Kalliokoski et al., 2020), but can also lead to their
 79enhancement (Turner et al., 2019). Turner et al. (2019) also found that sheaths tend to
 80cause a two-part outer belt structure at MeV energies.

81 Many studies of the outer radiation belt response consider events generating mod-
 82erate or stronger geomagnetic storms (e.g., evaluated with *Dst* or *SYM-H* index drop-
 83ping below -50 nT; Gonzalez et al., 1994) and assess the changes in electron flux over
 84long time periods, up to a few days, and can even exclude the day of the storm in their
 85quantitative analysis (e.g., O’Brien et al., 2001; Reeves et al., 2003; Turner et al., 2015;
 86Moya et al., 2017). Investigations of the response to sheaths have generally used a sim-
 87ilar approach (Kilpua et al., 2015; Turner et al., 2019). It has however been shown that
 88significant variation in the outer belt electron fluxes can occur also during small storms
 89and nonstorm periods (e.g., Schiller et al., 2014; Anderson et al., 2015; Katsavrias et al.,
 902015). The statistical analysis in Kalliokoski et al. (2020) detailed the immediate (6 h)
 91response of the outer belt electrons to both geoeffective and nongeoeffective sheaths from
 92source to ultrarelativistic energies (10s keV – several MeV). Regardless of whether they
 93cause a geomagnetic storm or not, sheaths predominantly deplete the outer parts ($L >$
 944) of the outer belt. Geoeffective sheaths often cause depletion also at lower L -shells at
 95MeV energies. Source and seed populations (10s – 100s keV) are similarly enhanced at
 96 $L > 4$ during sheaths, while the geoeffective sheaths also enhance the fluxes at $L <$
 974. The study also revealed a clear energy dependence of the depletion. While losses mainly
 98occur at MeV energies, the likelihood of depletion of the seed population (100s keV) in-
 99creases with radial distance. This was concluded to be likely due to wave-particle inter-
 100actions dominating the losses in the inner part of the belt, in particular by EMIC waves
 101that can cause rapid loss at MeV energies (e.g., Summers & Thorne, 2003; Kurita et al.,
 1022018), and due to intense substorms effectively replenishing the source and seed popu-
 103lations. Losses at high L -shells were suggested to be dominated by magnetopause shad-
 104dowing arising from the combination of the magnetopause inward incursion and ULF Pc5
 105wave driven outward radial transport (e.g., Turner, Shprits, et al., 2012). The determi-
 106nation of the exact physical mechanisms causing the depletion and enhancement dur-
 107ing sheaths however needs a more detailed analysis.

108 Phase space density (PSD), which is obtained by converting electron fluxes from
 109a function of energy and pitch angle into adiabatic invariant coordinates (see, e.g., Green
 110& Kivelson, 2004), provides a useful tool for such analysis. Since PSD remains constant
 111for adiabatic processes, the evolution of the shape of PSD radial profiles can be used to
 112infer the electron acceleration and loss mechanisms in the radiation belts (e.g., Green,
 1132006; Chen, Reeves, & Friedel, 2007; Turner, Shprits, et al., 2012; Shprits et al., 2017).
 114That is, PSD allows for distinguishing between adiabatic and nonadiabatic effects, as well
 115as between local acceleration and local losses from those caused by radial transport and
 116magnetopause shadowing. A drawback of the method is that calculating the adiabatic
 117invariants requires the use of a global geomagnetic field model. Deviations in the model
 118from the real conditions, especially during storms when the magnetosphere becomes com-
 119plex, lead to uncertainties in PSD (Chen, Friedel, et al., 2007; Morley et al., 2013; Boyd
 120et al., 2014). Uncertainties are also introduced by errors in the instrument measurements
 121and possible interpolations and fits that need to be done to acquire adequate resolution

122 in PSD (Turner, Angelopoulos, et al., 2012). Nevertheless, careful PSD analysis is ad-
 123 vantageous in investigating nonadiabatic outer belt electron dynamics on short timescales,
 124 for example, during the sheath and ejecta of an ICME (Da Silva et al., 2020).

125 Da Silva et al. (2020) studied an ICME sheath region that produced a small ge-
 126 omagnetic storm and a dropout in relativistic electron fluxes. Examining wave measure-
 127 ments and modeling results, they found that the dropout was likely caused by magne-
 128 topause shadowing along with ULF wave driven outward radial diffusion and local loss
 129 via pitch angle scattering by chorus and EMIC waves, which was confirmed by the PSD
 130 analysis. They concluded that wave-particle interactions were efficient only during the
 131 sheath, and thus different ICME sub-structures generate a different outer belt response.
 132 It is therefore interesting to compare whether similar processes dominate the electron
 133 response during other sheaths.

134 In this paper, we analyze the outer radiation belt electron response to two distinct
 135 ICME sheaths. One sheath was geoeffective causing a notable magnetospheric distur-
 136 bance (min. *SYM-H* of -90 nT), while the other was nongeoeffective, i.e., it did not cause
 137 a significant geomagnetic storm (min. *SYM-H* of -32 nT). This selection of events al-
 138 lows us to compare how the outer belt electron populations are shaped by a geoeffective
 139 and a nongeoeffective sheath, both of which can be important for radiation belt electron
 140 dynamics but which have significant differences in their responses, as indicated by Kalliokoski
 141 et al. (2020). Similar to earlier studies (e.g., Hietala et al., 2014; Kilpua et al., 2015, 2019;
 142 Kalliokoski et al., 2020), this work highlights that significant variations occur in the outer
 143 belt electron fluxes during ICME-driven sheath regions. We further show that such dras-
 144 tic changes can also arise at ultrarelativistic energies, and even during a nongeoeffective
 145 sheath. Such relatively short time-scale variations (\sim half-a-day) are missed by studies
 146 considering the electron response over the whole geomagnetic storm period that often
 147 lasts over several days. In contrast to the prior sheath studies, we perform here a detailed
 148 analysis of electron phase space density, which combined with consideration of the in-
 149 ner magnetospheric wave activity, sheds light on the dominant mechanisms that act on
 150 the outer belt electrons. We focus on the nonadiabatic dynamics driven specifically by
 151 the sheath region impact, and our aim is to compare and contrast how the outer radi-
 152 ation belt responds to sheaths with different properties. The various data and method-
 153 ology used in this study are presented in Section 2. In Section 3, we describe the obser-
 154 vations of the properties of the two sheaths, as well as the activity of waves and the outer
 155 belt conditions in terms of both electron flux and PSD during the sheath events. We dis-
 156 cuss the results and especially the interpretation of the PSD radial profiles in Section 4
 157 and conclude in Section 5.

158 2 Data and Methods

159 2.1 Solar Wind Data

160 We consider two interplanetary coronal mass ejections (ICMEs) with sheath regions,
 161 one on 2 October 2013 and the other on 15 February 2014. The timing of the sheath re-
 162 gions were based on the shock times from the University of Helsinki Heliospheric Shock
 163 Database (<http://www.ipshocks.fi>, last access: 4 June 2021) and visual inspection
 164 of the solar wind data to determine the ejecta interval. The characteristics of sheath re-
 165 gions and ejecta and the determination of their boundaries are discussed, for example,
 166 in Richardson and Cane (2010) and Kilpua, Koskinen, and Pulkkinen (2017). Both events
 167 are listed as magnetic clouds in the Richardson and Cane ICME list ([http://www.srl
 168 .caltech.edu/ACE/ASC/DATA/level3/icmetable2.htm](http://www.srl.caltech.edu/ACE/ASC/DATA/level3/icmetable2.htm), last access: 4 June 2021), i.e.,
 169 the ejecta have signatures of a magnetic flux rope.

170 We used solar wind data measured by the Wind spacecraft (Lepping et al., 1995;
 171 Ogilvie et al., 1995), and geomagnetic activity indices (*AL* and *SYM-H*) were taken from

172 the OMNI database. Both Wind and OMNI data had 1 min resolution. Wind and OMNI
 173 data were obtained via the NASA Goddard Space Flight Center (NASA–GSFC) Coor-
 174 dinated Data Analysis Web (CDAWeb, <https://cdaweb.gsfc.nasa.gov/index.html/>,
 175 last access: 4 June 2021). The Wind data were propagated to the bow shock nose. We
 176 used the Wind data instead of solar wind properties from OMNI database since the lat-
 177 ter had data gaps during the periods of interest.

178 The solar wind data is also used to calculate the subsolar magnetopause location
 179 with the Shue et al. (1998) model.

180 2.2 Wave Activity and Chorus Proxy

181 Ultra-low frequency (ULF) waves in the Pc5 and electromagnetic ion cyclotron (EMIC)
 182 ranges were obtained from a Geostationary Operational Environmental Satellite (GOES-
 183 15) at $L \sim 6.6$. The magnetic field data has a time resolution of 0.512 s (Singer et al.,
 184 1996). We derived the ULF power spectrum via wavelet analysis of the magnetic field
 185 magnitude measured by GOES-15, and calculated the mean over the frequency range
 186 2–7 mHz for Pc5 pulsations and 0.1–1 Hz for EMIC waves (Jacobs et al., 1964), where
 187 the upper bound for EMIC waves is restricted by the GOES time resolution. We note
 188 that ULF wave activity at the Van Allen Probes location might not always be represented
 189 by the ULF observations at geostationary orbit (Engebretson et al., 2018; Georgiou et
 190 al., 2018).

