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Van Allen Probes observations linking radiation belt electrons to chorus waves during 2014 multiple storms

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Abstract During 18 February to 2 March 2014, the Van Allen Probes encountered multiple geomagnetic storms and simultaneously observed intensified chorus and hiss waves. During this period, there were substantial enhancements in fluxes of energetic (53.8–108.3 keV) and relativistic (2–3.6 MeV) electrons. Chorus waves were excited at locations \( L = 4–6 \) after the fluxes of energetic were greatly enhanced, with a lower frequency band and wave amplitudes \( \sim 20–100 \) pT. Strong hiss waves occurred primarily in the main phases or below the location \( L = 4 \) in the recovery phases. Relativistic electron fluxes decreased in the main phases due to the adiabatic (e.g., the magnetopause shadowing) or nonadiabatic (hiss-induced scattering) processes. In the recovery phases, relativistic electron fluxes either increased in the presence of enhanced chorus or remained unchanged in the absence of strong chorus or hiss. The observed relativistic electron phase space density peaked around \( L^* = 4.5 \), characteristic of local acceleration. This multiple-storm period reveals a typical picture that chorus waves are excited by the energetic electrons at first and then produce efficient acceleration of relativistic electrons. This further demonstrates that the interplay between both competing mechanisms of chorus-driven acceleration and hiss-driven scattering often occurs in the outer radiation belts.

1. Introduction

Since the launching of Van Allen probes on 30 August 2012 [Mauk et al., 2012], new progresses have been made in understanding the radiation belt dynamics. Reeves et al. [2013] found that electron phase space density peaked in the heart of the radiation belts and are strongly associated with local accelerations. Baker et al. [2013] discovered a new relativistic electron ring lasting over four weeks between the locations \( L = 3 \) and 3.5 during September 2012. Such slow-decay relativistic electron ring was suggested to be attributed to small hiss-driven pitch angle scattering [Thorne et al., 2013a]. Li et al. [2013a] reported an unusually low (~20 Hz) hiss waves in the outer plasmasphere related to an strong electron injection. Correlated data analyses and numerical modelings demonstrated that chorus waves were indeed the primary mechanism responsible for acceleration of the radiation belt relativistic electrons during geomagnetic storms [Thorne et al., 2013b; Xiao et al., 2014].

In this study, we provide a overview of data on energetic (53.8–108.3 keV) and relativistic (2–3.6 MeV) electrons, whistler-mode (chorus and hiss) waves, collected by Van Allen Probes instruments from 18 February to 2 March 2014 when multiple geomagnetic storms occurred. We show a clear link between the flux enhancements of energetic electrons and excitations of chorus waves. We also show a complex variation behaviour of relativistic electron fluxes throughout the whole period. We focus on the discussions how variations of relativistic electron fluxes correlate with the activities of chorus and hiss waves.

2. Overview of Van Allen Probes Data

The scientific instruments onboard two Van Allen Probes can collect comprehensive data of particles and fields throughout their orbit, with excellent detection sensitivity, energy resolution, and temporal sampling.
Figure 1. Overview of Van Allen Probes data during 18 February to 2 March 2014. (a) The solar wind dynamic pressure. (b) The interplanetary magnetic field. (c) The Dst index and $K_p$ index. (d–f) Fluxes of electrons (2–3.6 MeV) measured by REPT instrument. The black trace in Figure 1d indicates the plasmapause location inferred by the measurement of the upper hybrid frequency.

capability. Here, relativistic electrons are measured by the Relativistic Electron-Proton Telescope (REPT) instrument [Baker et al., 2012]. Energetic electrons are detected by the Magnetic Electron Ion Spectrometer (MagEIS) [Blake et al., 2013]. Whistler-mode (chorus and hiss) waves are obtained by the Electric and Magnetic Field Instrument Suite and Integrated Science (EMFISIS) [Kletzing et al., 2013; Wygant et al., 2013].

