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Key Points:

- Hiss and chorus waves aid EMIC waves in depleting near equatorial mirroring electrons
- In the presence of EMIC waves, chorus wave-particle interactions can result in a net loss instead of acceleration of multi-MeV electrons
- In long-term simulations, hiss waves play a dominant role in aiding multi-MeV electron depletion by EMIC waves

Supporting Information:

- Supporting Information S1

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The Role of Hiss, Chorus, and EMIC Waves in the Modeling of the Dynamics of the Multi-MeV Radiation Belt Electrons

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Abstract In this study, we performed a series of long-term and individual storm simulations with and without hiss, chorus, and electromagnetic ion cyclotron (EMIC) waves. We compared simulation results incorporating different wave modes with Van Allen Probes flux observations to illustrate how hiss and chorus waves aid EMIC waves in depleting multi-MeV electrons. We found that EMIC, hiss, and chorus waves are required to reproduce satellite measurements in our simulations. Our results indicate that hiss waves play a dominant role in scattering near-equatorial mirroring electrons, and they assist EMIC waves, which scatter only small pitch angle electrons. The best agreement between the observations and the simulations (long-term and 17 January 2013 storm) is achieved when hiss, chorus, and EMIC waves are included.

1. Introduction

The study of the mechanisms that drive acceleration and loss of the radiation belts is one of the most fundamental tasks in space physics. While the understanding of the processes that control the radiation belt dynamics has improved since the launch of the Van Allen Probes mission in 2012 (Mauk et al., 2013; Stratton et al., 2013), our knowledge of losses is still incomplete. Recent studies show that the dynamics of the relativistic (~MeV) and ultrarelativistic (multi-MeV) electron populations and their response to the various geomagnetic conditions are significantly different (Baker, Kanekal, Hoxie, Henderson, et al., 2013; Shprits et al., 2013, 2016). The dynamics of those particles are determined by their interaction with several distinct classes of plasma waves.

Wave-particle interactions induced globally by ultralow frequency (ULF) waves cause radial diffusion as a result of the violation of the third adiabatic invariant (Fälthammar, 1965; Walt, 1970). Radial diffusion can produce acceleration and loss of particles depending on the gradient of their phase space density (PSD) on the time scale corresponding to the particle drift period (e.g., Riley & Wolf, 1992; Schulz & Lanzerotti, 1974). On the short time scale, substorm injections can also lead to electron energization up to ≥MeV energies (e.g., Dai et al., 2014, 2015; Kanekal et al., 2016; Schiller et al., 2016) due to rapid transport into the stronger magnetic field with conservation of the first adiabatic invariant. The approach of radial diffusion coefficient calculation from the observed and modeled ULF wave intensity and power spectral density has been widely used and employed in radiation belt simulations (e.g., Brautigam et al., 2005; Brautigam & Albert, 2000; Fei et al., 2006; Huang, Spence, Hudson, et al., 2010; Huang, Spence, Singer, et al., 2010; Ozeke et al., 2014; Ukhorskiy et al., 2009). Although radial diffusion is very effective in transporting electrons across the radiation belts (e.g., Shprits, Thorne, Friedel, et al., 2006; Shprits, Thorne, Horne, et al., 2006), locally generated whistler waves can play a definitive role in acceleration and loss (Shprits et al., 2008; Thorne, 2010). For example, cyclotron resonance interactions with dayside chorus, hiss, and lightning-generated whistler waves can lead to electron precipitation (Meredith et al., 2007; Thorne et al., 2005). Hiss waves are typically observed in the high-density regions within the plasmasphere (with more intense waves at the evening sector) and within dayside plasmaspheric plumes (Meredith et al., 2004; Millan & Thorne, 2007). The relativistic electron lifetimes due to the interaction with hiss waves are within the range of ~10–100 days. The continuous pitch-angle

scattering of radiation belt electrons by the hiss waves and lightning-generated whistlers leads to the formation of the slot region (Lyons & Thorne, 1973).