191 Data of very low frequency (VLF) wave activity, namely whistler mode chorus and
 192 plasmaspheric hiss, were obtained from the Electric and Magnetic Field Instrument Suite
 193 and Integrated Science (EMFISIS; Kletzing et al., 2013) on the Van Allen Probes. Specif-
 194 ically, we used the level-2 waveform receiver diagonal spectral matrix data that has a fre-
 195 quency range from 2 Hz to 12 kHz and 6 s time cadence available on the EMFISIS web-
 196 page (<https://emfisis.physics.uiowa.edu/data/index>, last access: 4 June 2021).
 197 Lower band chorus has the frequency range 0.1–0.5 f_{ce} and upper band chorus has 0.5–
 198 0.8 f_{ce} (Burtis & Helliwell, 1969; Koons & Roeder, 1990), where f_{ce} is the electron cy-
 199 clotron frequency, which was here obtained from the Tsyganenko and Sitnov (2005) ge-
 200 omagnetic field model. Chorus waves occur outside the dense plasmasphere, whereas plas-
 201 maspheric hiss occurs inside the plasmasphere at frequencies from 100 Hz to 0.1 f_{ce} . To
 202 discriminate chorus from plasmaspheric hiss, we estimated the plasmopause location based
 203 on the electron density derived from the upper hybrid resonance frequency (Kurth et al.,
 204 2015). The density is provided as a level-4 data product by the EMFISIS team.

205 Van Allen Probes measure the local chorus wave activity and can therefore miss
 206 the global chorus distribution. This is especially the case when the perigee of the space-
 207 craft is in the dawn sector because chorus predominantly occurs at $L > 4$ on the dawn-
 208 side (e.g., Lam et al., 2010). In both considered events, little local chorus activity was
 209 observed by Van Allen Probes. The perigee of both spacecraft was at dawn for the 2 Oc-
 210 tober 2013 event and at midnight for the 15 February 2014 event, indicating that their
 211 observations might not reflect the global chorus activity. Thus, we used low-energy elec-
 212 tron precipitation data as a proxy for chorus activity (Chen et al., 2014).

213 Electron precipitation data is provided by the low-altitude and polar-orbiting Po-
 214 lar Operational Environmental Satellites (POES). We used data from the Medium En-
 215 ergy Proton and Electron Detector (MEPED) instrument of the Space Environment Mon-
 216 itor (SEM-2; Evans & Greer, 2004) suite on board six such polar-orbiting spacecraft (NOAA-
 217 15, NOAA-16, NOAA-18, NOAA-19, MetOp-A and MetOp-B). MEPED measures elec-
 218 trons with two detectors, namely the 0° and 90° telescopes. The former points radially
 219 away from the Earth, primarily along the local magnetic field and loss cone, while the
 220 latter is antiparallel to satellite velocity, i.e. perpendicular to the 0° telescope viewing
 221 direction, and primarily measures trapped fluxes. The electron channels measure at en-
 222 ergies > 30 keV, > 100 keV and > 300 keV. The MEPED data used here has been re-

223 processed (Asikainen & Mursula, 2013; Asikainen, 2017) to correct for proton contam-
 224 ination and other instrumental problems that affect the POES measurements (see, e.g.,
 225 Rodger et al., 2013).

226 At high latitudes, the MEPED 0° telescope underestimates precipitating fluxes as
 227 the bounce loss cone is significantly larger than the 30° field of view of the detector (Rodger
 228 et al., 2013). On the other hand, the 90° telescope measures some fluxes in the loss cone
 229 at high latitudes in addition to the trapped flux (Rodger et al., 2010). Therefore, to bet-
 230 ter estimate the precipitating fluxes at high latitudes, which were considered in this study,
 231 we combined the data from the two detectors and considered the geometric mean of the
 232 fluxes (e.g., Hargreaves et al., 2010; Rodger et al., 2013; George et al., 2020):

$$j_{precip} = \sqrt{j_0 * j_{90}}, \quad (1)$$

233 where j_0 and j_{90} are the fluxes from the 0° and 90° telescopes, respectively. We note that
 234 by including the 90° telescope measurements we overestimate precipitating flux when
 235 trapped fluxes are high, and we might also underestimate precipitation when precipitat-
 236 ing fluxes are high during low levels of trapped flux. Nevertheless, in this study where
 237 we are considering precipitation qualitatively, we expect this method to provide a bet-
 238 ter estimate of the precipitating fluxes than the 0° telescope measurements alone.

239 We used the chorus proxy derived by Chen et al. (2014) which gives the chorus wave
 240 power as

$$B_w^2(L) = \frac{j_{precip}(L)}{P * [(L - 3)^2 + 0.03]}, \quad (2)$$

241 where P is a scaling factor. The proxy is restricted to $L > 3.5$. The Van Allen Probes
 242 detected almost no chorus waves, so we did not scale the proxy with spacecraft chorus
 243 observations and set $P = 1$ which suffices for our qualitative analysis of the chorus ac-
 244 tivity.

245 Following Chen et al. (2014) we calculated the chorus proxy for low-energy, 30–100 keV
 246 electrons. That is, we subtracted the POES > 100 keV electron channel measurements
 247 from the > 30 keV measurements for each detector and combined the data using Eq. 1.
 248 The data was then binned 0.1 in L -shell and 100 min in time, which corresponds to the
 249 orbital period of POES spacecraft. The high resolution data from multiple spacecraft
 250 on polar orbits allows us to inspect the chorus proxy up to high L -shells, and here we
 251 show the proxy up to $L = 10$.

252 2.3 Electron Flux Data and Outer Belt Response Parameter

253 Outer radiation belt electron fluxes were obtained from the Energetic Particle, Com-
 254 position, and Thermal Plasma instrument suite (ECT; Spence et al., 2013) on board the
 255 twin Van Allen Probes, which provide a wide coverage in electron energy at radial dis-
 256 tances up to $L = 6$ (Mauk et al., 2013). The Magnetic Electron Ion Spectrometer (MagEIS;
 257 Blake et al., 2013) observes the source, seed and core electron populations from 30 keV
 258 to 1.5 MeV, while the Relativistic Electron Proton Telescope (REPT; Baker, Kanekal,
 259 Hoxie, Batiste, et al., 2013) measures the core and ultrarelativistic populations from 1.8
 260 to 10 MeV. The employed MagEIS fluxes were background corrected when available (Claude-
 261 pierre et al., 2015). The L -shell of the spacecraft, derived from the Tsyganenko and Sitnov (2005)
 262 geomagnetic field model, was acquired from the magnetic ephemeris data available on
 263 the ECT website (<https://rbsp-ect.lanl.gov/>, last access: 4 June 2021).

264 We determined the outer radiation belt response to the sheath region, following Kalliokoski
 265 et al. (2020), by calculating the response parameter (R) as the ratio of the post-sheath
 266 flux average to the pre-sheath flux average. The flux average was taken over 6 h. The
 267 response parameter was computed for 0.1 sized L -shell bins in $L = 2-6$ using the level-
 268 2 spin-averaged differential electron flux data from both Van Allen Probes. We calcu-
 269 lated the response parameter for four energy channels representing the source (54 keV),

seed (346 keV), core (1064 keV) and ultrarelativistic (4.2 MeV) populations. The response is categorized as *depletion* when the flux average decreased by over a factor of 2 ($R < 0.5$), *enhancement* when the flux average increased by over a factor of 2 ($R > 2$) and *no change* when the flux average remained on a similar level ($0.5 \leq R \leq 2$). Note that in the visualization of the electron fluxes we have chosen 4 h time bins (instead of 6 h) for a clearer and more detailed view of the temporal evolution.

The method of computing the response parameter is adapted from Reeves et al. (2003) and Turner et al. (2015, 2019), who applied it to study the outer belt response to entire geomagnetic storms and considered periods ranging from 12 h up to a few days. In contrast, we focus here on the immediate response of the electron fluxes due to the sheath region, which we aim to capture with the 6 h averaging period. The post-sheath flux average is embedded in the ejecta, but we expect the main response due to the ejecta to occur at later times. We do note that the ejecta in both studied events were shorter than the sheath regions. The ejecta duration is 15.0 h on the 2 October 2013 event and 8.6 h on the 15 February 2014 event – the latter is close to the averaging period but we see that the main changes in electron fluxes occur during the sheath region. The ejecta times match approximately with those reported in the Richardson and Cane ICME list.