As shown in Figure 1, during 18 February to 2 March 2014, four strong interplanetary shocks successively hit the Earth’s magnetosphere, leading to four strong geomagnetic storms (A–D). Figures 1a–1c show the solar wind dynamic pressure $P$, the interplanetary magnetic field $B_z$, and the geomagnetic activity Dst index, respectively. The storm A started at 14:00 UT on 18 February. The Dst index dropped rapidly down to $-112$ nT at 09:00 UT on 19 February, corresponding to a positive pulse $P \approx 15$ nPa and a negative (or southern) $B_z \approx -4.5$ nT. The “two-step” storm B began at 04:00 UT on 20 February when there were a sharp pulse $P \approx 10$ nPa and a negative $B_z \approx -10$ nT. On 20 February, the Dst index at first dropped from $-40$ nT down to $-86$ nT at 13:00 UT and recovered rapidly up to $-40$ nT at 19:00 UT. It remained almost the same level for 28 h, dropped rapidly again down to $-66$ nT at 02:00 UT on 22 February, and then gradually increase to 4 nT until the onset of the storm C at 08:00 UT on 23 February when $P \approx 14$ nPa and $B_z \approx -5$ nT. In the meanwhile, the Dst index dropped from $-4$ nT down to $-56$ nT at 00:00 UT on 24 February. The storm D began at 16:00 UT on 27 February when $P \approx 16$ nPa and $B_z \approx -18$ nT, with a minimum Dst $\approx -99$ nT at 00:00 UT on 28 February.

Figures 1d–1f show the variations in fluxes of radiation belt relativistic (2.0–3.6 MeV) electrons measured by REPT instrument onboard both Van Allen Probes. The black trace (Figure 1d), which denotes the plasmapause location derived by the measurement of the upper hybrid frequency, varied dramatically even downward to $L \approx 2.5$. Obviously, relativistic electron fluxes remained almost constant throughout the whole storm A period and even in the first main phase of the storm B. After then, electron fluxes continuously increased to a level higher than the previous storm level by a factor of $\sim 100$. In the storm C main phase,
electron fluxes remained at the same high level before the "dip" and then slightly dropped. In the recovery phase, electron fluxes increased and remained at the level slightly lower than the previous storm C level. In the storm D, electron fluxes dropped substantially in the main phase, and then gradually increased in the recovery phase, but much lower than that of the storm B or C. In the following, we will present discussions why the relativistic electron fluxes display different behaviours during the aforementioned storms A–D. In addition, we shall adopt the Gaussian distribution fitting method [Lyons et al., 1972] to calculate the chorus and hiss wave amplitude $B_t$.

3. Discussions

It is well-known that chorus waves are generated by anisotropic electrons with energies of a few keV ~100 keV in the low density plasma trough region [Xiao et al., 1998, 2006a; W. Li et al., 2009; Summers et al., 2009; Jordanova et al., 2010]. Chorus waves can in turn yield the temporal variation of relativistic (~1 MeV or above) electrons in the radiation belts [Summers et al., 1998, 2002; Horne et al., 2005a, 2005b; Xiao et al., 2009, 2010]. In Figure 2, we plot fluxes of energetic (53.8–108.3 keV) electrons detected by the MagEIS instrument (Figures 2b–2d) and whistler-mode (chorus and hiss) waves observed by EMFISIS instrument (Figures 2f and 2g) onboard Van Allen Probes during the storm A. Starting from 00:00 UT on 19 February to 04:00 on 20 February, fluxes of energetic electrons increased a factor of 1–2 orders mainly at $L = 4–6$. Distinct chorus waves mainly below the half electron gyrofrequency ($f_{ce}$) occurred in the main phase—00:00–04:30 UT, $L = 5.0–6.2$, and 10.0–14.0 MLT—and the recovery phase—08:00–15:00 UT, $L = 3.2–6.2$, and 8.9–14.2 MLT. Such enhanced chorus waves tend to be strongly associated with those
energetic electrons. Using the Gaussian distribution fitting method (not shown for brevity), we find the chorus wave amplitude $B_t \approx 67 \text{ pT}$ in the main phase and $B_t \approx 34 \text{ pT}$ in the recovery phase. In the meanwhile, hiss waves became strong in the main phase and weak in the recovery phase around the location $L = 5.3–6.2$. Relativistic ($2.0 \text{ MeV}$) electron flux dropped by a factor of 0.5 order in the main phase, probably due to the competition between the chorus-driven acceleration and the loss induced by either hiss waves or the $Dst$ effect [X. Li et al., 2009] or the magnetopause shadowing (because of inward motion of the magnetopause). In the recovery phase, relativistic ($2.0 \text{ MeV}$) electron flux gradually increased to the level comparable to the prestorm level, mainly because of the $Dst$ effect since chorus and hiss waves are relatively weak.

