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Key Points:

- Low latitude chorus is known for its ability to accelerate electrons to relativistic and ultra-relativistic energies during active times
- High latitude chorus can remove these electrons from the radiation belts but we found that it does not intensify during active conditions
- Distribution of chorus under extreme conditions therefore leads to large fluxes of ultra-relativistic electrons in the radiation belts

Supporting Information:

Supporting Information may be found in the online version of this article.

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Strong Effects of Chorus Waves on Radiation Belts Expected for Future Magnetic Superstorms

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Abstract Processes in the radiation belts under extreme geomagnetic conditions involve the interplay between acceleration and loss processes, both of which can be caused by wave-particle interactions. Whistler mode waves play a critical role in these interactions, and up to now their properties during extreme events remained poorly sampled and understood. We employ extensive databases of spacecraft observations to specify their distribution. We show that under extreme geomagnetic conditions, lower-band whistler mode chorus waves have a net effect of accelerating ultra-relativistic electrons, which results in an increase of fluxes at multi-MeV energies by several orders of magnitude. During future magnetic superstorms, the radiation levels in the outer zone could therefore experience a substantial increase beyond what has been previously observed during the space age.

Plain Language Summary We investigate effects of a specific type of electromagnetic waves at audible frequencies, called chorus, on radiation levels around the Earth. These waves are generated naturally in the magnetosphere around a region of radiation trapped by the Earth's magnetic field in the outer Van Allen belt. Chorus occurring close to the geomagnetic equator is known for causing rapid increases of radiation under disturbed geomagnetic conditions. However, chorus can also propagate to high latitudes and here its presence may lead to decreases of radiation. We analyzed a large database of spacecraft measurements to determine how chorus waves behave under extreme geomagnetic conditions. Our results show that during future superstorms, surpassing the levels observed during the space age, the radiation levels can be much larger than what has been measured up to now. This has significant implications for our understanding of the dynamics of the Earth's radiation belts during extreme events, for determining outcomes of future solar superstorms, for our understanding of acceleration of particles at gas giant planets, and for future space exploration.

1. Introduction

The Van Allen radiation belts (Li & Hudson, 2019; Van Allen et al., 1958) are two torus-shaped regions of the near-Earth environment that contain highly energetic particles trapped in the Earth's magnetic field. The dynamics of the radiation belts result from the competition of acceleration and loss mechanisms (Reeves et al., 2013). Energetic particles can be diffused inwards or outwards and, most importantly, accelerated locally by electromagnetic waves (Horne et al., 2005; Thorne et al., 2013) or scattered by them into the atmosphere (Kasahara et al., 2018; Millan & Thorne, 2007; Miyoshi et al., 2021). Particle fluxes are often enhanced during magnetic storms and substorms, which typically occur during the declining phase of the solar cycle in connection with the high-speed solar wind streams coming from coronal holes (Hajra et al., 2015). It is known that magnetic storms can be much stronger than has been observed during the satellite era (Shprits et al., 2011; Tsurutani et al., 1992), as was the Carrington event in 1859 (Carrington, 1859; Tsurutani et al., 2003). Whether such extreme events would result in an extremely harsh environment will depend on the balance of acceleration and loss mechanisms.

Electromagnetic whistler mode chorus waves have been found to be efficient in energy diffusion and in acceleration of electrons to relativistic and ultra-relativistic energies (Horne, 2007; Horne et al., 2005; Thorne et al., 2013) on time scales on the order of one day or even shorter (Hsieh et al., 2020), leading thus to significant increases of energetic electron fluxes in the radiation belts. However, chorus can also scatter these relativistic electrons by diffusing the pitch angle of the electron momentum with respect to the background magnetic field. If the pitch angle decreases, radiation belt electrons can move into the loss cone, precipitate along the magnetic field lines down to the atmosphere, and stop bouncing in the Earth's magnetic field, thus causing losses of relativistic electrons from the radiation belts. This interaction can efficiently happen at higher latitudes, where the relativistic electrons close to the loss cone are likely to be in the most efficient first order cyclotron resonance with chorus waves (Miyoshi et al., 2015, 2020, 2021; Shprits et al., 2006; Thorne et al., 2005; Wang & Shprits, 2019). It is therefore essential to know how chorus at higher latitudes reacts to external drivers during geomagnetically disturbed conditions, and what are its effects on the ultra-relativistic electron fluxes. The interplay of acceleration and loss processes under these conditions is not properly captured by existing wave models (Agapitov et al., 2018, 2019; Li et al., 2009; Meredith et al., 2012, 2020; Santolík et al., 2014; Wang et al., 2019; Zhu et al., 2019), which mostly describe properties of low-latitude chorus and do not state any conclusions concerning effects of geomagnetic activity on chorus at high latitudes, even when a subset of high-latitude data is used (Agapitov et al., 2018, 2019).

