

Global distribution of reversed energy spectra of ring current protons based on Van Allen Probes observations

Juan Yi¹, Song Fu¹, Binbin Ni¹, Xudong Gu¹, Man Hua¹, Zheng Xiang¹, Xing Cao¹, Run Shi¹, and Yiwen Zhao¹

¹Wuhan University

November 24, 2022

Abstract

Energy spectra of ring current protons are crucial to understanding the ring current dynamics. Based on high-quality Van Allen Probes RBSPICE measurements, we investigate the global distribution of the reversed proton energy spectra using the 2013-2016 RBSPICE datasets. The reversed proton energy spectra are characterized by the distinct flux minima around 50 - 100 keV and flux maxima around 200 - 400 keV. Our results show that the reversed proton energy spectrum is prevalent inside the plasmasphere, with the occurrence rates > 90% at $L \sim 2 - 4$ during geomagnetically quiet periods. Its occurrence also manifests a significant decrease trend with increasing L-shell and enhanced geomagnetic activity. It is indicated that the substorm-associated processes are likely to lead to the disappearances of the reversed spectra. These results provide important clues for exploring the underlying physical mechanisms responsible for the formation and evolution of reversed proton energy spectra.

Global distribution of reversed energy spectra of ring current protons based on Van Allen Probes observations

Juan Yi¹, Song Fu^{1*}, Binbin Ni^{1,2*}, Xudong Gu¹, Man Hua¹, Zheng Xiang¹,
Xing Cao¹, Run Shi¹, and Yiwen Zhao¹

¹ Department of Space Physics, School of Electronic Information, Wuhan University, Wuhan, China

² CAS Center for Excellence in Comparative Planetology, Hefei, China

Corresponding authors: Drs. Song Fu and Binbin Ni, Wuhan University

Email: fusion@whu.edu.cn, bbni@whu.edu.cn

Key Points:

- The reversed energy spectra of ring current protons were observed by RBSPICE to show the distinct flux minima $\sim 50 - 100$ keV and flux maxima $\sim 200 - 400$ keV.
- The reversed proton energy spectra mostly occur inside the plasmasphere during geomagnetically quiet periods.
- The global distributions of reversed proton energy spectra suggest the underlying contributions of various physical processes.

Abstract

Energy spectra of ring current protons are crucial to understanding the ring current dynamics. Based on high-quality Van Allen Probes RBSPICE measurements, we investigate the global distribution of the reversed proton energy spectra using the 2013-2016 RBSPICE datasets. The reversed proton energy spectra

are characterized by the distinct flux minima around 50 - 100 keV and flux maxima around 200 - 400 keV. Our results show that the reversed proton energy spectrum is prevalent inside the plasmasphere, with the occurrence rates $> 90\%$ at $L \sim 2 - 4$ during geomagnetically quiet periods. Its occurrence also manifests a significant decrease trend with increasing L-shell and enhanced geomagnetic activity. It is indicated that the substorm-associated processes are likely to lead to the disappearances of the reversed spectra. These results provide important clues for exploring the underlying physical mechanisms responsible for the formation and evolution of reversed proton energy spectra.

Plain language summary

The energy spectra of ring current protons are significant for us to understand the ring current dynamics. Several previous studies reported the reversed energy spectra of ring current protons that represent flux minima at lower energies and flux maxima at higher energies. In the literature, there is rather limited statistical investigation on the global distribution features of such spectra. The availability of high quality Van Allen Probes RBSPICE data enables a comprehensive study in this regard. Based on RBSPICE measurements, we report the reversed energy spectra of ring current protons particularly featured by the distinct flux minima around 50 - 100 keV and flux maxima around 200 - 400 keV. We further adopt 4-year RBSPICE proton datasets from 2013 to 2016 to investigate the occurrence rate, corresponding energies of flux maximum and minimum, and the ratio of flux maximum to minimum as a function of L shell, MLT and geomagnetic activity level. Our results demonstrate that these reversed proton energy spectra are prevalent inside the plasmasphere, with the occurrence rates $> 90\%$ at $L \sim 2 - 4$ during geomagnetically quiet periods. The strong L and geomagnetic activity dependence imply the physical processes in association with proton substorm injections.