Outside of the plasmasphere, chorus waves provide pitch-angle scattering of electrons over a broad energy range. The corresponding electron lifetimes vary from hours for energies of 10 keV, up to several days for relativistic electrons (Orlova & Shprits, 2014). However, chorus waves play a dual role in the radiation belt electron dynamics. At energies above ~ 300 keV, electrons are generally accelerated by chorus waves faster than they are lost, while below ~ 300 keV, chorus interactions result in a competition between acceleration and loss (Horne et al., 2005) that is influenced heavily by energy gradients in phase space density (Allison et al., 2019). Interactions with night-side chorus waves can locally accelerate electrons (Horne et al., 2005) up to ultrarelativistic energies (Thorne et al., 2013) on the time scale of a day. Concurrently, electromagnetic ion cyclotron (EMIC) waves can efficiently remove multi-MeV electrons from the outer radiation belts on a timescale of a few minutes to hours (Meredith et al., 2003; Mourenas et al., 2016; Ni et al., 2015; Qin et al., 2019; Zhang et al., 2016, 2017).

EMIC waves are transverse plasma waves generated by anisotropic proton distributions with temperature anisotropy, $T_{\perp} > T_{\parallel}$ (where parallel and perpendicular components are defined with respect to the background magnetic field). Anisotropic ion distributions can be formed during storm-time enhancements in the convection electric field and are associated with the intensification of the ring current, injections from the magnetospheric tail, and magnetospheric compressions by the solar wind (see Usanova & Mann, 2016). EMIC occurrence rate increases with enhancement in solar wind dynamic pressure, the effect being most pronounced close to the subsolar magnetopause (Usanova et al., 2012). Enhanced solar wind dynamic pressure can also lead to generation of EMIC waves in the inner magnetosphere (Usanova et al., 2008, 2010).

The possibility of radiation belt electron scattering by EMIC waves has been discussed for almost half a century. Thorne and Kennel (1971) showed that EMIC waves can resonate with relativistic electrons through Doppler-shifted resonance. For MeV electrons, this condition is satisfied in the region of high plasma number density just inside the plasmasphere boundary where the minimum electron energy in resonance with EMIC waves falls to just above 1 MeV. Further estimation of electron lifetimes showed that intense EMIC waves can produce strong pitch-angle diffusion (Kennel, 1969) and remove resonant electrons from the magnetosphere at the maximum possible rate. Lyons and Thorne (1972) calculated electron pitch angle diffusion coefficients due to EMIC waves and confirmed that EMIC scattering is important for electrons at energies above 1 MeV. However, they do not affect electrons with equatorial pitch angles around 90° . This leads to the narrowing of multi-MeV electron pitch angle distribution as a result of EMIC wave activity (Usanova et al., 2014). Therefore, other wave modes are required to enable EMIC waves to deplete near equatorially mirroring electrons. Li et al. (2007) examined the effect of EMIC wave scattering in combination with hiss and chorus waves using a quasi-linear approach. The authors performed several 2-D simulations solving the Fokker-Planck equation, incorporating both energy and pitch-angle diffusion, and demonstrated that EMIC waves can provide dominant electron losses close to the loss cone, while hiss waves provide the diffusion of high pitch angle electrons toward the loss cone. Their simulations showed that EMIC and hiss waves induce loss during the main phase of geomagnetic storms faster than the acceleration associated with chorus emissions. During the storm recovery phase, owing to a reduction in EMIC wave activity, acceleration becomes the dominant process resulting in a gradual increase in the relativistic electron flux. However, EMIC waves can be very localized (Blum et al., 2016) and can be observed at a magnetic local time (MLT) where hiss and chorus waves are not present (e.g., Meredith et al., 2003; Saikin et al., 2015). If scattering by EMIC waves exceeds the limit of strong diffusion, the loss rate of particles due to the interaction with hiss and chorus waves along the drift orbit can be reduced. Shprits et al. (2009) performed MLT-dependent pitch angle diffusion simulations and showed that while EMIC waves create sharp gradients in pitch angle distribution at a localized MLT region, chorus waves produce electron scattering at other MLT sectors along the drift orbit. For moderate EMIC wave amplitudes, the decay rates are well modeled, using MLT-averaged diffusion coefficients. Similarly, Mourenas et al. (2016) showed that fast electron loss on the time scale of 2–10 hr may occur when hiss or chorus waves coexist with EMIC waves on the same L-shell, either in the same or different MLT region. To summarize the above, scattering by EMIC, hiss, and chorus waves cannot be treated independently of each other for the accurate representation of multi-MeV electron dynamics.