In this study, we collect data from recent spacecraft missions, which span over two solar cycles. At higher latitudes, our data set is substantially larger than in previous studies, allowing us to better characterize the results for the rarely occurring disturbed conditions. Our results allow us to conclude that extreme conditions lead to properties of whistler mode waves, which are conducive to further local acceleration of relativistic electrons while direct scattering by these waves is suppressed. Thus, contrary to previous assumptions, we suggest that whistler mode waves may not cause saturation of relativistic electron flux levels in the outer radiation belt, and extreme storms may have a more severe impact than previously thought. Our results have broader implications for future understanding of the dynamics of the Earth's radiation belts during extreme events, for predicting extreme values of the radiation, for acceleration of particles at gas giant planets (Horne et al., 2008), and for future space exploration.

2. Inter-Calibrated Data Sets From the Van Allen Probes and Cluster Missions

To capture the global climatology of whistler mode waves in the Earth's magnetosphere, we use the entire available Survey mode data set of the Electric and Magnetic Field Instrument Suite and Integrated Science (EMFISIS) Waves instrument (Kletzing et al., 2013, 2023) onboard two NASA Van Allen Probes spacecraft. We also use Normal mode data of the Spatio-Temporal Analysis of Field Fluctuations Spectrum Analyser (STAFF-SA) instrument (Cornilleau-Wehrlin et al., 2003) on all four ESA Cluster spacecraft between 7 January 2001 and 30 April 2020. We carefully condition the data to avoid any instrumental or operational artifacts, such as intervals of erroneous onboard calibration and intervals when the attitude thrusters were fired on Van Allen Probes, or intervals of active soundings, calibration and burst mode intervals, and intervals when the de-spin procedure was not used onboard the Cluster spacecraft. The resulting data set provides us with a nearly uniform coverage of magnetic local time and a good coverage of magnetic latitudes up to 60° under different geomagnetic activity conditions (see Figure S1 in Supporting Information S1). In our analysis we pay special attention to the cross-calibration of experimental data from different instruments. Their sensitivity varies with time during the mission of each spacecraft, as their electronics degrade. We have therefore carefully selected calm intervals without any natural electromagnetic waves throughout the six separate data sets from the six spacecraft. We have then used these intervals to derive a frequency and time varying model of the probability distribution of the noise power spectral density, based on the properties of the observed instrumental noise convolved with the effects of the onboard analysis procedure on each spacecraft. We use this model to define the sensitivity thresholds, above which the instrumental noise reaches with a predefined probability of 10^{-7} at each analyzed frequency, minimizing thus the probability of false detections of natural waves. An essential aspect of our study is the enhancement of the statistical significance of our results, especially for rare extreme conditions, by combining data of the two missions. Inter-calibrated measurements of the STAFF-SA instruments on four Cluster spacecraft and EMFISIS Waves instruments on two Van Allen Probes spacecraft showed that, after proper characterization of sensitivity thresholds, we obtained consistent results from both missions, which allowed us to join their data sets and maximize their coverage across the parameter space.

We focus on the lower band whistler mode chorus (Burtis & Helliwell, 1969; Storey, 1953), which has important and sometimes dominant effects (Thorne et al., 2013) on relativistic electrons in the outer radiation belt. We select the data according to the characteristic frequency range and polarization properties of these waves and according to the location of the spacecraft at the time of the measurement. Origin of chorus is linked to the cyclotron resonance close to the geomagnetic equator (Hanzelka & Santolík, 2023; LeDocq et al., 1998; Santolík et al., 2004), and the frequency range of lower band chorus is typically between 0.1 and 0.5 of the equatorial electron cyclotron frequency. To estimate this frequency, we use local measurements of the magnetic field

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strength at the spacecraft position, and we assume propagation of chorus along the dipole magnetic field lines from its equatorial source to the spacecraft. As chorus propagates in the right-hand polarized whistler mode, we further select only right hand polarized electromagnetic waves (Verkhoglyadova et al., 2010) with magnetic ellipticity (Santolík, Gurnett, et al., 2003; Santolík, Parrot, & Lefeuvre, 2003) above 0.2. We also select only measurements, which occur in the outer radiation belt region and outside of the plasmapause with $L < 7$ and $L > L_{pp}$, where L_{pp} corresponds to the plasmapause position (O'Brien & Moldwin, 2003).

