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Zhenpeng Su
*University of Science and Technology of China*

Fuliang Xiao
*Changsha University of Electric Power*

Huinan Zheng
*University of Science and Technology of China*

Zhaoguo He
*Chinese Academy of Sciences, Beijing*

Hui Zhu
*University of Science and Technology of China*

See next page for additional authors

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Authors

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Nonstorm time dynamics of electron radiation belts observed by the Van Allen Probes

Zhenpeng Su1,2, Fuliang Xiao3, Huinan Zheng1,2, Zhaoguo He4, Hui Zhu1,2, Min Zhang5,1, Chao Shen6, Yuming Wang1,2, Shui Wang1, C. A. Kletzing7, W. S. Kurth8, G. B. Hospodarsky7, H. E. Spence8, G. D. Reeves9, H. O. Funsten10, J. B. Blake11, and D. N. Baker12

1CAS Key Laboratory of Geospace Environment, Department of Geophysics and Planetary Sciences, University of Science and Technology of China, Hefei, China, 2State Key Laboratory of Space Weather, Chinese Academy of Sciences, Beijing, China, 3School of Physics and Electronic Sciences, Changsha University of Science and Technology, Changsha, China, 4Center for Space Science and Applied Research, Chinese Academy of Sciences, Beijing, China, 5Department of Mathematics and Physics, Anhui University of Architecture, Hefei, China, 6State Key Laboratory of Space Weather, Center for Space Science and Applied Research, Chinese Academy of Sciences, Beijing, China, 7Department of Physics and Astronomy, University of Iowa, Iowa, Iowa, USA, 8Institute for the Study of Earth, Oceans, and Space, University of New Hampshire, Durham, New Hampshire, USA, 9Space Science and Applications Group, Los Alamos National Laboratory, Los Alamos, New Mexico, USA, 10ISR Division, Los Alamos National Laboratory, Los Alamos, New Mexico, USA, 11The Aerospace Corporation, Los Angeles, California, USA, 12Laboratory for Atmospheric and Space Research, University of Colorado Boulder, Boulder, Colorado, USA

Abstract Storm time electron radiation belt dynamics have been widely investigated for many years. Here we present a rarely reported nonstorm time event of electron radiation belt evolution observed by the Van Allen Probes during 21–24 February 2013. Within 2 days, a new belt centering around $L = 5.8$ formed and gradually merged with the original outer belt, with the enhancement of relativistic electron fluxes by a factor of up to 50. Strong chorus waves (with power spectral density up to $10^{-5} \text{nt}^2/\text{Hz}$) occurred in the region $L > 5$. Taking into account the local acceleration driven by these chorus waves, the two-dimensional STEERB can approximately reproduce the observed energy spectrums at the center of the new belt. These results clearly illustrate the complexity of electron radiation belt behaviors and the importance of chorus-driven local acceleration even during the nonstorm times.

1. Introduction

The Van Allen radiation belts normally comprise two distinct zones of geomagnetically trapped particles spatially separated by the slot region. The inner radiation belt is populated by both energetic electrons ($\sim$100 keV) and positive ions ($\sim$100 MeV), which is quite stable over time scales of years to decades. The outer radiation belt is populated by energetic electrons ($\sim$100 keV), which is highly dynamic over time scales of minutes to days. Benefiting from the growing network of satellites since the 1990s, the global and complex radiation belt dynamics have been revealed. Many storm-related events on 9 October 1990 [e.g., Brautigam and Albert, 2000; Summers et al., 2002; Horne et al., 2003; Thorne et al., 2007; Albert et al., 2009; Su et al., 2011], 24 March 1991 [e.g., Blake et al., 1992; Li et al., 1993; Hudson et al., 1997], 10 January 1997 [Reeves et al., 1998], 28 October 2003 [e.g., Horne et al., 2005b; Shprits et al., 2006], 1 September 2012 [e.g., Baker et al., 2013b; Thorne et al., 2013; Shprits et al., 2013], and 8 October 2012 [Reeves et al., 2013] have been extensively investigated. However, relatively few events during nonstorm times have been studied. Meredith et al. [2002] analyzed the dropout and buildup of outer zone energetic electron fluxes associated with prolonged substorm activity (but weak storm activity) during 11–16 September 1990. Park et al. [2010] presented some correlated observations on the slot region injection during a nonstorm time substorm on 24 February 2004. In particular, however, simultaneous observation and corresponding simulation regarding nonstorm time radiation belt dynamics are rarely reported.