2.4 Phase Space Density (PSD) Analysis

For a more detailed investigation of the acceleration, transport and loss processes taking place during the events, we calculated the phase space density (PSD) at chosen adiabatic invariant coordinates (e.g., Green & Kivelson, 2001, 2004; Green, 2006; Chen et al., 2005; Chen, Reeves, & Friedel, 2007; Turner, Shprits, et al., 2012; Turner, Angelopoulos, Li, et al., 2014; Shprits et al., 2017). Adiabatic invariants correspond to the three constants of motion in the geomagnetic field when changes occur slowly (e.g., Roederer, 1970): gyration about field lines (1st invariant, μ), bounce along field lines (2nd invariant, K) and drift about the Earth (3rd invariant, L^*).

We used the level-3 pitch angle resolved electron fluxes from MagEIS and REPT on both Van Allen Probes to compute the PSD. The size of the pitch angle bins is 16.4° for MagEIS and 10.6° for REPT. We acquired invariants K and L^* from the ECT magnetic ephemeris files that are computed with the global magnetic field model of Tsyganenko and Sitnov (2005) (TS04D; <https://rbsp-ect.1anl.gov/>, last access: 4 June 2021). The time resolution of these modeled parameters is typically 5 min and the pitch angle resolution is 5° . K and L^* were interpolated to the equatorial pitch angles, mapped from the Van Allen Probes' local pitch angle measurements using the TS04D modeled equatorial magnetic field magnitude. The magnetic moment μ was calculated using the magnetic field magnitude observed by Van Allen Probes' magnetometers (EMFISIS; Kletzing et al., 2013) and the local pitch angle measurements. The electron fluxes were binned to 1 min prior to calculating PSD.

We used all low and medium energy channels from MagEIS, except the highest medium channel which was replaced by the first MagEIS high channel. The employed MagEIS channels cover the energy range from 30 keV to 1 MeV, while we use REPT to capture the ultrarelativistic electrons from 1.8 MeV to 9.9 MeV. In order to improve the energy resolution for the PSD calculation, we added two artificial energy channels in between each instrument channel. Fluxes in these added channels were interpolated from the measured fluxes. The central energies of the artificial channels were defined as the geometric mean of the lower and upper limits as defined in Chen et al. (2005). We also followed the Chen et al. (2005) formulation in calculating the relativistic momenta for each channel and converting electron fluxes to PSD. The steps in the calculation of PSD at fixed μ and K are summarized in, e.g., Hartley and Denton (2014). We note that no fitting of the energy or pitch angle distributions were performed in our method.

320 We investigated electrons mirroring near the equator by fixing K to an upper limit
 321 of $0.05 R_E G^{1/2}$. Two energy ranges were evaluated, $\mu = (300 \pm 10)$ MeV/G and $\mu =$
 322 (3000 ± 100) MeV/G, in order to probe the core and ultrarelativistic electron popula-
 323 tions. The PSD of the core and ultrarelativistic populations were calculated using MagEIS
 324 and REPT data, respectively. The PSD values were binned to $\Delta L^* = 0.15$ when plot-
 325 ting the L^* profile, as multiple values of PSD can be found at similar L^* . The purpose
 326 of the binning is to smooth the profiles and indicate the average shape of the curves. We
 327 have provided the unbinned PSD profiles in the Supporting Information (Figure S2).

328 The fluctuation in PSD at similar L^* arises from the employed ranges in μ and K .
 329 The ranges are broad enough for PSD points with μ and K values within these ranges
 330 to be found at two or more energy channels or pitch angle bins at the same time. The
 331 different bins correspond to different values of PSD, but have similar L^* , causing the fluc-
 332 tuations. Fluctuations seem to arise in particular from large jumps (\sim order of magni-
 333 tude) in flux between REPT energy channels. Similar fluctuation effects are seen in other
 334 PSD studies using ranges (e.g., Schiller et al., 2014). Naturally, the fluctuations increase
 335 for larger ranges of μ and K . The additional interpolated energy channels, while increas-
 336 ing the energy resolution, reproduce the fluctuations originating from flux variation be-
 337 tween the instrumental channels. On the other hand, these ranges allow for a better res-
 338 olution in PSD as opposed to fixing μ and K to a single value. We have chosen the ranges
 339 for this study as a compromise of being restrictive enough to remove major fluctuations,
 340 but broad enough to allow for a sufficient resolution of PSD points as a function of L^* .

341 3 Results

342 In this section, we present the geospace response to two ICME events with sheath
 343 regions on 2 October 2013 and 15 February 2014 in terms of solar wind parameters, ge-
 344 omagnetic activity indices, inner magnetospheric wave activity, outer radiation belt elec-
 345 tron fluxes and phase space density.

346 3.1 Overview of Solar Wind Observations

347 Figure 1 shows the evolution of solar wind parameters and geomagnetic activity
 348 during the two analyzed events, 2 October 2012 (Event 1) on the left and 15 February
 349 2014 (Event 2) on the right. The panels give from top to bottom the magnetic field mag-
 350 nitude, magnetic field components in Geocentric Solar Magnetospheric (GSM) coordi-
 351 nate system, solar wind speed, solar wind dynamic pressure, subsolar magnetopause po-
 352 sition from the Shue et al. (1998) model, and AL and $SYM-H$ indices. The sheath is de-
 353 picted with the blue shaded area.

354 For Event 1, the shock associated with the sheath region occurred on 2 October
 355 2013 at 1:11 UT (or at 1:58 UT when time-shifted to the magnetopause). The sheath
 356 extended until 23:50 UT on the same day (0:37 UT on the next day at magnetopause),
 357 spanning 22.7 h. The interplanetary magnetic field (IMF) direction had large-amplitude
 358 fluctuations and the IMF magnitude and dynamic pressure were enhanced during the
 359 front part of the sheath region, which was concurrent with the largest geomagnetic im-
 360 pact, as shown by both the $SYM-H$ and AL indices. The sheath caused a moderate ge-
 361 omagnetic storm with a minimum $SYM-H$ of -90 nT reached shortly after the shock
 362 impact. The IMF Bz -component changed from strongly negative to positive after a few
 363 hours in the sheath and turned slightly negative near the end of the sheath causing some
 364 substorm activity. The ejecta did not cause a geomagnetic storm or any substorm ac-
 365 tivity as the Bz -component was positive during the ejecta. The subsolar magnetopause
 366 was compressed beyond 10 Earth radii and briefly beyond the geostationary orbit dur-
 367 ing the front part of the sheath region. After reaching the minimum value, the magne-
 368 topause gradually relaxed to a nominal position during the rest of the sheath and moved
 369 to large distances ($\sim 15 R_E$) during the low dynamic pressure ejecta.

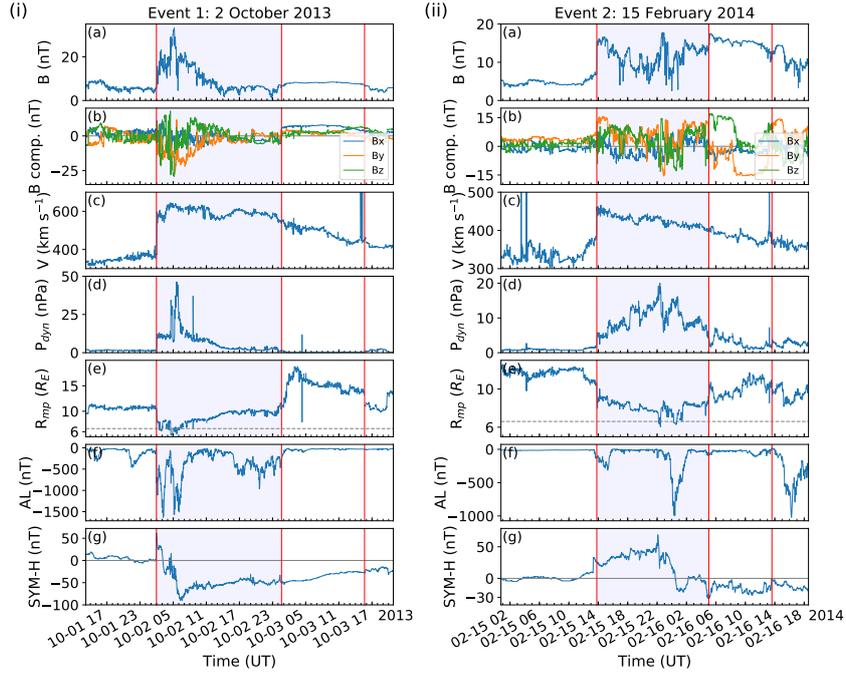


Figure 1. Solar wind properties and geomagnetic activity indices for the sheath events (i) on 2 Oct 2013 and (ii) on 15 Feb 2014. (a) Magnetic field magnitude, (b) magnetic field components in the geocentric solar magnetospheric coordinate system, (c) solar wind speed, (d) solar wind dynamic pressure, (e) subsolar magnetopause location from the Shue et al. (1998) model with the location of the geostationary orbit indicated ($6.6 R_E$), (f) AL index and (g) $SYM-H$ index. The red vertical lines indicate the shock, ICME ejecta leading edge and ejecta trailing edge in UT (universal time). The shaded area marks the sheath interval. The Wind data has been shifted from L1 to the magnetopause.