The launch of the Van Allen Probes on 30 August 2012 provided a remarkable opportunity to investigate the dynamics of the multi-MeV electrons and, in particular, the role of EMIC waves in radiation belt variability. Recently, simulations with EMIC waves provided an understanding of electron dynamics during several storm times (Shprits et al., 2013, 2016) and geomagnetically quiet periods (Ma et al., 2015). The comparison of the long-term simulations with observations also showed that EMIC waves are required for successful modeling of multi-MeV electron populations in the radiation belts (Drozdov et al., 2015; Drozdov, Shprits, Usanova, et al., 2017). However, the role of EMIC waves in ultrarelativistic electron loss was questioned in several studies (e.g., Mann et al., 2016; Ozeke et al., 2017), noting that EMIC waves alone cannot affect the ultrarelativistic electrons at large pitch angles. While it is true that EMIC waves do not often resonate with nearly equatorial mirroring electrons, there is always some very low frequency/extremely low frequency wave activity that is present on the time scales of azimuthal drift (e.g., Pokhotelov et al., 2008), providing additional scattering (Shprits et al., 2009). In this paper, we demonstrate in detail how hiss and chorus waves assist EMIC waves in scattering the core population (near 90° equatorial pitch angle) of multi-MeV electrons.

Here we conduct several long-term simulations and consider in detail simulations of an individual storm, extending our previous analysis. For these simulations, we perform sensitivity studies by including various combinations of waves to investigate how different wave modes collectively scatter electrons, covering the bulk population, up to near-equatorially mirroring particles.

2. Data and Methodology

2.1. Observations

In this study, we use the same data set as in the long-term simulations in Drozdov, Shprits, Usanova, et al. (2017) and individual storm stimulations in Shprits et al. (2016). These data sets contain electron flux measurements from the Energetic particle, Composition, and Thermal (ECT) plasma instrument set (Spence et al., 2013) on board the Van Allen Probes. We use ultrarelativistic (4.2 MeV) electron observations from the Relativistic Electron Proton Telescope (REPT) (Baker, Kanekal, Hoxie, Batiste, et al., 2013) and relativistic (0.9 MeV) electron observations from the Magnetic Electron Ion Spectrometer (MagEIS) (Blake et al., 2013). We calculate equatorial pitch angles and the generalized L value, L^* (see Roederer, 1970) using the TS05 magnetic field model (Tsyganenko & Sitnov, 2005).