An important challenge of radiation belt research is to resolve the precise mechanism for the acceleration of relativistic (~MeV) electrons. There are two leading acceleration mechanisms: (1) inward radial diffusion enhanced by the drift resonance of ULF waves [Elkington et al., 1999; Zong et al., 2007] and (2) local acceleration driven by the gyroresonance of VLF waves [e.g., Horne and Thorne, 1998; Summers et al., 1998, 2002; Thorne, 2010]. Recently, numerous observations [e.g., Green and Kivelson, 2004; Horne et al., 2005b;
Figure 1. Overview of the nonstorm time event of radiation belt evolution: (a) geomagnetic activity indices $D_s$, $K_p$, and $A_E$ obtained from the CDAWeb database; (b–e) radial profiles of spin-averaged relativistic electron fluxes at energies $E_k = 1.040 \text{ MeV}$, $2.000 \text{ MeV}$, $2.300 \text{ MeV}$, and $2.850 \text{ MeV}$, observed by the ECT instrument on board RBSP-B satellite during its outbound passes of five continuous orbits (indicated by five different colors). The black and red vertical dashed lines approximately denote the centers of original and new radiation belts.

Chen et al., 2007] and simulations [e.g., Shprits et al., 2006; Albert et al., 2009; Su et al., 2010] have shown the evidence for the dominance of local acceleration during geomagnetic storms. In this letter, we report a nonstorm time event of electron radiation belt evolution observed by the recently launched Van Allen Radiation Belt Storm Probes (RBSP) [Mauk et al., 2012] in late February 2013 and further identify a potentially dominant acceleration mechanism through the combination of observations and simulations.

2. Radiation Belt Dynamics

Figure 1 gives an overview of this radiation belt reformation event from 21 to 24 February 2013. The geomagnetic activity indices $D_s$, $K_p$, and $A_E$ are obtained from the coordinated data analysis web (CDAWeb) database (http://cdaweb.gsfc.nasa.gov/), and the radial profiles of spin-averaged relativistic electron fluxes at the selected energy channels are observed by the Energetic Particle, Composition, and Thermal Plasma (ECT) instrument [Spence et al., 2013] on board RBSP-B satellite. Our study primarily covers five continuous orbits of RBSP-B satellite (orbital period $\sim 9.5$ h), and the corresponding outbound passes are denoted by the colored shadows. During this period, both the $D_s$ and $K_p$ indices showed slow fluctuations in relatively limited ranges ($-35 \text{nT} \leq D_s \leq 10 \text{nT}$ and $0 \leq K_p \leq 3.33$), indicating the nonstorm state of magnetosphere. However, the $A_E$ index (with maximum value $\sim 1000 \text{nT}$) was predominantly enhanced, indicating the occurrence of prolonged substorm activity. In the first orbit (black lines), the outer zone fluxes peaked in the range $L = 4.0$–5.0 (depending on the electron energy) with the outer boundary $L \approx 5.0$. In the following four orbits, the outer zone fluxes gradually exhibited a new peak around $L = 5.8$ but had tiny changes in the spatial range $L = 2.5$–5.0. Within 2 days, the relativistic electron fluxes at $L = 5.8$ increased by a factor of up to 50.

In the fifth orbit (red lines), the peak location of outer zone electron fluxes at the energies $E_k = 1.040$, 2.000, and 2.300 MeV thoroughly moved to $L \approx 5.8$, while two peaks (at $L \approx 4.0$ and 5.8) coexisted at the energy $E_k = 2.850 \text{ MeV}$.

The current phenomenon can be interpreted as the gradual emergence of new radiation belt (centering around $L = 5.8$) and the simultaneous merging with the original radiation belt (centering at $L = 4.0$–5.0). The present nonstorm time “new belt” located near the outer boundary of original belt was identified at the
energies $E_k < 3.0$ MeV. Some storm-related events of “new radiation belt” formation have also been reported [e.g., Blake et al., 1992; Shprits et al., 2006; Baker et al., 2013b]. These storm time “new belts” located around $L = 3$ were spatially separated from (instead of merging with) the other belts at the energies $E_k = 2 – 6$ MeV or higher. Different physical mechanisms have been proposed to explain these storm time events: The 24 March 1991 event [Blake et al., 1992] was caused by the impulsive injection of electrons [Li et al., 1993]; the 28 October 2003 event [Shprits et al., 2006] mainly resulted from the chorus-driven local acceleration; and the 1 September 2012 event [Baker et al., 2013b] was largely produced by the loss of a distant portion of the outer zone electrons. For this nonstorm time event, the strength of radial diffusion (evaluated from the $K_p$ dependent expressions [Brautigam and Albert, 2000]) may be relatively weak. In fact, we have checked that ULF waves had no significant enhancement throughout this event (compared to those ULF waves before the event). Hence, radial diffusion may contribute little to the acceleration of relativistic electrons, especially in the heart of new belt. Further, considering the evolution time scale of the event (~ 2 days), local acceleration by VLF waves was the most promising physical mechanism.