1. Introduction

Energy spectrum distributions of energetic particles are an essential indicator for understanding the underlying physics of magnetospheric particle dynamics. In general, it is well recognized that both electron and proton energy spectra in space plasmas follow a Kappa or Kappa-like profile having fluxes steeply falling with increasing energy (e.g., Freden, 1965; Pizzella et al., 1962; Summers et al., 2009). In contrast, a number of previous studies reported ‘reversed’ energy spectra of energetic particles that do not follow monotonically decrease profiles of fluxes with increasing energy but represent flux minima at lower energies and flux maxima at higher energies. Based on the Molniya 1 measurements, Vakulov et al. (1975) observed a flux maximum of the outer belt electron energy spectra at energy $\sim 1 - 2$ MeV. West et al. (1981), using 60 keV to 3 MeV electron data from Ogo5, showed a flux maximum at ~ 1.5 MeV and a minimum at ~ 500 keV. By analyzing the ring current proton spectra (1 - 300 keV) observed by the Explorer 45, Williams et al. (1973) reported the flux minima of proton energy spectra at energies $\sim 20 - 100$ keV over $L \sim 3.2 - 4.0$, which they attributed to the ion-cyclotron instability. Based on the AMPET CCE measurements, Krimigis et al. (1985) observed the flux maxima at energies $\sim 100 - 300$ keV during both the main and recovery phases of a geomagnetic storm.

Along with the launch of the twin Van Allen Probes mission in August 2012 (Mauk et al., 2012), the long-term accumulation of unprecedented, high quality particle datasets with fine energy resolutions has fueled a resurgence in magnetospheric particle dynamics studies. By combining the MagEIS and REPT measurements, Zhao et al. (2019a) reported a reversed energy spectrum of radiation belt electrons, which is featured by the flux maximum $\sim 1 - 2$ MeV and flux minimum ~ 100 's keV and is reasonably accounted for energy-dependent electron losses induced by hiss wave (e.g., Ni et al., 2019; Fu et al., 2020). A following statistical analysis of Zhao et al. (2019b), on basis of the detailed analysis of reversed electron energy spectra, found that reversed energy spectra dominate inside the plasmasphere at $L < 2.5$.

Comparatively, there remains lacking the systematic information about the global distribution of the reversed energy spectra of ring current protons. The availability of Van Allen Probes RBSPICE data enables a comprehensive study in this regard. Therefore, this letter is dedicated to investigate the global distribution of reversed proton energy spectra based upon multi-year RBSPICE data from Van Allen Probes. By establishing

an automatic identification criterion for the reversed proton energy spectra, we intend to perform a statistical analysis to explore the global distribution features of the reversed proton energy spectrum, its occurrence pattern, its dependence on geomagnetic activity, and its profile characteristics in terms of the energy range of local flux minimum and the ratio of local flux maximum to minimum.

2. Instrumentation and Datasets

The Van Allen Probes, launched in August 2012, consist of two identical satellites and operate in almost same orbits with perigees of ~ 600 km, inclination of $\sim 10^\circ$, apogees of ~ 5.8 Earth radii (R_E) and spin period of ~ 11 s (Mauk et al., 2012). The Radiation Belt Storm Probes Ion Composition Experiment (RBSPICE) instrument onboard the Van Allen Probes, which are designed to obtain a comprehensive physical understanding of ring current, provides measurements of protons in the energy range of $\sim 7 - 600$ keV (Mitchell et al., 2013). The level 3-PAP data with pitch angle information are adopted in this study. Due to the high-voltage issues during the early phase of the emission of RBSPICE-A, we only adopted the data from RBSPICE-B in the present study (Summers et al., 2017). The L shell used in this study is McIlwain L calculated with IGRF and OP77Q (Olson and Pfitzer, 1982) magnetic field model.