2.2. Simulations

2.2.1. The VERB Code

Following the methodology of our previous papers, we use the Versatile Electron Radiation Belt (VERB) code (e.g., Shprits et al., 2015; Subbotin & Shprits, 2009) to perform all numerical simulations in this study. The VERB code solves the Fokker-Planck equation for electron PSD, providing representation of the radiation belt dynamics. The code allows us to take into account different plasma waves in the simulation; hence, we can study how various plasma wave combinations influence the simulation results. To be consistent with our previous simulations, we use the same parameterization of whistler-mode chorus and hiss, EMIC waves, radial diffusion, initial, and boundary conditions as in the previous studies (Drozdov, Shprits, Usanova, et al., 2017; Shprits et al., 2016). Brautigam and Albert's (2000) parameterization is used for the radial diffusion. This model is chosen because it produces the best agreement with the observations (e.g., Drozdov, Shprits, Aseev et al., 2017; Wang et al., 2020). The statistics from Spasojevic et al. (2015) and Orlova et al. (2016) are used for the hiss waves (considering realistic spectrum from Li et al. (2015) that takes into account low-frequency hiss), and the model presented in Zhu et al. (2019) is used for chorus waves. For the long-term simulation, we use EMIC wave parameterization, as in Drozdov, Shprits, Usanova, et al. (2017) and Carpenter and Anderson's (1992) plasmopause model. The EMIC waves spectrum is based on statistics from Meredith et al. (2014). To perform the modeling of a storm, we use the same setup for the EMIC waves as in Shprits et al. (2016), as well as the plasmopause test particle (PTP) model described by Goldstein et al. (2014). The EMIC waves spectrum is based on observations from the GOES 15 satellite. Hence, we perform three-dimensional simulations of electron PSD, including radial, energy, and pitch-angle diffusion with mixed terms. The outer radial boundary conditions at $L^* = 5.5$ are obtained from the Van Allen Probes observations and updated on every simulation step as in Drozdov, Shprits, Usanova, et al. (2017), thereby providing variable boundary conditions and loss due to outward radial diffusion (Shprits, Thorne, Friedel,

et al., 2006; Turner et al., 2012). We calculate the magnetopause location following Shue et al. (1998). The initial conditions are also determined by the Van Allen Probes A and B measurements, averaged over 1 day and interpolated on the simulation grid. In comparison to constant boundary conditions (statistically averaged PSD determined by spacecraft observations), the data driven boundary and initial conditions provide less ambiguity in the analysis since they provide better agreement with the observations (e.g., Shprits, Thorne, Horne, et al., 2006). Hence, any changes in the model due to the selected combination of the waves will reflect their role in the dynamics of radiation belts.

2.2.2. Long-Term Simulations

These long-term simulations cover the time range from 1 October 2012 to 1 October 2013. This period includes multiple storms and periods of different geomagnetic activity levels. Drozdov, Shprits, Usanova, et al. (2017) performed a simulation of radiation belt flux evolution during this period, investigating different EMIC wave parameterizations. To study how hiss, chorus, and EMIC waves affect the overall dynamics of multi-MeV electrons, we perform multiple long-term simulations with and without these waves. We use the identical (with an exception for the combination of hiss, chorus, and EMIC waves) simulation setup as in Drozdov, Shprits, Usanova, et al. (2017). Also, we chose to use $\alpha_{eq} = 85^\circ \pm 5^\circ$ for comparison to emphasize the dynamics of near equatorial electrons, as they cannot be directly affected by EMIC waves.

2.2.3. Simulations of 17 January 2013 Storm

To study the dynamics of electron pitch angle distribution in more detail, we choose to model the 17 January 2013 storm, as it was well discussed and reproduced in Shprits et al. (2016). The simulation period covers the time range from 15 to 22 January 2013. The observed PSD radial profiles at $\mu = 3,500$ MeV/G and $K = 0.1$ $G^{1/2} R_E$ (which correspond to electron energy around 4.6 MeV at $L^* = 4$) during this storm show a clear formation of a local PSD minimum followed by its depletion (Shprits et al., 2017). Since the PSD increases at the outer boundary ($L^* \sim 5.5$) but decreases at lower L^* , it indicates the presence of a very efficient and localized loss process. Such loss can be produced by EMIC waves, which were detected during this period on the ground and in space. This allows us to use the realistic frequency spectrum of EMIC waves, which plays a critical role in the evolution of the pitch angle distribution. The simulation by Shprits et al. (2016) included EMIC waves and successfully reproduced the pitch angle distribution of relativistic and ultrarelativistic electrons during this event, which makes it a perfect candidate for the purpose of this study. Similar to the long-term simulations described in section 2.2.2, we use the same setup as in Shprits et al. (2016). Hence, we use the same data-driven initial conditions (starting from 15 January 2013) and boundary conditions for all simulations with different wave combinations.