In the storm B, energetic ($53.8–108.3 \text{ keV}$) electron fluxes were greatly enhanced throughout the entire period with a peak value $\sim 10^{5.5} \text{ cm}^{-2} \text{s}^{-1} \text{ sr}^{-1} \text{ keV}^{-1}$ (Figures 3b–3d), consequently leading to strong chorus waves most of the storm time in the region: $L = 3.5–6.2$ and $8.7–15.0 \text{ MLT}$ (Figures 3f and 3g). Chorus waves were scaled with $f_{ce}$ and stayed between 0.1 and 0.5 $f_{ce}$, with a peak amplitude $B_t \approx 89 \text{ pT}$ which is capable of accelerating electrons to relativistic energies in a time scale of tens of hours to a few days [Glauert and Horne, 2005; Xiao et al., 2009; Thorne et al., 2013b]. Strong hiss waves were also present in the main phase mainly at the locations $L = 4–6.2$ and in the recovery phase mainly below $L = 3.5$. As shown in Figure 3e, at the locations $L = 4–6$, $2 \text{ MeV}$ electron flux dropped rapidly by a factor of 1–2 orders during the first main phase 04:00–12:00UT on 20 February and then gradually increased in the recovery phase. In the second main phase and recovery phase, electron flux at the location $L = 4–6$ continuously increased and finally reached a level by $\sim 100$ higher than the first main phase level. It is interesting that relativistic electron flux enhancement was much more pronounced even though $Dst$ was smaller than that in the storm A. This is mainly due to acceleration by the enhanced chorus waves over the most period of the storm B. As mentioned below, we already made a rough check by using those parameters at different MLT regions.
Figure 4. The same as Figure 2, but for the storm C.

comparable to the Gaussian fitting parameters in the storm B and found that those chorus waves could produce such pronounced flux enhancement. This suggests that the acceleration induced by chorus plays a more important role than the loss driven by hiss.

In the storm C, energetic (53.8–108.3 keV) electron fluxes at locations $L = 4–6$ remained at a high level in the main phase and gradually decreased in the recovery phase (Figures 4b–4d). Distinct chorus waves, with amplitudes $B_t \approx 14–39$ pT and a lower frequency region $0.1–0.5 f_{ce}$, existed primarily before 00:00 UT on 25 February when energetic electron fluxes are relatively high (Figures 4f and 4g). Hiss waves occurred over a longer time period but were pronounced below the location $L = 4.5$ (Figures 4f and 4g). Electron flux of 2 MeV dropped rapidly by a factor of 1 order in the main phase due to the aforementioned non-adiabatic or adiabatic processes (Figure 4e). In the recovery phase, at the locations $L = 4–5$, 2 MeV electron flux started to increase and reached a level higher than the main phase level mainly due to chorus-driven acceleration. After 00:00 UT on 25 February, electron flux remained almost the same level due to either the absence of continuous chorus or strong hiss primarily below the location $L = 4.5$. The very interesting feature here is that the removal of relativistic electrons above $L \approx 5$ occurred after 20:00 UT on 23 February and throughout the whole period of the storm. This is mainly due to the magnetopause shadowing in the main phase and absence of chorus-driven acceleration above $L \approx 5$.