3. Observations and Statistical Results

Figure 1 displays the observations of proton fluxes during 16 - 30 March, 2015. The solar wind parameters and geomagnetic indices obtained from the OMNIweb are plotted in Figures 1a-b. On 17 March 2015 when an intense geomagnetic storm occurred, the solar wind speed jumped from ~ 400 to ~ 600 km/s and the interplanetary magnetic field (IMF) B_z turned quickly from northward (~ 15 nT) to southward (~ -15 nT). The Dst index dropped from ~ 30 to ~ -220 nT with the AE index increasing significantly from ~ 100 to 1500 nT. At the same time, the RBSPICE onboard the Van Allen Probe B observed evident proton flux increases at energies of 44.7 and 81.6 keV (Figures 1c-d). However, the enhancements of 268.9 keV proton fluxes did not occur until 18 March. The black solid lines in Figures 1c-e indicate the plasmopause location calculated using Liu et al., (2015) model. In Figures 1c-d, the proton fluxes outside the plasmasphere are higher than those inside the plasmasphere during quiet times. During the recovery phase after 18 March, 44.7 and 81.6 keV proton fluxes at lower L ($\sim 2 - 4$) gradually decreased while the 268.9 keV proton fluxes increased and then remained relatively stable. Figures 1f-h further show the proton energy spectra at the indicated time intervals. As shown in Figure 1f, the proton fluxes generally decreased monotonically with increasing energy over L $\sim 3.0 - 5.6$. However, several days later (Figures 1g-h), the proton energy spectra at L $< \sim 5.2$ exhibited “reversed” structures with fluxes decay more significantly at low energies $< \sim 200$ keV, leading to flux minima at energies ~ 80 keV. These flux minima reduced with decreasing L shells.

Figure 2 illustrates some key parameters of the reversed proton energy spectra. This representative example occurred at 02:04:47 on 29 March 2015 at L = 3.15. In this example, proton energy spectrum has a clear flux minimum (f_{\min}) at $E_{\min} \sim 82$ keV and a flux maximum (f_{\max}) at $E_{\max} \sim 221$ keV with the ratio of flux maximum to minimum reaching ~ 60 . To automatically identify the reversed proton energy spectra, we adopted three criteria: (1) proton energy spectra show the existence of the maximum and minimum, and the corresponding energy of flux maximum (E_{\max}) is greater than that of flux minimum (E_{\min}), (2) $\frac{f_{\max}}{f_{\min}} > 3$, and (3) there must be at least one energy channel between the E_{\max} and E_{\min} to avoid the misclassification.

To further investigate the relation between the geomagnetic activities and the reversed proton spectra in a long period, we present the geomagnetic indices and proton fluxes with three energy channels (44.7, 81.6 and 268.9 keV) during 2015 in Figures 3a-d with the white solid lines representing plasmopause locations. When the Dst index suddenly decreased and the AE index increased, the locations of plasmopause were reduced to lower L ($\sim 2 - 3$). For 44.7 and 81.6 keV protons, the fluxes outside the plasmasphere are ~ 1 order of the magnitude higher than those inside the plasmasphere in most cases, yet this is opposite to the fluxes of 268.9 keV protons. While inside the plasmasphere, the proton fluxes at energies 44.7 and 268.9 keV are generally 1-2 orders higher than those at energies 81.6 keV. With increasing energy, the proton energy spectra are going to show the decreasing and then increasing trend which is the reversed feature depicted in Figure 2. Figures 3e-h demonstrate the key parameters of automatically selected reversed proton energy spectra. The

occurrence rate of the reversed proton energy spectra is calculated with the grids of 0.1 L and one day. The locations of plasmapauses match well with the upper boundaries of the region with the occurrence rate > 90%. During quiet times, the plasmapauses usually locate at $L > 4.5$ so that the reversed proton energy spectra locate at $L \sim 2 - 4$. We find that the proton reversed energy spectra are likely to be observed under active geomagnetic conditions ($Dst > -50$ nT and the AE > 1000 nT). As shown in Figures 3f-h, the proton energies of flux maxima mostly lie in the range of ~ 82 -400 keV, decreasing with increasing L shells. Similarly, the proton energies of flux minima for reversed energy spectra are tens of keV. Note that there still are a few events which distribute outside the plasmasphere at $L > \sim 4.5$ with $E_{\max} > 328$ keV and $E_{\min} > 100$ keV. Figure 3f reveals that the flux maxima are ~ 10 to 30 times greater than the flux minima at $L < 4$, while the ratios decrease from ~ 10 to 3 with increasing L shells at $L > 4$.