3. Results and Discussion

Figure 1 shows the measurements of the near-equatorial 4.2 MeV electron flux ($\alpha_{eq} = 85^\circ \pm 5^\circ$) and the simulation results for the October 2012–2013 period. Figure 1b shows the simulation result with hiss and chorus waves but without EMIC waves. The overestimation of the observed electron flux by orders of magnitude indicates a lack of an additional loss mechanism, which is expected since EMIC waves are not accounted for in this simulation. To include EMIC waves, we use the same methodology as described in Drozdov, Shprits, Usanova, et al. (2017). The EMIC wave presence is defined based on the solar wind dynamic pressure, and the waves are included only when the pressure exceeds 3 nPa. The EMIC waves are included with respect to the plasmapause location L_{pp} in the range of $-1 < \Delta L < 4$ ($\Delta L = L - L_{pp}$) according to findings by Fraser and Nguyen (2001). The simulation shown in Figure 1c is performed with EMIC waves but without hiss and chorus waves and it results in overestimated electron flux. This is the result of the ineffective scattering of electrons at $\alpha_{eq} = 85^\circ$ by EMIC waves. Chorus waves play a dual role in this model. They provide local acceleration of relativistic and ultrarelativistic electrons and pitch-angle scattering in a wide range of pitch angles. Figure 1d shows the simulation result with chorus and EMIC waves but without hiss waves. Regardless of local acceleration, chorus waves provide pitch angle diffusion from near-equatorial to lower pitch angles, where EMIC waves are effective. However, in this simulation, such a loss mechanism operates only outside the plasmasphere, and the model still significantly overestimates the observed fluxes. Similarly, hiss waves provide diffusion from high to low pitch angles inside the plasmasphere. The simulation result with hiss waves and without chorus waves (Figure 1e) becomes comparable to the observations. However, without chorus waves, the local acceleration is excluded from the simulation, which is unrealistic. This leads to the underestimated flux level during some periods of time in comparison to the observations.

Figure 1. Evolution of 4.2 MeV electron flux at 85° equatorial pitch angle, α as a function of time and L^* . (a) REPT observations, $\alpha = 85^\circ \pm 5^\circ$, (b–f) VERB code simulations results: (b) with hiss and chorus but without EMIC waves; (c) with EMIC but without hiss and chorus waves; (d) with EMIC and chorus but without hiss waves; (d) with EMIC and hiss but without chorus waves; and (e) with hiss, chorus, and EMIC waves. The black dotted curve shows the plasmapause location.

The effect of local acceleration is evident from the comparison of simulation results in Figure 1e and simulation with hiss, chorus, and EMIC waves in Figure 1f. The logarithmic difference of such a comparison is presented in Figure 2a, and it indicates that contribution of the chorus waves leads to the overall enhancement of the electron flux, despite the contribution of EMIC waves scattering. The comparison of the simulations with and without hiss waves (Figure 2b) demonstrates that hiss waves provide necessary loss inside the plasmapause, as expected. The modeled pitch angle distributions indicate that both hiss and chorus waves

Figure 2. (a) Logarithmic difference between Figures 1f and 1e; (b) logarithmic difference between Figures 1f and 1d. The black dotted curve shows the plasmopause location.

enable rapid scattering of near-equatorial 4.2 MeV electrons when EMIC waves are included (see supporting information Text S1 and Figure S1).