In the storm D, as shown in Figures 5b–5d, energetic (53.8–108.3 keV) electron fluxes at locations $L = 4–6$ started to increase by a factor of $\sim 10$ after 19:00 UT on 27 February and then slightly decreased after 02:00 UT on 1 March. Consequently, enhanced chorus waves are detected by the EMFISIS instrument during the period 00:00–06:30 UT on 28 February in the region $L = 4–6.2$ and 7.7–14.4 MLT (Figures 5f and 5g), with a maximum amplitude $B_t \approx 100$ pT. During 00:00–02:00 UT on 2 March, energetic electron fluxes increased by a factor of $\sim 10$ at the locations $L = 5.2–6.2$. The EMFISIS instrument observed both enhanced
chorus ($B_t \approx 20$ pT) and hiss ($B_t \approx 70$ pT) waves in 11.4–13.0 MLT. In the rest of time, distinct hiss waves stay primarily at the locations $L = 2.0–3.5$. As shown in Figure 5e, in the main phase, 2 MeV electron flux decreased very quickly by a factor of 3 orders. In the recovery phase, at $L = 3.5–4.2$, electron flux gradually increased to a level by $\sim 10$ times higher than the lowest main phase level primarily due to acceleration by chorus. Instead, the radial diffusion contribution at $L = 3.5–4.2$ should be small [Xiao et al., 2010, 2014] since the radial diffusion coefficient decreases rapidly with decreasing $L$ [X. Li et al., 2009; Brautigam and Albert, 2000].

In order to check whether the energetic electrons are really responsible for the enhanced chorus waves, in Figure 6, we plot simultaneous data on pitch angle distribution of electron flux and wave magnetic field spectral density and ellipticity in the storms B and C. Energetic (53.8 and 79.8 keV) electron flux peaked at $90^\circ$ and drops remarkably at small pitch angles particularly close to $0^\circ$ or $180^\circ$ during 12:00–12:29 UT on 20 February (Figures 6a and 6b) and 00:30–01:00 UT on 24 February (Figures 6f and 6g). This indicates that there is an electron anisotropy and free energy for the excitation of chorus waves. Consequently, enhanced chorus waves were observed in the aforementioned periods with maximum magnetic field spectral density $\sim 10^{-5}$ nT$^2$/Hz and an ellipticity $\approx 1$ (the right-hand polarization). Figures 6e and 6i show the Gaussian distribution fit to the chorus wave data together with the fitting wave amplitude $B_t = 88$ pT (storm B) and 45 pT (storm C). Verification of correlated data for different periods (not shown for reasons of brevity) indeed show similar link between anisotropic energetic electrons and enhanced chorus waves. As done in previous numerous studies [Gary and Wang, 1996; Gary et al., 2000, 2005; Xiao et al., 1998, 2006b; Summers et al., 2009, Jordanova et al., 2010], anisotropic electrons with energies tens of keV can excite chorus waves. We actually check and found that those anisotropic electrons were indeed responsible for those strong chorus waves in cases of interest. However, detailed calculations of chorus wave growth induced by anisotropic energetic electrons are straightforward but very lengthy. We prefer to leave it to a future study.
Figure 6. Pitch angle distribution of electrons (53.8 and 79.8 keV) measured by MagEIS instrument in the storms (a–b) B and (g–h) C. Wave magnetic field spectral density and ellipticity measured by EMFISIS instrument in the storms (c–d) B and (i–j) C. A Gaussian distribution fit to the wave data together with the fitting parameters in the storms (e) B and (k) C. The insert in Figure 6c or 6i corresponds to the specific fitting time. Relativistic electron phase space density profiles measured by the REPT instrument in the storms (f) B and (l) C at \( \mu = 2533 \text{ MeV G}^{-1} \) and \( K = 0 \).