370 The shock of Event 2 was observed on 15 February 2014 at 12:46 UT (13:47 UT
 371 at magnetopause) and the sheath lasted until 16 February at 4:00 UT (5:01 UT at mag-
 372 netopause), i.e. the sheath duration was 15.2 h. The IMF direction presented again large-
 373 amplitude fluctuations during the sheath, but now the largest fluctuations with south-
 374 ward fields occurred in the trailing part of the sheath. In the front part of the sheath,
 375 the IMF was directed northward. Dynamic pressure was elevated and peaked at the centre
 376 of the sheath, and consequently, the magnetopause reached closest to Earth in the
 377 middle of the sheath. Again, the magnetopause was briefly pushed beyond geostation-
 378 ary orbit. The magnetopause then relaxed back to its nominal position during the ejecta.
 379 There was some substorm activity during the sheath, as evidenced by the AL index. A
 380 small substorm occurred just after the shock passage, while a bigger took place close to
 381 the sheath trailing edge. The $SYM-H$ index was first positive during most of the sheath
 382 and then decreased to minimum value of -32 nT at the very end of the sheath. The $SYM-$
 383 H index remained negative but above -30 nT during the ejecta.

384 The main difference between the two events was the strength of the geomagnetic
 385 storm, as evidenced by the $SYM-H$ index, and the location of the strong substorm ac-
 386 tivity, seen in the AL index, which coincided with the $SYM-H$ minimum. Stronger geo-
 387 magnetic activity occurred near the start of the sheath with a -90 nT $SYM-H$ min-
 388 imum for the geoeffective Event 1. On the contrary, for the nongeoeffective Event 2, which

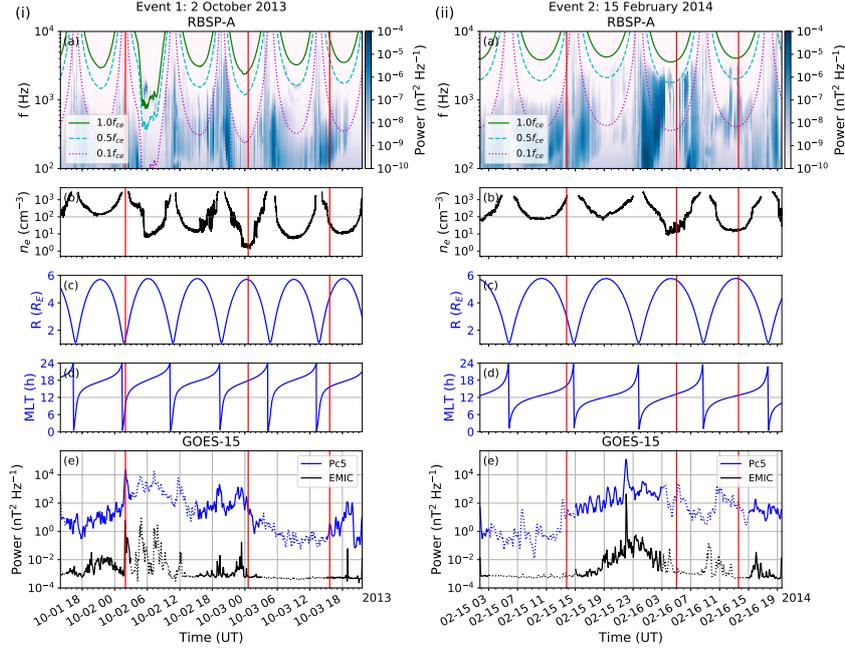


Figure 2. Very-low and ultra-low frequency (VLF and ULF) wave activity (i) on 2 Oct 2013 and (ii) on 15 Feb 2014. (a) Power spectrum of VLF waves from the EMFISIS instrument on Van Allen Probe A. The curves indicate different values of the equatorial gyrofrequency f_{ce} calculated from the TS04D geomagnetic field model. Chorus waves have frequencies $> 0.1f_{ce}$ outside the plasmasphere, and plasmaspheric hiss is present at lower frequencies. (b) Estimated electron density, where the horizontal line at 100 cm^{-3} illustrates an estimate of the plasmopause location. (c) TS04D model spacecraft radial location and (d) magnetic local time (MLT). (e) Wave power of ULF Pc5 and EMIC waves calculated with wavelet analysis from the magnitude of the magnetic field as measured by GOES-15. Solid and dotted lines indicate when the GOES spacecraft was on the dayside and nightside, respectively. The red vertical lines indicate the sheath and ICME ejecta intervals.

389 had a *SYM-H* minimum of -32 nT , the stronger substorm activity occurred near the end
 390 of the sheath.

391 3.2 Inner Magnetospheric Wave Activity

392 The wave activity in the inner magnetosphere is shown in Figure 2. Again the left
 393 panels show the data for Event 1 and the right panels for Event 2. The panels give from
 394 top to bottom the power spectrum of chorus and hiss waves; plasma density; location
 395 of the spacecraft; magnetic local time (MLT); and the ULF Pc5 and EMIC wave pow-
 396 ers. The power spectrum plot includes the f_{ce} , $0.5f_{ce}$ and $0.1f_{ce}$ curves of equatorial gy-
 397 rofrequency represented by the green, cyan and magenta curves. We show here data for
 398 Van Allen Probe A and GOES-15 only, the similar plot for Van Allen Probe B and GOES-
 399 13 is found in the Supporting Information (Figure S1).

400 Van Allen Probes are expected to be inside the plasmasphere when the density is
 401 high. Here we have marked 100 cm^{-3} as the limiting value (e.g., Malaspina et al., 2018)
 402 with the horizontal line in panels b.

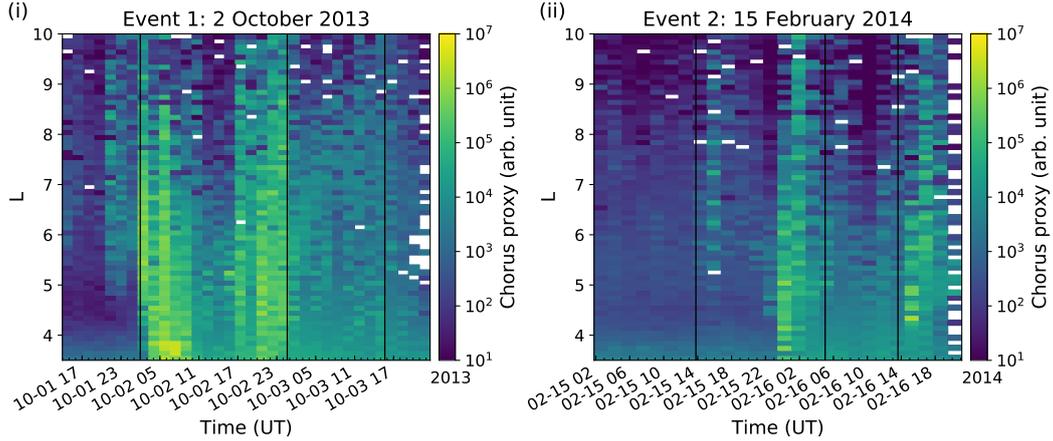


Figure 3. Chen et al. (2014) chorus proxy (with scaling factor $P = 1$) calculated from the geometric mean of the low-energy (30–100 keV) POES precipitating and trapped electron fluxes (i) for 2 Oct 2013 and (ii) for 15 Feb 2014.

403 The top panel of Figure 2 shows that, according to the Van Allen Probes measure-
 404 ments during the sheath of Event 1, there was only little chorus activity, but hiss was
 405 present almost throughout the whole sheath. This was also the case for Event 2. For Event 1,
 406 during the period ~ 12 – 18 UT on 2 October, Van Allen Probe B was inside the plasmas-
 407 sphere according to density (see Figure S1), so the stripes of enhanced emission extend-
 408 ing to $> 0.1f_{ce}$ are likely plasmaspheric hiss. At this time Van Allen Probe A was mostly
 409 outside the plasmasphere according to the density, and saw only weak enhancements in
 410 the lower chorus range. The same applies to emission detected at $> 0.1f_{ce}$ for Event 2
 411 when density was close to the 100 cm^{-3} limit.

412 The ULF Pc5 and EMIC wave power were in turn elevated for Event 1 during the
 413 sheath region, and especially so in the front part of the sheath. The EMIC power was
 414 low during most of the trailing part of the sheath and remained low during the ejecta,
 415 while the ULF Pc5 remained elevated and then quickly dropped during the ejecta. Event 2
 416 also showed considerably elevated Pc5 and EMIC power throughout the sheath, but the
 417 highest power occurred at the centre of the sheath when the dynamic pressure peaked.
 418 Similar results were measured by GOES-13 (see Figure S1).

419 For both events we see (panels d in Figure 2) that Van Allen Probes spent only a
 420 relatively short time on the dawnside, i.e. between 0 and 12 UT, where the main chorus
 421 activity is expected to occur. To obtain a better estimate of the chorus activity we
 422 investigated the chorus proxy based on Chen et al. (2014) and POES 30 to 100 keV elec-
 423 trons (see Section 2.2). These are shown in Figure 3 for both of our events.