3. Latitudinally Dependent Response of Chorus to Geomagnetic Activity

Under the quasi-linear approximation, particle dynamics is controlled by the diffusion coefficients, which are proportional to squared amplitudes of the resonant waves. Chorus waves are known for a large variance and a heavy tail distribution of their squared amplitudes (Santolík et al., 2014; Tsurutani & Smith, 1974; Watt et al., 2017) that is generally close to the log-normal shape. The one-sigma interval spans over 2–4 orders of magnitude around the median value, and the mean value is typically near one sigma level above the median. The mean values obtained from time intervals when chorus was observed can be multiplied by finite occurrence rates of chorus waves to obtain the long-term averages of their squared amplitudes. We assume that the quasi-linear diffusion coefficients are determined by these long-term averages, which can be parametrized by the position within the magnetosphere. They also depend on external drivers of chorus, which can be characterized by recent history of geomagnetic activity. In relation to sources of chorus, it can be described by the AL* index calculated as a minimum of the AL index (World Data Center for Geomagnetism Kyoto, 2023) in a time interval of 180 min before the observation. This index is inferred from ground-based high-latitude observations of fast fluctuations of the geomagnetic field with a cadence of 1 min. For comparison, we also characterize the global geomagnetic activity by the planetary Kp index, a low cadence index, which is also derived from the ground-based measurements of the magnetic field (see Figure S2 in Supporting Information S1).

For our analysis, we have defined three levels of geomagnetic activity with approximately the same fraction of observations within the predefined boundaries of the AL* and Kp indices:

(a) Periods of low activity are represented by 36.2% of observations with -AL* index below 100 nT, and 40.8% cases with Kp index ≤ 1, respectively.
(b) Moderately active times are represented by 61.4% of cases with -AL* index between 100 and 1,000 nT, and 58.4% of cases with Kp between 1 and 6, respectively;
(c) Periods of extreme activity are defined for 2.4% of cases with -AL* index above 1,000 nT, and for 0.8% of extreme cases with $\text{Kp} \geq 6$, respectively.

Figure 1 confirms a strong influence of external conditions on amplitudes of chorus (Thorne et al., 2013; Tsurutani & Smith, 1974) at latitudes below 10°–20° on the night side and dawn side. This is also confirmed using the planetary Kp index (Figure S3 in Supporting Information S1). The chorus intensity starts to gradually grow already toward the upper edge of the moderate activity levels and continues to significantly grow for the extreme activity levels (Figure S4 in Supporting Information S1), reaching squared amplitudes by at least two orders of magnitude larger compared to the low activity periods. Similar results are also obtained if we limit the McIlwain's parameter more strictly to $L < 5$ (Figure S4 in Supporting Information S1). These low-latitude waves lead to acceleration of electrons to ultra-relativistic energies (Horne, 2007; Thorne et al., 2013) and they do not directly produce a significant loss, since they are not in the first order cyclotron resonance with ultra-relativistic electrons near the loss cone, as we demonstrate it in Section 4.

At higher latitudes above 30°, where the interactions of waves with particles are expected to lead to the pitch angle diffusion and consequent losses of relativistic electrons from the radiation belts, average squared amplitudes of chorus maximize around local noon and grow by less than one order of magnitude with increasing geomagnetic activity, showing signs of saturation at extreme activity levels. It means that losses of relativistic electrons induced by high latitude chorus waves are likely to be always the same, independent of external conditions. Results are very similar using both the auroral AL* index (Figure 1) and the planetary Kp index (Figure S3 in Supporting Information S1). Detailed analysis (Figure S4 in Supporting Information S1) indicates an intensification of high latitude chorus for moderate activity, which is larger when we limit the data to $L < 5$, but no further increase is observed for extreme activity. We can therefore expect chorus induced acceleration to win over chorus induced loss for extreme external driving.