The simulation in Figure 1f is performed with hiss, chorus, and EMIC waves, providing the best agreement with the observations. The observed electron enhancements that are underestimated by the model can be a result of missing physics of electron injections. Injections, on occasion, can provide an enhancement of multi-MeV electrons and can also serve as a source of the seed population leading to local energization. However, the model outer boundary condition is data driven. Hence, phase space density changes at $L^* = 5.5$ due to the electron transport from the tail are accounted for. Another possible reason for the underestimated electron flux enhancement could be due to statistical plasma density models that are used in the calculation of the diffusion coefficients. Occasionally, the background plasma density can be significantly reduced, leading to more efficient local acceleration. For example, such phenomena occurred during the 9 October 2012 storm (Thorne et al., 2013) or the 17 March 2013 storm (Li et al., 2014), which are covered in the simulation period. The small overestimation of the modeled electron flux in comparison with observations can be a result of the whistler wave models used. For example, Orlova and Shprits (2010) showed that the pitch-angle scattering by chorus waves in a realistic magnetic field (Tsyganenko, 1989) can occur not only on the dayside but also on the nightside. The calculation of the diffusion coefficients in the realistic magnetic field for the long-term simulation remains a challenging task and will be a subject of future research. Malaspina et al. (2016) emphasized that the hiss wave power can be organized better using the location of the plasmopause in comparison with traditional L-shell sorting. The model of hiss waves parameterized by the plasmopause location leads to a different scattering rate, and it is under development (Malaspina et al., 2020).

Several studies performed 1-D simulations using observed ULF wave power to drive radial diffusion (Mann et al., 2016; Ozeke et al., 2017) and suggested that the fast loss of the ultrarelativistic electrons can be explained by fast outward radial diffusion. In addition, Olifer et al. (2018) conducted an analysis of several storms and suggested that the proximity of the last closed drift shell (LCDS) to the outer boundary of the radiation belts is related to the observed electron loss. Drozdov et al. (2019) performed a statistical analysis of the pitch angle distributions during storms that result in a depletion of multi-MeV electrons and found that in the heart of the outer radiation belt ($L^* = 3 - 5$), most of the depletions are consistent with EMIC wave activity. Other evidence of the importance of EMIC waves in ultrarelativistic electron loss was found from the analysis of PSD profiles and the formation of PSD minima (Aseev et al., 2017; Shprits

Figure 3. Evolution of electron flux at equatorial pitch angle of $85^\circ \pm 5^\circ$ as a function of time and L^* for the 17 January 2013 storm. (left panels) Energy 4.2 MeV and (right panels) energy 0.9 MeV. (a, f) Observation from REPT and MagEIS. (b–e and g–j) VERB code simulation results with parameterized EMIC waves: (b, g) without hiss and chorus waves; (c, h) with chorus but without hiss waves; (d, i) with hiss but without chorus; and (e, j) with hiss and chorus waves.

et al., 2017, 2018). The agreement between observations and the long-term simulation performed in this study, including hiss, chorus, and EMIC waves, can be improved. However, the obtained results demonstrate the importance of each of the wave modes in the radiation belt dynamics. For relativistic

Figure 4. (a) Logarithmic difference between Figures 3j and 3i. (b) Logarithmic difference between Figures 3j and 3h. The black dotted curve shows the plasmapause location.

0.9 MeV electron flux, the simulation results with hiss and chorus waves but with and without EMIC waves also agree well with the observations (see Figure S2 and supporting information Text S2). The results of relativistic electron simulations are consistent with previous studies (e.g., Drozdov, Shprits, Aseev, et al., 2017; Drozdov et al., 2015; Kim & Shprits, 2013; Subbotin et al., 2011).

Figure 3 shows an example of different MeV and multi-MeV electron dynamics during the 17 January 2013 storm (presented in the same format as in Shprits et al. [2016]). To test how hiss, chorus, and EMIC waves influence scattering of electrons, we include these waves one by one into our simulations. (The simulation results without EMIC waves are omitted in this paper but are shown in Figures 3 and 4 in Shprits et al. [2016].) EMIC waves were observed for 3 hr on 17 January 2013 at 15:00, and we include them in all simulations for this period in the same way as in Shprits et al. (2016). The EMIC waves are assumed to be in the plume region, whose presence is confirmed by the PTP model, and are included above the minimum plasmapause location. The spectrum of EMIC waves is obtained from observations, and we use statistical models of hiss and chorus waves as described in section 2.2.1.