424 The left panel of Figure 3 reveals that in Event 1 significant chorus wave activity
 425 was expected to occur in particular close to the shock and ejecta leading edges where
 426 the substorms occurred. According to the proxy, the chorus activity extended through-
 427 out the outer belt, from $L = 3.5$ to about $L = 9$, and peaked at $L = 3.5$ – 4 just after
 428 the shock, i.e. when the strongest substorm took place and *SYM-H* dipped. For Event 2,
 429 there was one interval of intense chorus close to the ejecta leading edge, again coincid-
 430 ing with the strongest substorm.

431 To summarize, both events caused significant Pc5 and EMIC activity, although wave
 432 activity peaked in different parts of the sheath region. The chorus activity was largely
 433 missed by the Van Allen Probes due to their orbit missing most of the dawnside, but the

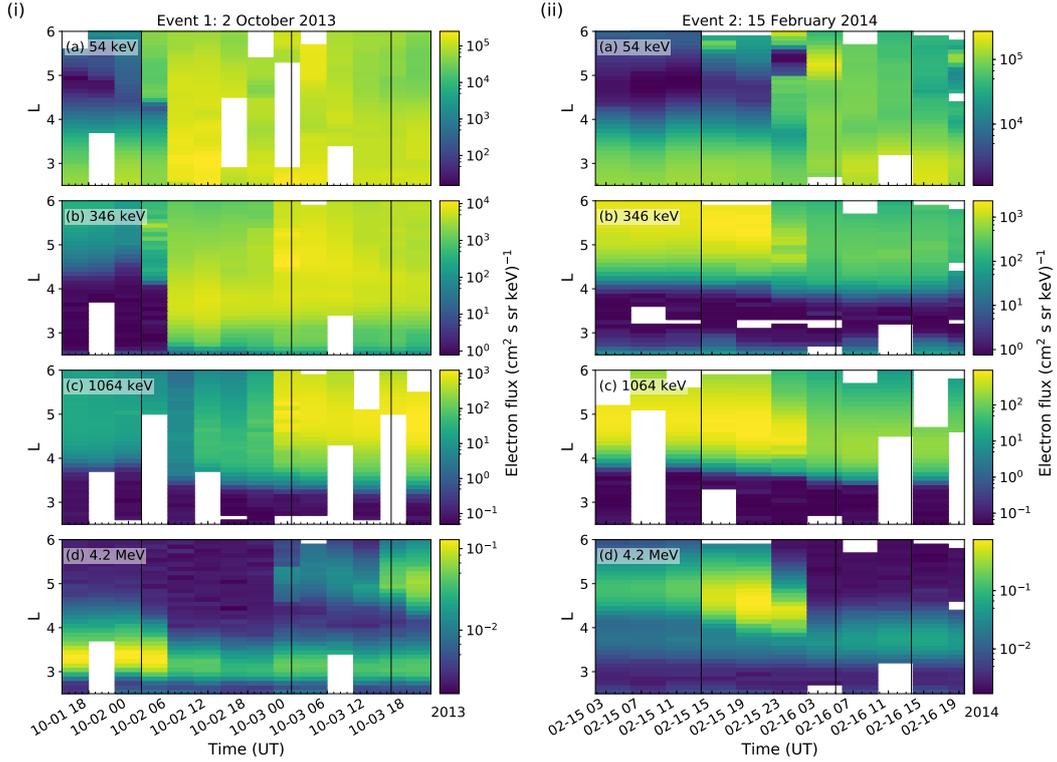


Figure 4. The spin-averaged electron fluxes measured by MagEIS at (a) 54 keV, (b) 346 keV and (c) 1064 keV and (d) by REPT at 4.2 MeV for the sheath events (i) on 2 Oct 2013 and (ii) on 15 Feb 2014. The data are combined from both Van Allen Probes and are binned by 4 hours in time and 0.1 in L -shell. The MagEIS electron fluxes are background corrected, except for the 54 keV fluxes in Event 2. The vertical lines mark the sheath region and ICME ejecta intervals.

434 chorus proxy suggested that the more geoeffective Event 1 had in particular significant
 435 chorus wave activity. The chorus activity was less intense and hiss more intense in Event 2.
 436 These indicate the first event to be more conducive to produce enhancement of core elec-
 437 trons, while the second is more susceptible to prolonged depletion.

438 3.3 Electron Flux Observations

439 Electron fluxes from four Van Allen Probes energy channels representing the source,
 440 seed, core and ultrarelativistic populations are presented in Figure 4.

441 For Event 1, source and seed electrons were enhanced near the start of the sheath
 442 during the strong substorm activity. Source and seed electron fluxes increased through-
 443 out the outer belt, but the strongest enhancement took place at $L = 3-4$. This is con-
 444 sistent with the chorus proxy in Figure 3 showing the peak at similar L range. Near the
 445 end of the sheath, during moderate substorm activity, the seed fluxes were further en-
 446 hanced at $L > 4$. For Event 2, the background corrected electron flux data at source
 447 energies is not available, so we have shown the uncorrected fluxes instead. Contamina-
 448 tion is not significant in this energy channel, so use of the uncorrected flux data has min-
 449 imal impact on the analysis. For Event 2, fluxes increased at source energies near the
 450 end of the sheath. Seed electrons were lightly enhanced at the shock, depleted near the
 451 end part of the sheath and remained at about that depleted level during the ejecta. This
 452 is consistent with much weaker substorm activity during Event 2.

453 On the other hand, for Event 1 core and ultrarelativistic fluxes decreased soon after
 454 the start of the sheath. Depletion was more dramatic for the highest energy and occurred
 455 in two parts, first a stronger decrease on 2 October at ~ 6 UT followed by a further
 456 depletion a bit later at ~ 14 UT. A weak remnant belt however remained from the
 457 high pre-event fluxes at $L \sim 3$. Both the core and ultrarelativistic populations enhanced
 458 at $L > 4$ near the end of the sheath, similar to lower energies. For the highest ener-
 459 gies, the remnant belt also intensified simultaneously, causing a clear two-part structure
 460 of the outer belt (Baker, Kanekal, Hoxie, Henderson, et al., 2013; Pinto et al., 2018).

461 For Event 2, similar to seed electrons, core electrons had a small enhancement at
 462 the shock. Ultrarelativistic electrons in turn experienced relatively strong enhancement
 463 at higher L -shells, with about an order of magnitude increase throughout $L > 4$. The
 464 band of the enhanced fluxes at MeV energies narrowed and moved to lower L -shells, and
 465 then depleted during the end part of the sheath simultaneously with the seed electrons.
 466 Again, no further significant changes were observed during the ejecta. For Event 2 the
 467 outer belt had a two-part structure at ultrarelativistic energies before the shock arrival
 468 that was destroyed during the sheath as the depleted fluxes at outer L -shells were not
 469 replenished, contrary to Event 1.

470 The overall response is given in Figure 5 in terms of the response parameter (Sec-
 471 tion 2.3) as a function of L -shell for the same four energy channels. This picture empha-
 472 sises the immediate response to the sheath. Firstly, the figure highlights that for the geo-
 473 effective event (Event 1) the sheath enhanced fluxes from source to core energies at all
 474 L -shells investigated (i.e. values above the red dashed line), while for ultrarelativistic en-
 475 ergies fluxes enhanced only at $L > 5$ and slightly at $L < 3$. For the nongeoeffective
 476 event (Event 2), in turn, fluxes mostly stayed unchanged or depleted, apart from source
 477 electrons which enhanced at $L > 4$. At other energies, enhancements occurred only at
 478 a narrow L range between 3.5–4, with the largest enhancement occurring for core elec-
 479 trons. The deepest depletion occurred for ultra-relativistic electrons at $L > 4$ (i.e., con-
 480 trary to the geoeffective event for which the fluxes enhanced at this part of the belt). We
 481 emphasize that the response parameter neglects the flux dynamics during the sheath,
 482 i.e., it only looks at the result after the sheath relative to conditions before the sheath.

483 3.4 PSD Analysis Results

484 To gain more insight into acceleration and loss mechanisms during the investigated
 485 sheaths, we examined the electron observations using PSD. The results are shown in Fig-
 486 ure 6 for Event 1 and Event 2 in the left and right hand panels, respectively. Two dif-
 487 ferent values of magnetic moment μ are considered, $\mu = (300 \pm 10)$ MeV/G and $\mu =$
 488 (3000 ± 100) MeV/G. The energy corresponding to a certain μ value varies according
 489 to geomagnetic field magnitude and thus with L^* . At $L^* = 4$, $\mu = 300$ MeV/G cor-
 490 responds roughly to 900 keV, i.e. core energies, and $\mu = 3000$ MeV/G corresponds roughly
 491 to 3.7 MeV, i.e. ultra-relativistic energies. Squares and dots show the inbound orbits for
 492 Van Allen Probes A and B, respectively, and pluses and stars show the outbound orbits.
 493 The color coding from purple to yellow indicates the increasing time. Videos highlight-
 494 ing the time evolution of PSD from pass to pass are available in the Supporting Infor-
 495 mation.