In particular, following the previous works [Chen et al., 2005, 2007], we plotted relativistic electron phase space density (PSD) profiles as a function of \( L^* \) (the Roederer parameter) measured by the REPT instrument at two specific times in Figures 6f and 6l. We use the first and second magnetic invariants \( \mu = 2533 \text{ MeV G}^{-1} \) and \( K = 0 \), which correspond to the electron energy range in 2.0–3.0 MeV within \( L^* = 4 – 5 \) and the equatorial pitch angle \( \alpha_e = 90^\circ \). PSD \( f \) is calculated by using the following relation [Chen et al., 2005]:

\[
\frac{f}{j} = 3.325 \times 10^{-8} \frac{f}{E_\beta (E_\beta + 2E_0)} \left( \frac{c}{\text{MeV cm}^{-3}} \right).
\]

where PSD \( f \) is in unit shown in the bracket, flux \( j \) is in units of \( \text{cm}^{-2} \text{s}^{-1} \text{sr}^{-1} \text{keV}^{-1} \), \( E_\beta \) is electron energy in MeV, and \( E_0 = m_e c^2 \approx 0.512 \text{ MeV} \) is the rest mass energy of an electron in a vacuum. Since the differential electron fluxes are detected with separated energy channels by Van Allen Probes, we interpolate between neighboring energy channels using an exponentially decaying energy spectrum to obtain the differential fluxes for these energies [Ni et al., 2011]. Obviously, peaks in electron PSDs occurred around \( L^* = 4.5 – 4.8 \) after chorus waves were enhanced, indicative of local wave acceleration. Furthermore, analysis of different times indeed shows similar results (not shown for brevity).

Moreover, as shown in Figure 7, we select each specific time period in the recovery phase of the storms A–D and model the chorus wave data by the Gaussian distribution, together with the corresponding fitting parameters. We then use those Gaussian fitting wave parameters above to obtain the bounce-averaged pitch angle \( \langle D_{\alpha \alpha} \rangle \), momentum \( \langle D_{\alpha p} \rangle \), and cross \( \langle D_{\alpha p} \rangle \) diffusion coefficients. The ratio of the electron plasma frequency to the gyrofrequency \( f_{pe}/f_{ce} \) for calculation of diffusion coefficients is obtained based on the measurement of the upper hybrid frequency and ECT-MagEIS magnetic field. The wave normal angle \( X = \tan \theta \) are also chosen to follow a Gaussian distribution [Glauert and Horne, 2005], with the
Figure 7. (upper panel) The Gaussian distribution (solid) fit to the wave data (dot) over a few minutes period together with the fitting parameters in the storms B–D. (lower panels) The bounce-averaged pitch angle ($\langle D_\alpha \rangle$), momentum ($\langle D_{pp} \rangle$) and cross ($\langle D_{\alpha p} \rangle$) diffusion coefficients corresponding to the Gaussian fitting wave parameters above.

lower angle $X_1 = 0$, the upper angle $X_2 = 1$, the half-width $X_m = 0.577$, and the peak angle $X_m = 0. We assume the constant field-aligned electron number density and the chorus wave spectral intensity, and choose the maximum latitude for wave occurrence as $\lambda_m = 15^\circ$ based on the observation. It is shown that in the storms A, B, and D, $(D_{pp})/p^2$ for 1 MeV electrons can approach $10^{-5}$ s$^{-1}$ at higher pitch angles, in the meanwhile, $(D_{pp})$ and $(D_{\alpha p})$ are approximately 10 and 3 times higher than $(D_{pp})$. Considering that the amplitude and morphology of all the diffusion coefficients are quite comparable to those previous results which can produce efficient acceleration of radiation belt electrons [Albert and Young, 2005; Xiao et al., 2009, 2014], it is reasonable to expect that the obtained excited chorus waves can be responsible for the flux enhancements of relativistic electron in the storms A, B, and D. In the storm C, all the diffusion rates are much smaller due to the smaller wave amplitude $B$, possibly explain the observed stable level of relativistic electron flux in the recovery phase of the storm C.