Figure 4 shows the global distributions of reversed proton energy spectra as a function of L shell and MLT for three indicated geomagnetic conditions ($Dst > -30$ nT, -50 nT < $Dst < -30$ nT and $Dst < -50$ nT) from January 2013 to December 2016. From top to bottom, each row presents the number of total samples, occurrence rate, the corresponding energies of flux maximum and minimum, and the ratio of flux maximum to minimum. The region of our interest has been divided into smaller bins with the resolution of $0.5 L \times 1$ MLT, and the blank bins means the observational samples are less than 50. Both the E_{\max} , E_{\min} , and the ratio of flux maximum to minimum in Figures 4g-o are valued by averaging the cases in one bin. Most samples are observed during quiet times ($Dst > -30$ nT) at $L \sim 2.5 - 4.5$ (Figure 4a). The reversed proton spectra almost persistently exist over $L \sim 2 - 4$ during quiet times, with occurrence rates >90%. Besides, the occurrence rates decrease with increasing L shells, which is consistent with the observations shown in Figure 1, and decreases under more active geomagnetic activities. The upper boundary of higher occurrence rate (>90%) regions shift from higher to lower L shells. Regarding to the MLT dependence, we find that the occurrence rates on the dayside are slightly higher than those of nightside, especially during the geomagnetically active periods ($Dst < -50$ nT). In Figures 4g-l, the statistical distributions of the E_{\max} and E_{\min} demonstrate that the proton fluxes mostly reach the peaks at energies $\sim 200 - 400$ keV and drop to the valleys at energies $\sim 50 - 100$ keV. Both E_{\max} and E_{\min} decrease first as the L shell increases to ~ 5 , while they suddenly increase on two MLT sectors (15-19, 22-05) at $L > 5$ with relatively small samples. In addition, the statistics of E_{\max} and E_{\min} show a less geomagnetic activity dependence. The ratios decrease with the increasing L shells, which are smaller under the more active geomagnetic conditions (Figures 4m-o).

4. Discussions

Our results show that the reversed proton spectra are preferentially inside the plasmasphere and show significant losses of lower energy ($\sim 50 - 100$ keV) protons after the geomagnetic storm (Figures 1f-h). It is significant for us to further understand the mechanisms that produce the reversed proton energy spectra. There are several possible explanations for the formation of the reversed proton energy spectra.

Firstly, charge exchange is found to be the main loss process of ring current protons by capturing electrons from neutral atoms (Ebihara & Ejiri, 2003; Dessler & Parker, 1959; Smith & Bewtra, 1976). The lifetime of proton due to charge exchange is shortest at energies around tens of keV with the value of 0.2 – 1 day (Fok et al., 1991). This energy range is consistent with our statistical distributions of E_{\min} in reversed proton spectra. Furthermore, the densities of neutral hydrogen are higher at lower L shells (Østgaard et al., 2003). Thus, the loss effect due to charge exchange is stronger at lower L shells. We also find that the reversed proton energy spectra show a high occurrence at low L shells ($L=2 - 4$). These agreements in spatial distribution suggest that charge exchange plays an important role in the formation of reversed proton energy spectral.

Another candidate for the loss of protons is Coulomb collision (Fok et al., 1996; Jordanova et al., 1996, 1999). When particles travel through the plasma, they will loss energy or change pitch angles due to collisions with other particles. Similar to charge exchange, Coulomb collision also likes to occur in lower L shells (Fok et al., 1991). However, this process is dominant in decreasing the proton fluxes at low-energies (< 10 keV) (Fok et al., 1996) and is not likely to produce the reversed proton energy spectra with local minima at energies $\sim 50 - 100$ keV.