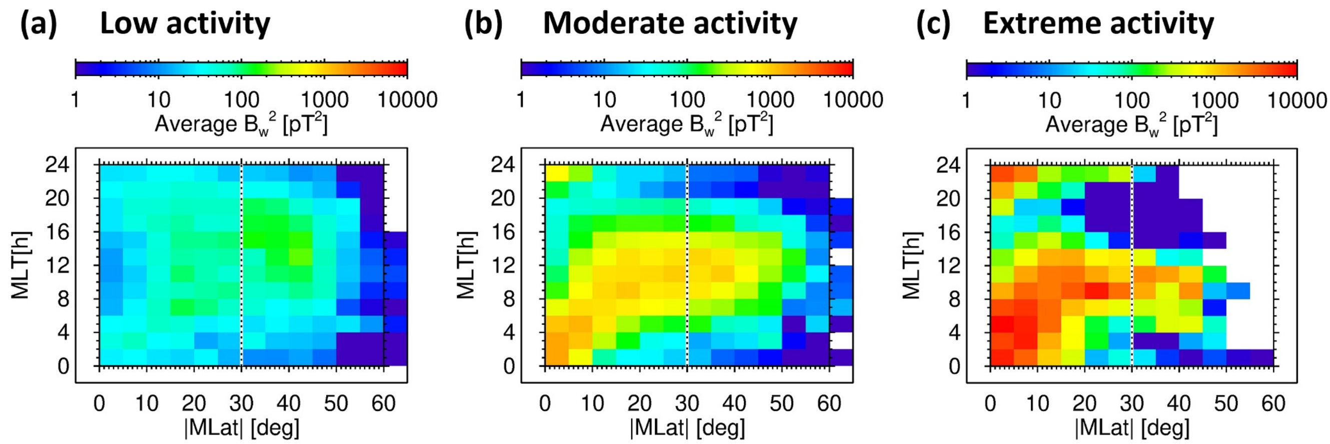

Figure 1. External driving of chorus. Color scale shows the long-term average squared amplitudes of chorus magnetic field fluctuations in pT^2. A joint data set of two Van Allen Probes and four Cluster spacecraft is analyzed in 12 × 13 discrete bins in magnetic local time MLT and absolute value of magnetic latitude |MLat|, where cumulative results for latitudes above 60° are shown on the outer edge of the plot. (a) Data from periods of low geomagnetic activity defined by the -AL* index below 100 nT; (b) the same for moderate geomagnetic activity with -AL* index between 100 and 1,000 nT; (c) the same for extreme cases of the highest geomagnetic activity with -AL* index above 1,000 nT. A vertical dotted line shows an approximate boundary between the equatorial region, where chorus strongly responds to geomagnetic activity, and the high-latitude region, where the response is weaker.

4. Electron Fluxes at Relativistic Energies

Since the loss of particles strongly depends on the value of the diffusion coefficients at the edge of the loss cone (Albert & Shprits, 2009) while the acceleration occurs at all values of the equatorial pitch angles, estimating the net effect of the wave distribution on the scattering and acceleration of electrons is not a trivial task. To understand how the observed distribution of waves affects particle energization, we conducted 2-D Fokker Planck simulations, detailed setting of which is described in Text S1 in Supporting Information S1. Based on the pitch angle and energy diffusion coefficients (see Figure S5 in Supporting Information S1), we model the evolution of the fluxes as a function of energy and pitch angle, including the mixed diffusion terms.

Figure 2 shows the flux of electrons at 1, 4, and 7 MeV as a function of the equatorial pitch angle. For a pitch angle near 90°, particles will mirror in the Earth's magnetic field close to the equator and will stay trapped near the equator. Small pitch angle particles will move along the field line until they reach the atmosphere, where they will be lost from the system. We compare the simulation results during moderately active and extreme conditions with the initial condition of our simulation. For both moderate and extreme cases, the dayside high-latitude chorus waves are kept unchanged. The nightside chorus waves are set to 30 pT during moderately active conditions, and