496 In agreement with electron fluxes discussed in the previous section, for Event 1 and
 497 for $\mu = 300$ MeV/G, PSD enhanced at $L^* > 3$. This indicated a combination of in-
 498 ward radial diffusion and substorm injections transported radially inward, and an increas-
 499 ing source population at higher L^* . PSD increased about three orders of magnitude be-
 500 low $L^* = 4$ and about two orders of magnitude at higher L^* in about one full orbit (9 h,
 501 from purple to magenta curves). PSD then continued to increase by almost an order of
 502 magnitude at $L^* > 4$ during about 12 hours (magenta to orange curves). This enhance-

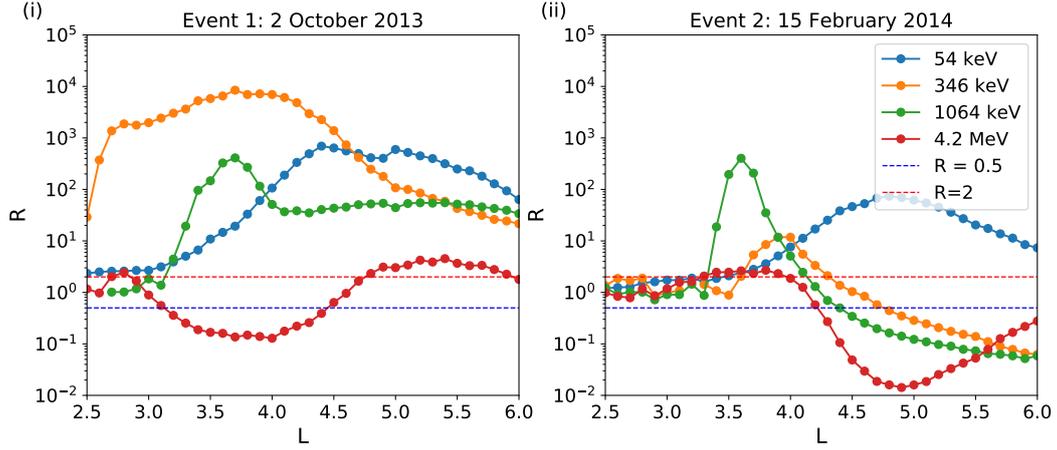


Figure 5. The response parameter (R) as a function of L -shell at four different energies representing the source (54 keV), seed (346 keV), core (1064 keV) and ultrarelativistic (4.2 MeV) populations for the sheath events (i) on 2 Oct 2013 and (ii) on 15 Feb 2014. The response parameter is defined as the ratio of electron flux averaged over 6 hours after and before the sheath region. The blue and red dashed lines show $R = 0.5$ and $R = 2$, respectively, indicating depletion ($R < 0.5$), no change ($0.5 \leq R \leq 2$) and enhancement ($R > 2$) of electron fluxes due to the sheath region.

503 ment persisted for the duration of the sheath, after which the PSD slightly declined dur-
 504 ing the ejecta at $L^* > 4$ (orange to yellow curves).

505 On the other hand, in the front part of the sheath PSD for $\mu = 3000$ MeV/G elec-
 506 trons in Event 1 showed a decrease in PSD at $L^* > 3$, while the PSD increased at $L^* <$
 507 3. This is a typical PSD signature of magnetopause shadowing losses due to combined
 508 magnetopause incursion and outward diffusion at higher L^* , and inward diffusion at lower
 509 L^* (e.g., Turner & Ukhorskiy, 2020). Later in the sheath and ejecta, PSD at $\mu = 3000$ MeV/G
 510 increased considerably at around $L^* \sim 4$ –5 and developed a peak. The peak was first
 511 detected by Van Allen Probe A during its inbound pass starting at 15:25 UT on 2 Oc-
 512 tober (magenta squares). PSD had increased by an order of magnitude compared to the
 513 earlier outbound pass. In the following inbound pass of Van Allen Probe A, starting at
 514 00:10 UT on 3 October, the peak had increased by two orders of magnitude. That is,
 515 the peak grew three orders of magnitude in about 12 hours. The outbound pass of Van
 516 Allen Probe A between the peak growth observations of the inbound passes did not have
 517 PSD available at the considered μ and K ranges. Similarly, PSD was not available from
 518 Van Allen Probe B at the time of peak formation and growth, so we cannot confirm the
 519 local growing peak with a two-point measurement.

520 Nevertheless, we calculated the peak growth rate based on the Van Allen Probe
 521 A passes before, during and after peak growth (magenta pluses, magenta squares and
 522 orange squares, respectively). We considered the three points at $L^* = 4.4$ –4.8 at the peak
 523 location, and fitted a line to the logarithmic PSD values as a function of time for each
 524 of these L^* bins. The mean peak growth rate is 6.3 days $^{-1}$ (i.e., orders of magnitude per
 525 day). The formation of this peak is discussed in detail in Section 4. After the peak growth
 526 observed by Van Allen Probe A, the peak was sustained at a similar level throughout
 527 the ejecta. The location of the peak also slowly drifted to higher L^* , from about $L^* =$
 528 4.6 to 5, indicating outward radial transport.

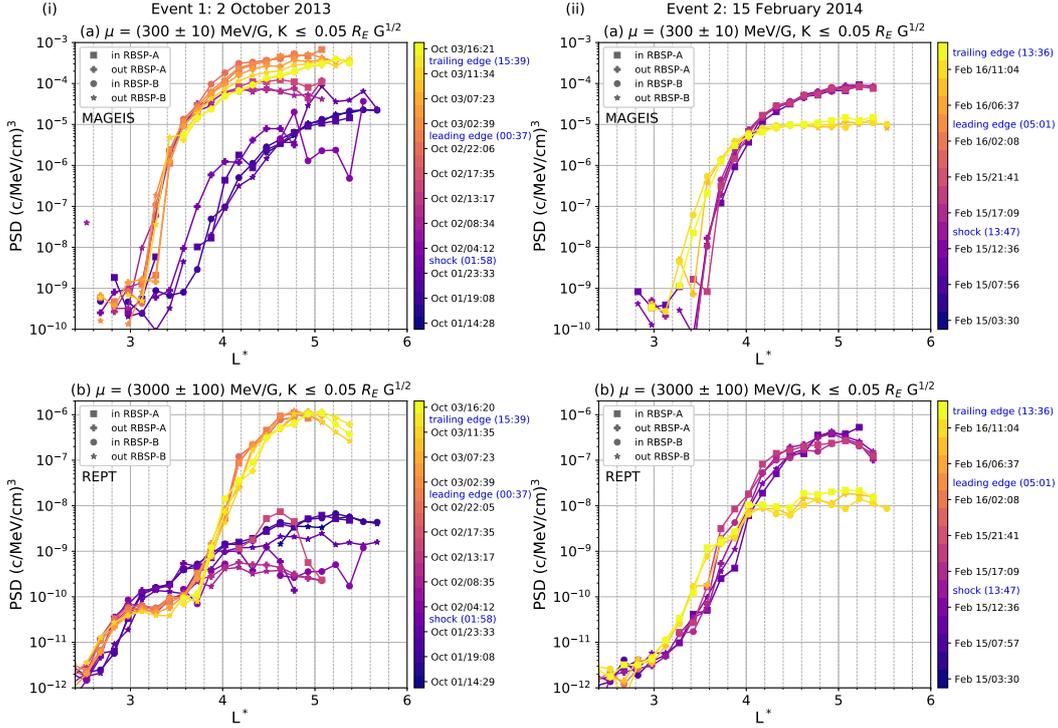


Figure 6. Phase space density (PSD) profiles (i) on 2 Oct 2013 and (ii) on 15 Feb 2014 representing nearly equatorially mirroring electrons with $K \leq 0.05 R_E G^{1/2}$. PSD versus L^* is shown for (a) lower energy particles (~ 900 keV at $L^* = 4$) at $\mu = (300 \pm 10)$ MeV/G and (b) higher energy particles (~ 3.7 MeV at $L^* = 4$) at $\mu = (3000 \pm 100)$ MeV/G. The profiles have been smoothed by averaging PSD to $0.15 L^*$ bins per pass. PSD calculations employed the TS04D magnetic field model and Van Allen Probes magnetic field measurements. The satellite passes are color-coded and the corresponding times are indicated in the color bar. The inbound and outbound passes of RBSP-A and RBSP-B are shown with different markers as indicated in the legend.

529 Onward from the pass starting at 08:35 UT on 2 October, there appeared to be a
 530 dip in PSD at $L^* \sim 3.3$ which remained throughout the rest of the event, consistent
 531 with Figure 5 (red curve for 4.2 MeV electrons). A local dip is a signature of local loss,
 532 mostly likely by EMIC waves (e.g., Aseev et al., 2017; Shprits et al., 2017).