There are also two collisionless scattering mechanisms for the ring current decay: wave-particle interactions and field line curvature (FLC) scattering. The electromagnetic ion cyclotron (EMIC) waves can effectively scatter several keV to hundreds of keV protons into the loss cone due to pitch angle diffusion with a time scale of a few hours (Cao et al., 2019, 2020; Cornwall, 1977; Jordanova et al., 1997; Xiao et al., 2011; Summers, 2005). The field line curvature scattering is of importance for the ring current decay when the field line configuration is stretching (Chen et al., 2019; Ebihara et al., 2011; Sergeev et al., 1993; Yu et al., 2020). Yu et al. (2020) investigated the role of FLC scattering in ring current decay during the 17 March 2013 storm and found that the associated proton precipitation mainly occurs at $L > 5$ on the nightside. This finding is basically consistent with our observations that the reversed proton energy spectra are distributed at $L > 5$ on two MLT sectors (15-19, 22-05). The formation mechanism of reversed energy spectra at $L > 5$ may be different from those at $L < 5$.

Although several loss mechanisms have been proposed to explain the decay of Earth's ring current. The relative contributions of difference mechanisms to the formation of the reversed proton energy spectra still remain to be fully understood, which however is outside the scope of this study and is left to a future study.

5. Conclusions

In this study, based on the high-resolution proton flux data from RBSPICE onboard the Van Allen Probe B during 2013 – 2016, we have performed a detailed statistical analysis of the global distribution of reversed energy spectra of ring current protons. The major conclusions are summarized as follows:

- (1) The reversed proton energy spectra are preferentially observed inside the plasmasphere, with the occurrence rates $> 90\%$ at $L \sim 2 - 4$ during geomagnetically quiet periods. As the geomagnetic activity intensifies, the preferential occurrence region of the reversed proton energy spectra shrinks to lower L shells ($\sim 2.5 - 3.5$).
- (2) The proton energies corresponding to the flux maxima and minima of the reversed energy spectra decrease with the increase of L shell in the region of $L < 5$. The flux minima of the reversed proton spectra mainly occur at $\sim 50 - 100$ keV, while the flux maxima are generally present at $\sim 200 - 400$ keV.
- (3) Similar to the global distribution of the reversed spectrum occurrence rate, the ratios between flux maxima and minima are strongly L shell and geomagnetic activity dependent, showing that the ratios during active times and at higher L shells are smaller than those during quiet times and at lower L shells.

Acknowledgments

This work was supported by the National Natural Science Foundation of China (grant nos. 42025404, 41674163, 41704162, 41974186, 41674162, 41904144, 41904143), the B-type Strategic Priority Program of the Chinese Academy of Sciences (grant no. XDB41000000), the pre-research projects on Civil Aerospace Technologies (grant nos. D020303, D020308, D020104) funded by the China National Space Administration, the National Key R&D Program of China (2018YFC1407303) and the China Postdoctoral Science Foundation Project (grant no. 2019M662700). We also acknowledge the Van Allen Probes mission, particularly the RBSPICE team, for providing particle data. at <http://rbspice.ftcs.com>. Profiles of the solar wind parameters and geomagnetic indices are from the OMNI website (<http://omniweb.gsfc.nasa.gov>).

References

- Cao, X., Ni, B., Summers, D., Shprits, Y. Y., Gu, X., Fu, S., Lou, Y., Zhang, Y., Ma, X., Zhang, W., Huang, H., & Yi, J. (2019). Sensitivity of EMIC wave-driven scattering loss of ring current protons to wave normal angle distribution. *Geophysical Research Letters*, 46, 590–598. <https://doi.org/10.1029/2018GL081550>
- Cao, X., Ni, B., Summers, D., Shprits, Y. Y., & Lou, Y. (2020). Effects of polarization reversal on the pitch angle scattering of radiation belt electrons and ring current protons by EMIC waves. *Geophysical Research Letters*, 47, e2020GL089718. <https://doi.org/10.1029/2020GL089718>
- Fok, M.-C., Kozyra, J. U., Nagy, A. F., & Cravens, T. E. (1991). Lifetime of ring current particles due to coulomb collisions in the plasmasphere. *Journal of Geophysical Research*, 96(A5), 7861–7867.