Figures 3b and 3g show the simulation results with EMIC waves but without hiss and chorus. The simulation of 0.9 MeV electron flux is comparable with the observations (Figure 3a) due to radial diffusion, since the EMIC waves in our model do not resonate with 0.9 MeV electrons. However, the evolution of 4.2 MeV electron flux is very different. The observations in Figure 3f show the depletion of electrons at $85^\circ \pm 5^\circ$ equatorial pitch angle after 17 January 2013. The simulation with EMIC but without hiss and chorus waves failed to reproduce the observed depletion. We add chorus waves into the simulation in Figures 3c and 3h. The local acceleration due to chorus waves leads to a small increase of 0.9 MeV electron flux. Concurrently, chorus waves provide necessary diffusion of near-equatorial electrons and, therefore, lead to the depletion of multi-MeV electron flux at 85° equatorial pitch angle. We add hiss waves instead of chorus waves in Figures 3d and 3i. Hiss waves provide a decrease of 0.9 MeV electron flux in comparison to the simulation with chorus waves (Figure 3c) and the simulation with EMIC waves alone (Figure 3b). Similar to chorus waves, hiss waves also provide pitch-angle diffusion of near-equatorial pitch angle electrons toward lower pitch angles where EMIC waves effectively scatter 4.2 MeV electrons into the loss cone. The modeled flux profiles of 4.2 MeV electrons accounting for both hiss and EMIC waves are in agreement with the observations. Finally, we include EMIC, hiss, and chorus waves in Figures 3e and 3j, providing the best agreement with observations. We assume the adiabatic nature of the apparent temporal dropout of 0.9 MeV fluxes on 17 January and discuss it in supporting information Text S3. Although the observed dropout can be a

combination of the adiabatic change and nonadiabatic loss followed by the rapid acceleration, the observed by GOES 13 similar dynamics of electron and proton suggests significant influence of adiabatic effects.

Figure 4 shows a logarithmic difference between 4.2 MeV electron flux simulation with all waves included and the simulations without hiss or chorus waves. In both cases, hiss and chorus waves contributed as a necessary loss process. EMIC waves create a very sharp gradient of the pitch angle distribution profile around the loss cone, leading to faster electron scattering (e.g., Shprits, Li, & Thorne, 2006). As a result, the effect of chorus wave local acceleration vanishes amid the chorus and EMIC waves local losses (Figure 4a). Together with contribution of hiss waves (Figure 4), the overall geomagnetic conditions lead to the observed multi-MeV electron flux dropout during this storm.

Note that all simulation results of 0.9 MeV electron flux (Figures 3b–3e) are comparable with the observations (Figure 3a). However, only the results in Figure 3i (with hiss waves) and in Figure 3j (with hiss and chorus waves) are in agreement with the observations of 4.2 MeV electrons. The detailed analysis of the pitch angle distributions described below shows that the best agreement is achieved only when all waves are included.