It should be mentioned that evaluation of long-term effects of waves on the particle population requires calculation of drift averaged diffusion rates. There are two distinct approaches used to treat this difficult problem. The first one, which has been performed for the last decade, is to use statistical models for the properties of the waves as a function of $L$ and MLT. The second one, which has been recently adopted in the works [Li et al., 2013b; Tu et al., 2013; Chen et al., 2014; Ni et al., 2014], is to employ low altitude data on precipitation flux as a proxy for the amplitude of waves in space. This approach moves a relatively large step...
forward toward obtaining realistic wave intensities over different regions of MLT and $L$ but still needs more improvement. Considering that chorus waves are excited by the injected anisotropic electrons with energies of tens of keV, the chorus intensities at different MLT regions should also scale with the observed fluxes of energetic electrons. Hence, based on the previous statistical model, we have used those chorus parameters at different MLT regions comparable to the Gaussian fitting parameters in the storms A–D to calculate the drift averaged diffusion rates (not shown for brevity). Then we solve the diffusion equation and find that chorus waves indeed produce efficient enhancements in fluxes of relativistic electrons in storm A, B, and D. However, detailed simulation combined with more realistic data on the flux evolution of relativistic electrons associated with solution of 2-D or 3-D Fokker-Planck diffusion equation [Varotsou et al., 2008; Albert et al., 2009; Shprits et al., 2009; Xiao et al., 2010] will be left in the future.

4. Summary

In the study, we have examined the multiple-storm events during 18 February to 2 March 2014 when the Van Allen Probes travelled then. Four strong geomagnetic storms (A–D) with a minimum $Dst = −112$ nT occurred after four strong interplanetary shocks successively hit the Earth’s magnetosphere. We present a overview of data on energetic (53.8–108.3 keV) and relativistic (2–3.6 MeV) electrons, whistler-mode (chorus and hiss) waves. In each storm period, the relativistic electron fluxes showed different dynamic variation behaviours. Then we analyze the potential correlation between excited chorus waves and flux enhancements of energetic or relativistic electrons particularly at the locations $L =$ 4–6. The following conclusions are obtained.

When fluxes of energetic electrons are greatly enhanced and an electron anisotropy occurs, strong chorus waves are present in the lower band $0.1–0.5f_{ce}$ over a broad region $L =$ 4–6.2 and 7.7–17 MLT. Using the the Gaussian distribution fitting method, we find the chorus wave amplitudes $B_i$ can approach 100 pT, capable of accelerating electrons to relativistic energies within tens of hours to a few days. Enhanced hiss waves are observed mainly in the main phases or below the location $L =$ 4 in the recovery phases, limiting hiss-driven scattering in the main phases or below $L =$ 4 in the recovery phases.

Relativistic electron fluxes dropped substantially in the main phases, which should be attributed to either the adiabatic loss ($Dst$ effect) or the magnetopause shadowing or hiss-driven scattering. In the recovery phases, relativistic electron fluxes at the locations $L =$ 4–6 are greatly enhanced when strong chorus waves are present and remain almost constant when there are no strong chorus or hiss waves. We calculate the bounce-averaged diffusion coefficients at indicated time period in the recovery phase of the storms A–D by the Gaussian distribution fit to the observed wave data. We find that the amplitude and morphology of all the diffusion coefficients potentially yield efficient acceleration of relativistic electrons in the storms A, B and D, but the much smaller diffusion coefficients in the storm C potentially allow the relativistic electron flux to remain stable in the recovery phase. In particular, we plot relativistic electron PSD profiles at two indicated times and find that electron PSD peaks around $L^* =$ 4.5–4.8 after chorus waves are enhanced, suggesting occurrence of local wave acceleration. The current results provide a direct observational support for the previous findings that energetic (∼10–100 keV) electrons can excited chorus waves and those chorus waves can in turn efficiently accelerate electrons up to relativistic energies. This further reveals that chorus and hiss waves can interplay in the dynamical variation of the outer radiation belt electrons.

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