<https://doi.org/10.1029/90JA02620>

Fok, M.-C., Moore, T. E., & Greenspan, M. E. (1996). Ring current development during storm main phase. *Journal of Geophysical Research*, 101(A7), 15,311– 15,322. <https://doi.org/10.1029/96JA01274>

Fu, S., Yi, J., Ni, B., Zhou, R., Hu, Z., Cao, X., et al. (2020). Combined scattering of radiation belt electrons by low frequency hiss: Cyclotron, Landau, and bounce resonances. *Geophysical Research Letters*, 47, e2020GL086963. <https://doi.org/10.1029/2020GL086963>

Freden, S. C., Blake, J. B., & Paulikas, G. A. (1965). Spatial variation of the inner zone trapped proton spectrum. *Journal of Geophysical Research*, 70(13), 3113– 3116. <https://doi.org/10.1029/JZ070i013p03113>

Jordanova, V. K., Kozyra, J., Nagy, A., & Khazanov, G. (1997). Kinetic model of the ring current-atmosphere interactions. *Journal of Geophysical Research*, 102(A7), 14,279–14,291. <https://doi.org/10.1029/96JA03699>

Krimigis, S. M., McEntire, R. W., Potemra, T. A., Gloeckler, G., Scarf, F. L., & Shelley, E. G. (1985). Magnetic storm of September 4, 1984—A synthesis of ring current spectra and energy densities measured with AMPTE/CCE. *Geophysical Research Letters* (ISSN 0094-8276), 12, 329–332. <http://doi.org/10.1029/GL012i005p00329>

Liu, X., Liu, W., Cao, J. B., Fu, H. S., Yu, J., & Li, X. (2015). Dynamic plasmopause model based on THEMIS measurements. *Journal of Geophysical Research: Space Physics*, 120, 10,543–10,556. <https://doi.org/10.1002/2015JA021801>

Mauk, B. H., Fox, N. J., Kanekal, S. G., Kessel, R. L., Sibeck, D. G., & Ukhorskiy, A. (2012). Science objectives and rationale for the Radiation Belt Storm Probes mission. *Space Science Reviews*, 1–15. <https://doi.org/10.1007/s11214-012-9908-y>

Mitchell, D. G., Lanzerotti, L. J., Kim, C. K., Stokes, M., Ho, G., Cooper, S., ... Kerem, S. (2013). Radiation belt storm probes ion composition experiment (RBSPICE). *Space Science Reviews*, 179. <https://doi.org/10.1007/s11214-013-9995-4>

Ni, B., Huang, H., Zhang, W., Gu, X., Zhao, H., Li, X., Baker, D. N., Fu, S., Xiang, Z., & Cao, X. (2019). Parametric sensitivity of the formation of reversed electron energy spectrum caused by plasmaspheric hiss. *Geophysical Research Letters*, 46, 4134–4143. <https://doi.org/10.1029/2019GL082032>

Olson, W. P., & Pfizter, K. A. (1982). A dynamic model of the magnetospheric magnetic and electric fields for July 29, 1977. *Journal of Geophysical Research*, 87, 5943–5948. <https://doi.org/10.1029/JA087iA08p05943>

Ostgaard, N., Mende, S. B., Frey, H. U., Gladstone, G. R., & Lauche, H. (2000). Neutral hydrogen density profiles derived from geocoronal imaging. *Journal of Geophysical Research Space Physics*, 108, 1300.