### 3. Relativistic Electron Acceleration

Figure 2 presents the distribution of magnetic power spectral density $B^2$ in the frequency range of 0.1 to 10.0 kHz observed by the Electric and Magnetic Field Instrument Suite and Integrated Science (EMFISIS) instrument [Kletzing et al., 2013] on board the RBSP-A satellite, and the variation of corresponding satellite locations ($L$ and MLT). The magnetic latitudes of satellite were restricted in the range $|\lambda| \leq 21^\circ$ [Mauk et al., 2012]. Strong chorus waves (with power spectral density up to $10^{-4}$ nT$^2$/Hz) can be clearly identified around the white line (one half the electron gyrofrequency), which primarily occurred in the nightside (MLT $\approx$ 0–6) and at the large $L$-shell region ($L \sim > 5$). Note that the similar chorus wave characteristics can also be observed by the RBSP-B satellite.

We next determine the chorus-driven buildup of radiation belt electron fluxes at $L = 5.8$ (the center of new belt) using the two-dimensional storm-time evolution of electron radiation belt (STEERB) code [Xiao et al., 2009; Su et al., 2010], which is based on the solution of Fokker–Planck equation for electron phase space density (PSD) $f$ evolution

$$\frac{df}{dt} = \frac{1}{G} \frac{\partial}{\partial \alpha_e} \left[ G \left( \langle D_{\alpha e} \rangle \frac{\partial f}{\partial \alpha_e} + \langle D_{\alpha p} \rangle \frac{\partial f}{\partial \alpha_p} \right) \right]$$

$$+ \frac{1}{G} \frac{\partial}{\partial \alpha_p} \left[ G \left( \langle D_{\alpha e} \rangle \frac{\partial f}{\partial \alpha_e} + \langle D_{\alpha p} \rangle \frac{\partial f}{\partial \alpha_p} \right) \right] - \frac{f}{\tau}\). \quad (1)$$
Figure 3. (a) Observed magnetic power spectral density $B^2 = B_f^2 / 2\pi$ in the spatial range $L = 5.5 - 6.1$ of five continuous orbits (dots) and modeled Gauss-type power spectral density distribution (line); (b-d) two-dimensional distributions of bounce-averaged diffusion coefficients as functions of pitch angle $\alpha_e$ and kinetic energy $E_k$ for modeled chorus waves at $L = 5.8$.

with

$$G = p^2 T(\alpha_e) \sin \alpha_e \cos \alpha_e,$$  \hspace{1cm} (2)

$$T(\alpha_e) \approx 1.30 - 0.56 \sin \alpha_e.$$  \hspace{1cm} (3)

Here $\langle D_{aa} \rangle$, $\langle D_{pp} \rangle$, and $\langle D_{ap} \rangle = \langle D_{pa} \rangle$ are the drift and bounce-averaged diffusion coefficients in the equatorial pitch angle $\alpha_e$, momentum $p$, and cross terms, depending on the wave spectral and normal angle distributions, as well as the ratio between plasma frequency $\omega_p$ and equatorial electron gyrofrequency $|\Omega_e|$; $\tau_e$ is the electron lifetime, which is assumed to be infinite out of the loss cone and be a quarter of bounce period in the loss cone.
The observed spectral distribution of chorus waves in the spatial range $L = 5.8 \pm 0.3$ of five continuous orbits exhibited considerable spatiotemporal variability, as shown in Figure 3a (dots). The average spectral property of chorus waves in this time range is approximately modeled by a Gauss-type spectral distribution with an amplitude $B_w = 60$ pT, a center $\omega_m = 0.35[\Omega_e]$, a half width $\Delta \omega = 0.12[\Omega_e]$, a lower cutoff $\omega_1 = 0.05[\Omega_e]$, and an upper cutoff $\omega_2 = 0.75[\Omega_e]$, as shown in Figure 3a (line). The modeled spectral distribution has the moderate power density and roughly covers the same frequency range as that of observed waves. Near the lower frequency limit, the observed occurrence rate of weak waves was relatively high; around the central frequency, relatively high occurrence rate of strong waves can be observed; near the upper frequency limit, the observed occurrence rate of strong waves significantly decreased. The wave normal angle distribution is also assumed to obey the typical Gauss-type distribution with a center $\theta_m = 0^\circ$, a half width $\Delta \theta = 15^\circ$, a lower cutoff $\theta_1 = 0^\circ$, and an upper cutoff $\theta = 45^\circ$. These waves are further assumed to spread in the spatial range $|\lambda| \leq 15^\circ$ and $0 \leq MLT \leq 6$. Note that these wave parameters are similar to those of nightside chorus wave model [e.g., Horne et al., 2005a; Li et al., 2007; Ni et al., 2008; Albert et al., 2009]. The ratio $\omega_{pe}/[\Omega_e]$ is set to be 4.6 based on the dipolar model and the electron density model of Carpenter and Anderson [1992]. Figures 3b–3d show the distribution of calculated bounce-averaged diffusion coefficients in the range of $0^\circ \leq \alpha_{eq} \leq 90^\circ$ and $0.2 \text{ MeV} \leq E_k \leq 5.0 \text{ MeV}$, comparable to the previous calculations [e.g., Li et al., 2007; Summers et al., 2007; Albert et al., 2009].