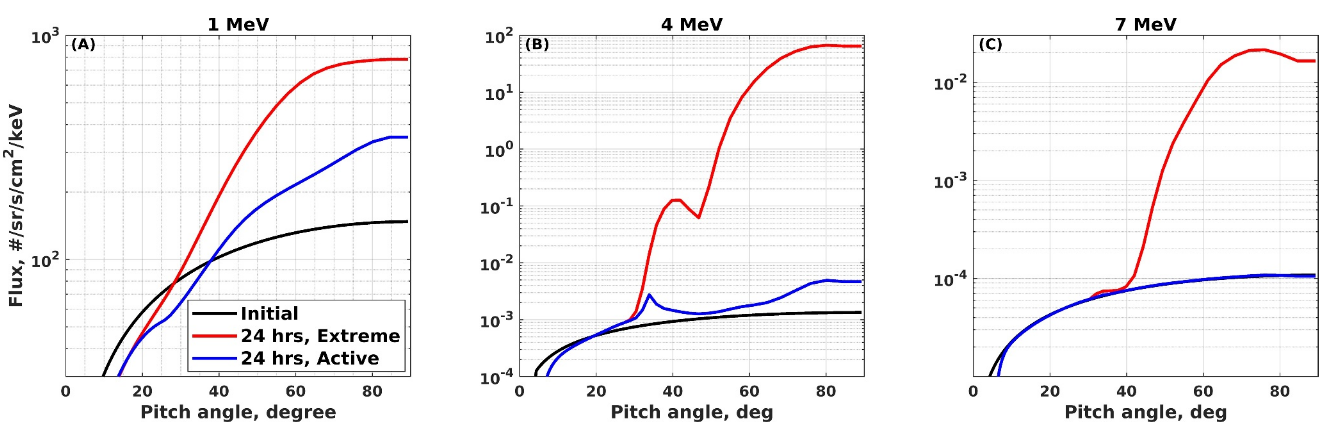

Figure 2. Simulated differential electron flux. (a) For electrons at an energy of 1 MeV, (b) 4 MeV, and (c) 7 MeV as a function of equatorial pitch-angle. Black lines show the initial condition. The red lines show the simulation results during the extreme conditions for 24 hr, while the blue lines show the simulation results during the moderately active conditions for 24 hr.

to 100 pT during extreme conditions, and for the dayside chorus waves, we use a constant amplitude of 30 pT, taken as an average value from the observations presented above.

Figure 2a demonstrates that the net effect of these waves on fluxes of 1 MeV electrons at pitch angles above 40° is an increase by a factor of two to three during extreme conditions, as compared to moderately active conditions in a 24-hr simulation. However, during extreme conditions, the strong waves near the equator also allow for very significant acceleration up to 4 and 7 MeV, increasing fluxes by two to four orders of magnitude (Figures 2b and 2c).

5. Discussion

Response of radiation belts to external driving, which originates from changes in the solar wind, comprises a number of different mechanisms acting at different time scales, such as the low frequency fluctuations causing both inward and outward radial diffusion (Hudson et al., 2021; Turner et al., 2012), interactions with the electromagnetic ion cyclotron waves (Shprits et al., 2016), or magnetopause shadowing (Thorne et al., 2013). In the present study, we focused on the contribution of lower-band chorus waves to these processes, knowing that effects of other mechanisms may also play a significant role. However, effects of chorus are often dominant on time scales of days (Horne et al., 2005; Thorne et al., 2013) and a study of this important component of the system separately from other mechanisms is useful for understanding of the global radiation belt dynamics. As electromagnetic waves similar to Earth's chorus have been observed in the radiation belts of Jupiter (Horne et al., 2008; Menietti et al., 2021) and Saturn (Menietti et al., 2013) and in the vicinity of their moons (Kurth et al., 2022; Santolík et al., 2011; Shprits et al., 2018), similar effects can also take place at these bodies.

Based on 2D simulations of electron dynamics in the presence of chorus waves during moderately active and extreme conditions, our analysis shows that fluxes of relativistic electrons increase by several orders of magnitude during extremely active times. This is a direct consequence of the intensification of low-latitude chorus, which is known to strongly respond to extreme levels of external driving. An important finding of our study is that these effects are not compensated by a similar intensification of chorus at higher latitudes where the loss processes take place. A large body of existing literature on chorus models (Agapitov et al., 2018, 2019; Li et al., 2009; Meredith et al., 2012, 2020; Santolík et al., 2014; Wang et al., 2019; Zhu et al., 2019) is mainly based on data from CRRES, Themis, and Van Allen Probes missions, which didn't measure at higher latitudes. No conclusions were drawn even when a substantially smaller subset of high-latitude Cluster data was used (Agapitov et al., 2018, 2019) probably because of the low statistical significance of these results at active times. Interestingly, previously unnoticed indications of the present results may be a posteriori identified in some published data displays (Agapitov et al., 2018).