Pizzella, G., Laughlin, C. D., & O'Brien, B. J. (1962). Note on the electron energy spectrum in the inner Van Allen Belt. *Journal of Geophysical Research*, 67(9), 3281–3287. <https://doi.org/10.1029/JZ067i009p03281>

Summers, D. (2005). Quasi-linear diffusion coefficients for field-aligned electromagnetic waves with applications to the magnetosphere. *Journal of Geophysical Research*, 110, A08213. <https://doi.org/10.1029/2005JA011159>

Summers, D., Tang, R., & Thorne, R. M. (2009). Limit on stably trapped particle fluxes in planetary magnetospheres. *Journal of Geophysical Research*, 114, A10210. <https://doi.org/10.1029/2009JA014428>

Summers, D., Shi, R., Engebretson, M. J., Oksavik, K., Manweiler, J. W., & Mitchell, D. G. (2017). Energetic proton spectra measured by the Van Allen Probes. *Journal of Geophysical Research: Space Physics*, 122, 10,129–10,144. <https://doi.org/10.1002/2017JA024484>

Vakulov, P. V., Kovrygina, L. M., Mineev, I. V., & Tverskaia, L. V. (1975). Dynamics of the outer belt of energetic electrons during moderate magnetic disturbances. *Geomagnetizm I Aeronomiia*, 15, 1028–1032.

West, H. I. Jr., Buck, R. M., & Davidson, G. T. (1981). The dynamics of energetic electrons in the Earth's outer radiation belt during 1968 as observed by the Lawrence Livermore National Laboratory's spectrometer on Ogo 5. *Journal of Geophysical Research*, 86(A4), 2111–2142. <https://doi.org/10.1029/JA086iA04p02111>

Williams, D. J., Fritz, T. A., & Konradi, A. (1973). Observations of proton spectra (1.0 [?] Ep [?] 300 keV) and fluxes at the plasmopause. *Journal of Geophysical Research*, 78, 4751–4755. <https://doi.org/10.1029/JA078i022p04751>

Xiao, F., Chen, L., He, Y., Su, Z., & Zheng, H. (2011). Modeling of precipitation loss of ring current protons by electromagnetic ion cyclotron waves. *Journal of Atmospheric and Solar - Terrestrial Physics*, 73, 106–111. <https://doi.org/10.1016/j.jastp.2010.01.007>

Zhao, H., Ni, B., Li, X., Baker, D. N., Johnston, W. R., Zhang, W., et al. (2019a). Plasmaspheric hiss waves generate a reversed energy spectrum of radiation belt electrons. *Nature Physics*, 15(4), 367–372. <https://doi.org/10.1038/s41567-018-0391-6>

Zhao, H., Johnston, W. R., Baker, D. N., Li, X., Ni, B., Jaynes, A. N., Kanekal, S. G., Blake, J. B., Claudepierre, S. G., Reeves, G. D., & Boyd, A. J. (2019). Characterization and evolution of radiation belt electron energy spectra based on the Van Allen Probes measurements. *Journal of Geophysical Research: Space Physics*, 124, 4217–4232. <https://doi.org/10.1029/2019JA026697>