The initial PSD is specified as a kappa-type distribution

$$f(\alpha_e, E_k)|_{\omega=0} = C \frac{E_k^{\kappa}}{\rho^2} \left(1 + \frac{E_k}{\kappa E_0}\right)^{-\kappa-1} \sin^\nu \alpha_e,$$

where $C$ is a constant, $\kappa = 9$ and $E_0 = 0.05 \text{ MeV}$ are chosen to fit the observed energy spectrum, $n = 2$ is the pitch angle index at $L = 5.8$ [see Thorne et al., 2005]. The boundary conditions are set to be

$$\frac{\partial f}{\partial \alpha_e}|_{\omega=0^\circ} = \frac{\partial f}{\partial \alpha_e}|_{\omega=90^\circ} = 0,$$

$$f|_{E_k=0.2 \text{MeV}} = \text{constant}, \quad f|_{E_k=5.0 \text{MeV}} = \text{constant}$$

The comparison between RBSP-B-observed and STEERB-simulated energy spectrums around $L = 5.8$ is presented in Figure 4. The spectrums observed by ECT-Magnetic Electron Ion Spectrometer (MagEIS) and ECT-Relativistic Electron Proton Telescope (REPT) had a mismatch around $E_k = 2.0 \text{ MeV}$, which was caused by the difference in response functions at the high-energy end of MagEIS [Blake et al., 2013] and the low-energy end of REPT [Baker et al., 2013a]. We generally trust the MagEIS data in the low-energy ($\sim < 2.0 \text{ MeV}$) range and the REPT data in the high-energy ($\sim > 2.0 \text{ MeV}$) range. In the first orbit (black), the simulations agree well with the observations except around the energy $E_k = 2.0 \text{ MeV}$. In the fifth orbit (red), the simulations basically reflect the observed characteristics of energy spectrum, suggesting that the chorus waves substantially accounted for the nonstorm time buildup of radiation belt electron fluxes. It should be noted that, compared to the observations, the simulations indeed show some overestimation at the low energies ($\sim 0.4–1.5 \text{ MeV}$) and underestimation at the high energies ($\sim 1.5–3.0 \text{ MeV}$), which may be caused by the inaccuracy of wave model constructed based on limited observations.
4. Conclusions and Discussions

Storm time electron radiation belt dynamics have been widely investigated for many years, and the strength of storm time has been found to possess poor correlation with the net changes of energetic electron fluxes [Reeves et al., 2003]. Here we report a nonstorm time event of electron radiation belt evolution observed by the Van Allen Probes from 21 to 24 February 2013. Within 2 days, a new belt centered around $L = 5.8$ (near the outer boundary of the original outer belt) formed and gradually merged with the original belt. In the region $L > 5$, the relativistic electron fluxes increased by a factor of up to 50. These results clearly illustrate that the electron radiation belt can exhibit dramatic variabilities not only during storm times but also during nonstorm times and that the radiation belt environment should be closely monitored for the space weather applications even in nonstorm times.

We further identify a potential acceleration mechanism responsible for the current nonstorm time enhancement of energetic electron fluxes through the quantitative comparison between STEERB simulations and RBSP observations. In the region $L \sim 5$, strong chorus waves (with power spectral density up to $10^{-10}$ Hz) were observed. The modeled wave parameters are input into the two-dimensional STEERB code to determine chorus-driven electron radiation belt evolution at $L = 5.8$. In about 2 days, the energy spectrums simulated by STEERB model are found to show reasonable agreement with those observed by RBSP-B satellite, suggesting that the local acceleration by chorus waves was the dominant acceleration mechanism for this nonstorm time event.

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