Chorus was also found to be generated near the magnetopause in the dayside high-latitude pockets of decreased magnetic field (Tsurutani & Smith, 1977), without significant influence of geomagnetic activity. However, later studies showed (LeDocq et al., 1998; Santolík et al., 2010; Taubenschuss et al., 2016) that the main chorus band propagated from the equator and the contribution of chorus from the high latitude pockets to the total Poynting flux of chorus was minor and located at high L values outside of the radiation belts. Another subset of chorus measurements consisted of obliquely propagating waves close to the whistler-mode resonance cone (Agapitov et al., 2018; Santolík et al., 2009; Taubenschuss et al., 2016). These waves are not considered in our 2D electron simulations, which assume quasi-parallel propagation. They may have some influence on electron dynamics but systematic studies showed that quasi-parallel chorus is by far dominant (Santolík et al., 2014).

Effects of changing configuration of the magnetosphere may play a role during the enhanced solar wind pressure events contributing to electron loss by magnetopause shadowing (Thorne et al., 2013). During extreme magnetic storms, the plasmasphere will be eroded and the local acceleration by chorus will also occur at lower L shells (Da Silva et al., 2023; Shprits et al., 2011; Tsurutani et al., 2018), where the frequency interval of lower-band chorus may shift beyond the maximum frequency of existing data sets of spacecraft measurements. In this case, our results are only valid at L shells, where we have the full data coverage, still implying strong effects of chorus on ultra-relativistic electron fluxes.

Larger loss cones may also lead to larger losses through electromagnetic ion cyclotron waves (Chen et al., 2023; Hogan et al., 2023), which are not considered in the present study. Compared to chorus, these waves are at frequencies, which are by three orders of magnitude lower. They also generally occur much less often but if they happen to be present at the same time as chorus, they may be also involved in a two-step process, concluded by precipitation of the ultra-relativistic electrons to the loss cone (e.g., Mourenas et al., 2016; Qin et al., 2019; Zhang et al., 2017). The first step of this process consists of the diffusion of electrons toward lower pitch angles by chorus, and therefore low latitude chorus could still play a role in the precipitation process in such cases. If these effects overweigh the chorus driven acceleration, then the response of radiation belts to external driving may be overestimated by our study, which solely focuses on the contribution of lower-band chorus to these processes.

Note also that our data set does not allow for distinguishing any discrete time-frequency structures of chorus elements or their subpackets (Santolík, Gurnett, et al., 2003; Santolík, Parrot, & Lefeuvre, 2003), which play a significant role in the microphysics of chorus interactions with energetic electrons (Hanzelka & Santolík, 2023). However, existing methods for global modeling of electron fluxes do not allow us to include these nonlinear effects into our analysis, and we therefore assume that the interactions are quasilinear.

We also assume that the energy and pitch angle diffusion coefficients scale with the long-term average values of the squared amplitudes of chorus. This is justified if the observed heavy-tailed distributions of squared amplitudes (Santolík et al., 2014; Watt et al., 2017) converge to their long-term averages on the spatial and temporal scales of the corresponding acceleration and loss processes. If the nonlinear effects lead to saturation of the electron fluxes in the equatorial region, or if the acceleration occurs on smaller spatiotemporal scales than the convergence of long-term averages, then the effects of chorus on the fluxes of ultra-relativistic electrons might be weaker than what we report here.

These interactions are also influenced by the local plasma density (Agapitov et al., 2019). It should be noted that the result of intensification of waves may be even more dramatic when the plasma density is depleted (Allison et al., 2021; Shprits et al., 2022), which is often the case during storms. Extreme driving will cause background plasma density to be much lower than the statistical values used in this study for simulations in Figure 2. The depletion of density during storms may lead to even more dramatic acceleration to extremely high energies, resulting in an extremely harsh radiation environment.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Data Availability Statement

The Van Allen Probes EMFISIS Waves Survey mode data are available on https://emfisis.physics.uiowa.edu/. The Cluster STAFF-SA data are available for the ESA Cluster Science Archive on https://csa.esac.esa.int. The Kp index of geomagnetic activity is available from the World Data Center for Geomagnetism Kyoto on https://wdc.kugi.kyoto-u.ac.jp/kp/. The 1-min AE index is available from the World Data Center for Geomagnetism Kyoto on https://wdc.kugi.kyoto-u.ac.jp/aeasy/. The full diffusion code (FDC) and the Versatile Electron Radiation Belt (VERB) code for the numerical simulations is available on https://rbm.epss.ucla.edu/downloads/.

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