533 For Event 2, PSD decreased about one order of magnitude at $L^* > 4$ in 13 hours
 534 for $\mu = 300$ MeV/G electrons, evidencing magnetopause shadowing and outward dif-
 535 fusion. The PSD profile also shows an increase at $L^* < 4$ caused by inward radial dif-
 536 fusion, which is further evidence for magnetopause shadowing causing the electron dropout,
 537 as discussed above for Event 1. It is however unclear if the dropout in PSD at $L^* > 4$
 538 is abrupt or gradual as no PSD data could be derived there at the chosen adiabatic in-
 539 variant coordinates from 21:41 UT on 15 February to 08:43 UT on 16 February (i.e., the
 540 latter half of the sheath region where the dropout in electron fluxes is observed).

541 Similar PSD evolution took place for $\mu = 3000$ MeV/G electrons in Event 2. There
 542 was about one order of magnitude decrease in PSD at $L^* > 4$ in 13 hours. PSD data
 543 is missing for the same time period as for $\mu = 300$ MeV/G during the latter part of the
 544 sheath, indicating that the spacecraft were not measuring electrons in the chosen K range

during this period. Similarly to $\mu = 300$ MeV/G profiles, PSD increased at $L^* < 4$. Therefore, PSD signatures indicate again magnetopause shadowing losses due to combined magnetopause incursion and outward transport. At $\mu = 3000$ MeV/G, the inward radial diffusion was also already observed early in the sheath accompanied by decreasing PSD at the highest probed L^* , as opposed to PSD at $\mu = 300$ MeV/G where increase at $L^* < 4$ was only observed during the ejecta. This indicates that magnetopause shadowing occurred throughout Event 2.

4 Discussion

The overall outer belt electron response, as shown by the response parameter (Figure 5), indicates opposite trends for the two investigated sheath regions. The geoeffective sheath caused a strong enhancement at all energies throughout the outer belt, except at $L = 3$ – 4.5 where ultrarelativistic electrons depleted. On the other hand, for the nongeoeffective event, depletion occurred from seed to ultrarelativistic energies, except at $L = 3.5$ – 4 where fluxes at all these energies were enhanced, in particular at seed and relativistic energies.

It is however important to note that the overall response should be interpreted with caution as it does not take into account the variations within the sheath that can be significant. For example, the response parameter misses the strong enhancement at ultrarelativistic energies that occurred during the beginning of the sheath at $L = 4$ – 5 in the nongeoeffective event (Figure 4ii, panel d) and only records the post-sheath depletion as compared to the pre-sheath levels. This initial brief enhancement was likely associated with the interplanetary shock impact that can quickly accelerate ultrarelativistic electrons via compression induced electric fields and drift resonant acceleration by related ULF waves (e.g., Kanekal et al., 2016; Hao et al., 2019). The response parameter calculated over short timescales (6 h) nevertheless reveals the outer belt electron flux variation in response to specific driver structures, as opposed to studies investigating considerably longer time periods (e.g., Reeves et al., 2003; Turner et al., 2015, 2019).

The analysis of electron fluxes and phase space density (PSD) for different Van Allen Probes orbits allowed for gaining more information of changes in the outer radiation belt during the sheath and insight into processes that govern the electron dynamics. The behaviour of relativistic $\mu = 300$ MeV/G electrons during the sheath was drastically different between the two events. For Event 1, PSD enhanced at all probed L^* after a mild initial depletion, while PSD during Event 2 enhanced only at lower L^* and decreased at higher L^* . As was mentioned in Section 3.4, the PSD behaviour of $\mu = 300$ MeV/G electrons for Event 2 evidenced the effective magnetopause shadowing resulting from the combined process of magnetopause inward incursion and radial diffusion (Turner, Shprits, et al., 2012; Turner & Ukhorskiy, 2020). In addition, the most distinct variations of $\mu = 300$ MeV/G PSD occurred in different parts of the sheath for Event 1 and Event 2. These differences in lower energy response and timing of dynamics can be largely related to different levels of substorm activity and different solar wind dynamic pressure profiles that caused the magnetopause compression and ULF activity to peak in different parts of the sheath. The dynamic pressure, and consequentially the strongest magnetopause incursion and ULF Pc5 activity, occurred just after the shock in Event 1, while for Event 2 they occurred in the latter part of the sheath. Substorm injections producing a sufficiently enhanced seed population during Event 1 also enabled the subsequent enhancements at core and ultrarelativistic energies (Boyd et al., 2016).

Lower energy electrons ($\mu = 300$ MeV/G) did not deplete significantly at the start of the sheath in Event 1 despite the magnetopause incursion, as opposed to higher energy electrons. This could be related to strong substorm activity quickly replenishing lower energy electrons and to their slower drift times about the Earth (from tens of minutes to more than an hour, compared to minutes for ultrarelativistic electrons in the heart

of the belt) combined with the briefness of the strongest magnetopause compression. The significant PSD enhancement after this initial light depletion is likely related to strong substorm activity continuing injecting electrons, and fast ULF wave driven inward radial diffusion, as well as the magnetopause relaxing toward a more nominal position. The evolution of the PSD gradient especially during the latter part of the sheath suggests the existence of an increasing source population at higher L^* (Chen, Reeves, & Friedel, 2007).

We note that the level of magnetopause compression and ULF wave activity was similar between the two events. The geoeffective event however resulted in significant substorm injections and a growing source population at high L^* that dominated over losses at the magnetopause and led to a drastically different response of $\mu = 300$ MeV/G electrons as compared to the nongeoeffective event.

Ultrarelativistic electron PSD ($\mu = 3000$ MeV/G) showed also very distinct responses between the studied events. For Event 2, high energy electrons evidenced a very similar response as lower energy electrons, i.e., effective magnetopause shadowing. The initial strong enhancement at ultrarelativistic energies seen in the electron fluxes is not noticeable in the PSD profiles (Figure 6ii, panel b) due to the lack of PSD measurements at $L^* > 4$ before the enhancement. The PSD profiles for Event 1 presented also a similar loss process during the closest magnetopause incursion just after the shock, but the geoeffective event experienced a very different response during the latter part of the sheath and ejecta, as described below. We note that the solar wind conditions in Event 1 follow the three criteria of Li et al. (2015) for efficient MeV electron acceleration. Event 1 had prolonged southward Bz during the sheath, high solar wind speed and PSD enhanced only after the dynamic pressure dropped to low values. This allowed the magnetopause to relax, leading to decreased magnetopause shadowing losses, while the elevated dynamic pressure throughout the sheath of Event 2 caused persistent losses via magnetopause shadowing.

A particularly distinct feature for high energy $\mu = 3000$ MeV/G PSD for Event 1 is the development of a peak. A local peak is usually taken as evidence for local acceleration by chorus waves. The chorus proxy suggests these waves were present throughout the sheath, and the activity also intensified at the time when the peak grew strongly. The chorus activity was spread along a wide range of L , but was strongest around the radial location of the PSD peak. The peak was observed at $L^* = 4.6$ –5 and it appeared near the middle of the sheath. The peak grew three orders of magnitude in ~ 12 hours. Local peaks near $L^* = 4$ –5 have been commonly observed in previous studies (e.g., Green & Kivelson, 2004; Reeves et al., 2013; Turner, Angelopoulos, Li, et al., 2014; Kanekal et al., 2015; Li et al., 2014, 2016). Similar peak growth rate as in our study was observed by Reeves et al. (2013), which was interpreted to have arisen due to local acceleration by chorus waves by Thorne et al. (2013). Slower growth rates of about two orders of magnitude in ~ 12 hours and about four orders of magnitude in ~ 2 days were observed by Li et al. (2014) and Li et al. (2016), respectively, and both concluded using diffusion simulations that chorus was the dominant cause for acceleration to MeV energies.

However, ambiguity arises for the mechanism generating the PSD peak in Event 1 due to the limited Van Allen Probes measurements beyond $L^* = 5$, and due to peak growth solely recorded by a single pass by Van Allen Probe A without confirmation from Van Allen Probe B. One possible explanation is chorus acceleration beyond the Van Allen Probes' apogee for lower energy electrons that get further energized when transported inward to the peak location by ULF waves, i.e., the peak is not necessarily fully generated by local chorus acceleration at $L^* = 4.6$ –5. However, the existence of a local peak in Event 1 has been confirmed by THEMIS spacecraft measurements beyond Van Allen Probes' apogee by Boyd et al. (2018), who also found local acceleration to be the typical cause for energization at MeV energies. In addition, since the peak retains its shape and magnitude for at least 12 hours, there must be an active source to balance the ULF-driven radial diffusion that would flatten and broaden the peak. This would be from lo-

649 cal acceleration or a sustained source of electrons further out, but there are no indica-
 650 tion of inward radial diffusion. Instead, the peak is slowly transported outwards during
 651 the ejecta which is consistent with typical recovery where chorus acceleration moves to
 652 higher L -shells.