Figure 5 shows the evolution of pitch angle distributions at $L^* = 3.9$ during the same period as in Figure 3. Figure 5 is also presented in the same format as in Shprits et al. (2016), for the same set of simulations as in Figure 3. The initial and boundary conditions are constructed from the observations and, hence, include the information about the measured pitch angle distribution. Thus, the pitch angle distribution of 0.9 MeV electrons in Figure 5b appears to be similar to the observations, even though the local pitch angle diffusion due to hiss and chorus waves is disabled. Chorus waves provide local acceleration increasing the 0.9 MeV electron flux in Figure 5c in comparison with Figure 5b (without hiss or chorus waves). Simulation with hiss waves results in lower electron flux in Figure 5d, compared to Figure 5b, since hiss waves do not provide local acceleration. Figure 5e, with hiss and chorus waves included, shows very similar results to Figure 5d (without chorus waves). Note that the difference in the dynamics of 0.9 MeV electron pitch angle distributions in multiple simulations shown in Figure 5 is less pronounced in comparison to 4.2 MeV electrons. Figure 5g (without hiss or chorus waves) shows very sharp and narrow pitch angle distributions at 4.2 MeV since EMIC waves do not resonate with near-equatorial electrons. Consequently, the depletion of electron flux in Figure 3g (that correspond to the same simulation) is absent. However, EMIC waves create a very steep gradient in the pitch angle distribution. Therefore, the addition of chorus waves in Figure 3h or addition of hiss waves in Figure 5i provides fast transport of near-equatorial electrons into the loss cone, resulting in multi-MeV electron depletion at all pitch angles. While fluxes modeled without chorus waves (Figure 5i) are comparable to the observations, the shape of the pitch angle distribution is incorrect. In turn, the pitch angle distribution in Figure 5i (simulation with hiss waves) is slightly narrower than in the observations. Only the combination of hiss, chorus, and EMIC waves (Figure 5j) provides the shape of pitch angle distribution and electron flux, as in the observations in Figure 5f. The noticeable delay of the observed 0.9 MeV flux enhancement (Figure 5a in comparison to Figure 5e) can be the result of imprecise radial diffusion and/or the use of a statistical density model in the calculation of the diffusion coefficients. The accounting for the realistic number density can change the efficiency of the local acceleration and provide better agreement with the data. Nevertheless, at the end of the simulation, the shape of the pitch angle distribution and the flux level match the observation.

4. Conclusions

In this study, we performed long-term and 17 January 2013 storm simulations, investigating the combined effect of hiss, chorus, and EMIC waves on scattering multi-MeV electrons. We showed that hiss and chorus waves provided additional necessary scattering of near-equatorial mirroring electrons, resulting in the best agreement of the modeling results with observations. The long-term simulation with EMIC waves alone failed to reproduce the dynamics of the 4.2 MeV electron population at 85° equatorial pitch angle. Also, the simulation of the 17 January 2013 storm with EMIC waves alone did not reproduce the observed depletion of 4.2 MeV electrons at 85° equatorial pitch angle nor the pitch angle distribution. However, the long-term simulation with only EMIC and hiss waves (without chorus waves) provided a reasonable agreement with the observations, indicating that hiss waves play a dominant role in aiding the depletion of ultra-relativistic electrons by EMIC waves. Despite chorus wave-particle interactions generally being considered

Figure 5. The pitch angle distribution evolution of electron flux at $L^* = 3.9$ for 17 January 2013 storm: (a–e) energy 0.9 MeV and (f–j) energy 4.2 MeV. (a, f) observation from MagEIS and REPT. (b–e and g–j) VERB code simulation results with parameterized EMIC waves: (b, g) without hiss and chorus waves; (c, h) with chorus but without hiss waves; (d, i) with hiss but without chorus; and (e, j) with hiss and chorus waves.

to result in a net acceleration for relativistic electron energies (Bortnik et al., 2016; Horne, Thorne, Glauert, et al., 2005; Li et al., 2007), in the presence of EMIC waves, chorus waves can induce additional loss when compared to the effect of EMIC waves alone. In general, the best agreement of both long-term and 17 January 2013 storm simulations with observations was achieved when all waves were included into the simulation. It confirms that hiss, chorus, and EMIC waves play an integral role in multi-MeV electron scattering.

Data Availability Statement

The authors used geomagnetic indices provided by OMNIWeb (<https://omniweb.gsfc.nasa.gov/>) and are grateful to the RBSP-ECT team for the provision of Van Allen Probes data (<http://rbsp-ect.lanl.gov/>). Used diffusion coefficients and the codes are available at <https://rbm.epss.ucla.edu> website.

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