653 There is another interesting feature in the PSD profiles of the geoeffective event
 654 at $\mu = 3000$ MeV/G: a dip in PSD at $L^* = 3-3.6$, which suggest a local loss. Consid-
 655 ering both the PSD and electron fluxes, clearly the strongest depletion of the ultrarel-
 656 ativistic population at low L ($L \sim 3.5$) occurred at 6–10 UT on 2 October ($\sim 18-23$ MLT
 657 for RBSP-A and for RBSP-B from ~ 22 MLT through a quick pass to early afternoon
 658 hours). Such depletions at low L for ultrarelativistic energies are commonly reported in
 659 previous studies (e.g., Turner et al., 2013; Turner, Angelopoulos, Li, et al., 2014; Turner,
 660 Angelopoulos, Morley, et al., 2014; Aseev et al., 2017), but their causes have remained
 661 uncertain. The depletion occurred when the inner magnetospheric wave activity was in-
 662 tense (Pc5, EMIC, chorus and hiss waves). In particular, Van Allen Probe A passed through
 663 the evening sector and was outside the plasmasphere, making wave-scattering losses by
 664 EMIC waves a possible cause (Aseev et al., 2017; Shprits et al., 2017). This can be as
 665 fast as hours for the ultrarelativistic population (e.g., Kurita et al., 2018). Another mech-
 666 anism that has been invoked to deplete ultrarelativistic fluxes quickly throughout the
 667 outer belt is the combined effect of magnetopause incursion, ULF wave transport and
 668 drift-shell splitting (Zhang et al., 2016). The speed of the depletion and the fact that
 669 the magnetopause was at this time already considerably relaxed makes the former scen-
 670 ario more likely.

671 It is also interesting to note that a three-part radiation belt structure for ultrarel-
 672 ativistic electrons (4.2 MeV, Figure 4) was created as a response to the sheath region
 673 of the geoeffective event, i.e., the outer belt split into two parts (Baker, Kanekal, Hoxie,
 674 Batiste, et al., 2013; Turner et al., 2013; Pinto et al., 2018). For the nongeoeffective event,
 675 in turn, a pre-existing two-part outer belt structure disappeared leaving only the rem-
 676 nant belt. For the geoeffective event, part of the intense remnant belt that was present
 677 before the shock/sheath arrival remained through the sheath despite suffering a consid-
 678 erable depletion at the start of the sheath and a further smaller depletion at the trail-
 679 ing part of the sheath. The largest L -shells of the outer belt captured by Van Allen Probes
 680 were largely devoid of ultrarelativistic electrons from the pre-event until the end of the
 681 sheath, after which fresh ultrarelativistic electrons appeared. The region $L \sim 4$ remained
 682 however devoid of electrons producing the two-part outer belt structure. For the non-
 683 geoeffective event, the disappearance of a two-part outer belt structure was caused by
 684 two processes, as indicated by the PSD analysis. First, ULF wave related inward trans-
 685 port filled the existing gap between the two bands of enhanced fluxes (remnant belt at
 686 $L = 3.5-4$ and an outer belt at $L > 4.5$) that were present before the event. Second,
 687 electrons were removed from high L -shells by magnetopause shadowing and outward trans-
 688 port by ULF waves without much further energization, leaving only the remnant belt.

689 This study highlights that regions close to the shock and ejecta leading edge seem
 690 to be key periods when changes in the radiation belt system occur, including most en-
 691 hanced precipitation from the radiation belts. The major variations of outer belt elec-
 692 tron fluxes, both depletion and enhancement, were observed under the influence of these
 693 regions. The statistical study of Kalliokoski et al. (2020) showed that the AL index dips
 694 after the shock for all sheath events and dips close to the ejecta leading edge for all geo-
 695 effective sheaths, indicating intense substorm activity in these key regions. Kilpua et al.
 696 (2019) similarly found that regions near the start and end of a sheath are the most geo-
 697 effective. These regions also exhibit enhanced ULF wave activity (Kilpua et al., 2013).

698 Additionally, this study indicated that the chorus proxy based on electron precip-
 699 itation was important for capturing the chorus wave activity. For both of the studied
 700 events, the Van Allen Probes spent little time in the dawn sector where chorus waves
 701 typically occur. The chorus proxy also allowed estimation of the L -range of chorus ac-

702 tivity showing that it encompassed the entire outer radiation belt. Some chorus activ-
 703 ity was almost continuous throughout the geoeffective event, but the activity peaked strongly
 704 in the above described key sheath sub-regions: just after the shock and close to the ejecta
 705 leading edge. This is consistent with strong disturbances in the AL index at these times,
 706 indicating large substorm activity that would likely generate chorus waves and provide
 707 a seed population for ultrarelativistic growth (Miyoshi et al., 2013; Jaynes et al., 2015).
 708 These sub-regions showed also the strongest chorus activity for the nongeoeffective event.

709 5 Conclusions

710 We studied the effects of two interplanetary coronal mass ejections with sheath re-
 711 gions on the outer radiation belt electrons. The two sheath events were geoeffective (2
 712 October 2013; Event 1) and nongeoeffective (15 February 2014; Event 2) based on the
 713 $SYM-H$ geomagnetic activity index during the sheath, and neither ejecta caused signif-
 714 icant geomagnetic disturbances.

715 Our study highlights that both geoeffective and nongeoeffective drivers caused dras-
 716 tic variations of the outer radiation belt electron fluxes up to ultrarelativistic energies.
 717 The overall response of the outer belt to the sheath for the geoeffective and nongeof-
 718 fective sheaths were the opposite: the geoeffective event led to enhancement for most of
 719 the energies and L -ranges, while the nongeoeffective event mainly resulted in depletion.
 720 The overall response however hides some distinct variations. For example, for the non-
 721 nongeoeffective event ultrarelativistic electrons experienced about an order of magnitude in-
 722 crease during the sheath before they depleted.

723 Analysis of electron phase space density at relativistic and ultrarelativistic ener-
 724 gies showed that the enhancement observed during the geoeffective sheath was likely due
 725 to substorm injections at lower energies and local acceleration by chorus waves at higher
 726 energies. In both events, depletion predominantly occurred via loss to the magnetopause
 727 driven by magnetopause compression and outward transport by ULF waves. Local loss
 728 at low L -shells in the geoeffective event was likely caused by pitch angle scattering by
 729 EMIC waves. These different responses derive from differences in substorm activity dur-
 730 ing the events and the properties of the two sheaths. The different timing and extent of
 731 the solar wind dynamic pressure pulse in the sheath contributed to the timing of the clos-
 732 est magnetopause inward incursion and thus when magnetopause shadowing losses were
 733 dominant. The relaxation of the magnetopause early in the geoeffective sheath along with
 734 mostly southward interplanetary magnetic field, leading to stronger substorm activity
 735 that generated chorus waves, created favorable conditions for energization of ultrarel-
 736 ativistic electrons, as opposed to the nongeoeffective sheath.

737 The results revealed the importance of ULF wave driven inward and outward ra-
 738 dial transport for governing electron dynamics, together with the compression of the mag-
 739 netopause. We also noted the existence of key sheath sub-regions, located at the start
 740 and end of the sheath, which cause the main variations. An interesting difference between
 741 the events was that the geoeffective sheath created a two-part outer belt structure, while
 742 the nongeoeffective sheath destroyed such pre-existing configuration.

743 Additional case studies are needed to determine if there are repeatable patterns
 744 in the response processes of the radiation belt system to sheaths. A statistical approach
 745 to phase space density analysis could shed light on the dominant electron dynamics (e.g.,
 746 Turner et al., 2017; Murphy et al., 2018; Zhao et al., 2019; Nasi et al., 2020). Future work
 747 will target events after August 2015 when data from the Magnetospheric Multiscale Mis-
 748 sion (MMS) is available. The orbit of MMS allows investigation of PSD distributions be-
 749 yond Van Allen Probes' apogee eliminating the ambiguity of PSD gradients near geosyn-
 750 chronous orbit (e.g., Cohen et al., 2021).

Acknowledgments

The authors are thankful to all of the Van Allen Probes, Wind, and OMNI teams for making their data available to the public. The OMNI and Wind data were obtained through CDAWeb (<https://cdaweb.sci.gsfc.nasa.gov/index.html/>). We thank Harlan Spence and the ECT team for Van Allen Probes MagEIS and REPT electron flux data (<https://rbsp-ect.lanl.gov/science/DataDirectories.php>) and Craig Kletzing and the EMFISIS team for Van Allen Probes wave data (<https://emfisis.physics.uiowa.edu/data/index>). POES data is available through NOAA (<https://www.ngdc.noaa.gov/stp/satellite/poes/dataaccess.html>) and we thank Timo Asikainen for providing the processed POES data which were obtained through the PROSPECT project (Academy of Finland grant 321440). The results presented here have been achieved under the framework of the Finnish Centre of Excellence in Research of Sustainable Space (Academy of Finland grant 1312390), which we gratefully acknowledge. E. K. acknowledges the European Research Council (ERC) under the European Union's Horizon 2020 Research and Innovation Programme Project SolMAG 724391, and Academy of Finland project 1310445. The work of L. T. is supported by the Academy of Finland (grant 322544). M. P. acknowledges ERC under the European Union's Horizon 2020 Research and Innovation Programme Project 682068-PRESTISSIMO, and Academy of Finland project 312351.

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