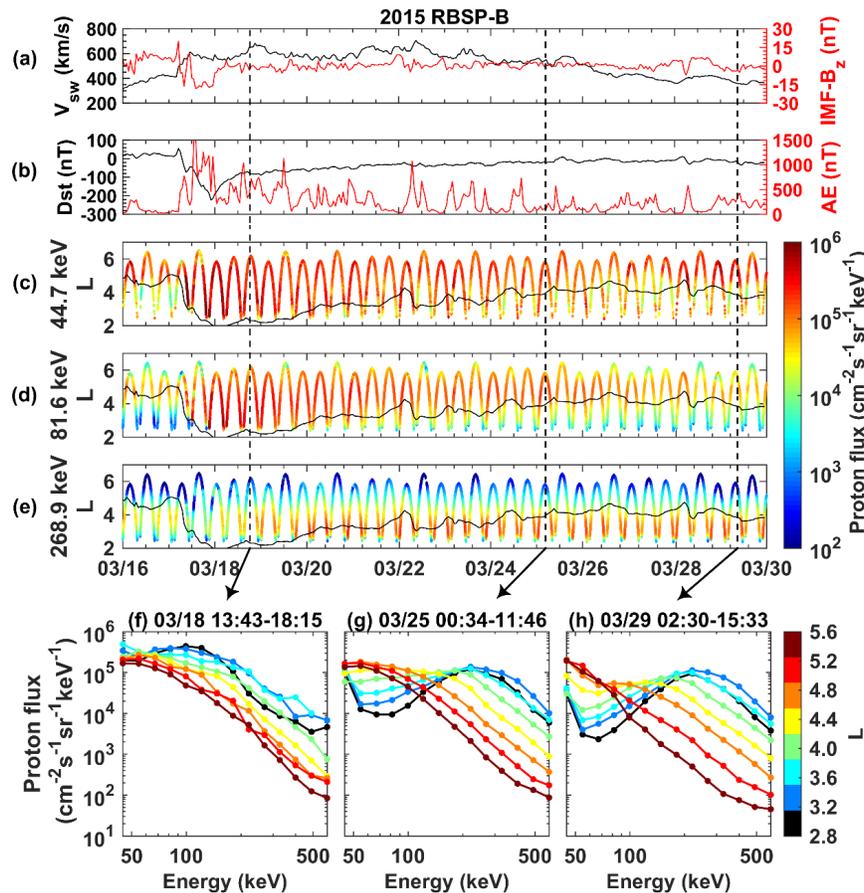


Figure 1. An overview of the 17 March 2015 strong geomagnetic storm. (a) solar wind speed (V_{sw}) and interplanetary magnetic field (IMF) B_z , (b) Dst and AE indices, (c-e) 90° pitch angle proton fluxes at energies

of ~ 44.7 keV, ~ 81.6 keV, and ~ 268.9 keV, respectively, with the black solid lines indicating the plasmopause location. (f-h) The proton energy spectra at $L \sim 2.8 - 5.6$ during three indicated time intervals of the storm.

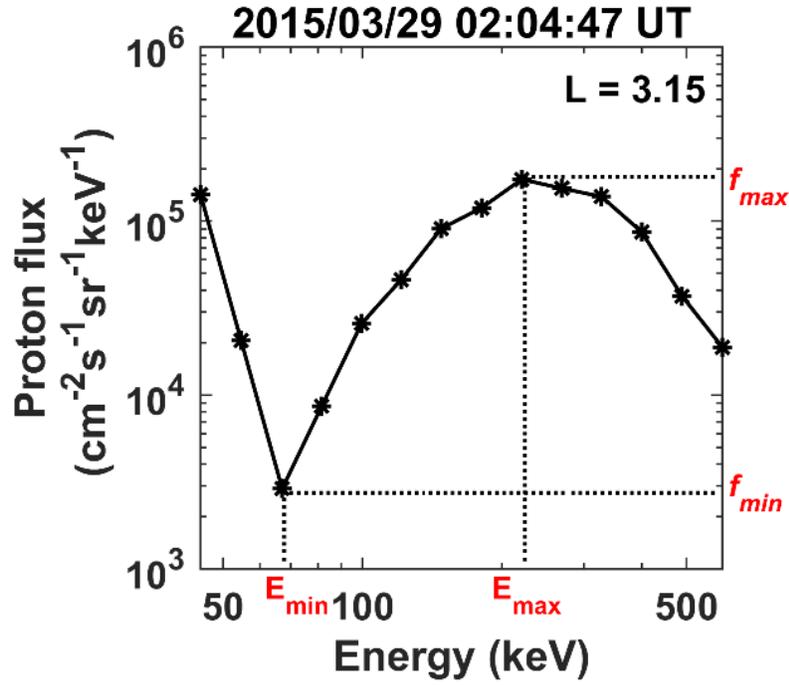


Figure 2. A representative example of the reversed proton energy spectrum at $L = 3.15$ based on the RBSPICE measurements at 02:04:47 UT on 29 March 2015. Four characteristic parameters of the reversed energy spectrum, i.e., flux maximum (f_{\max}), flux minimum (f_{\min}), the energy of flux maximum (E_{\max}), and the energy of flux minimum (E_{\min}), are defined on the plot.

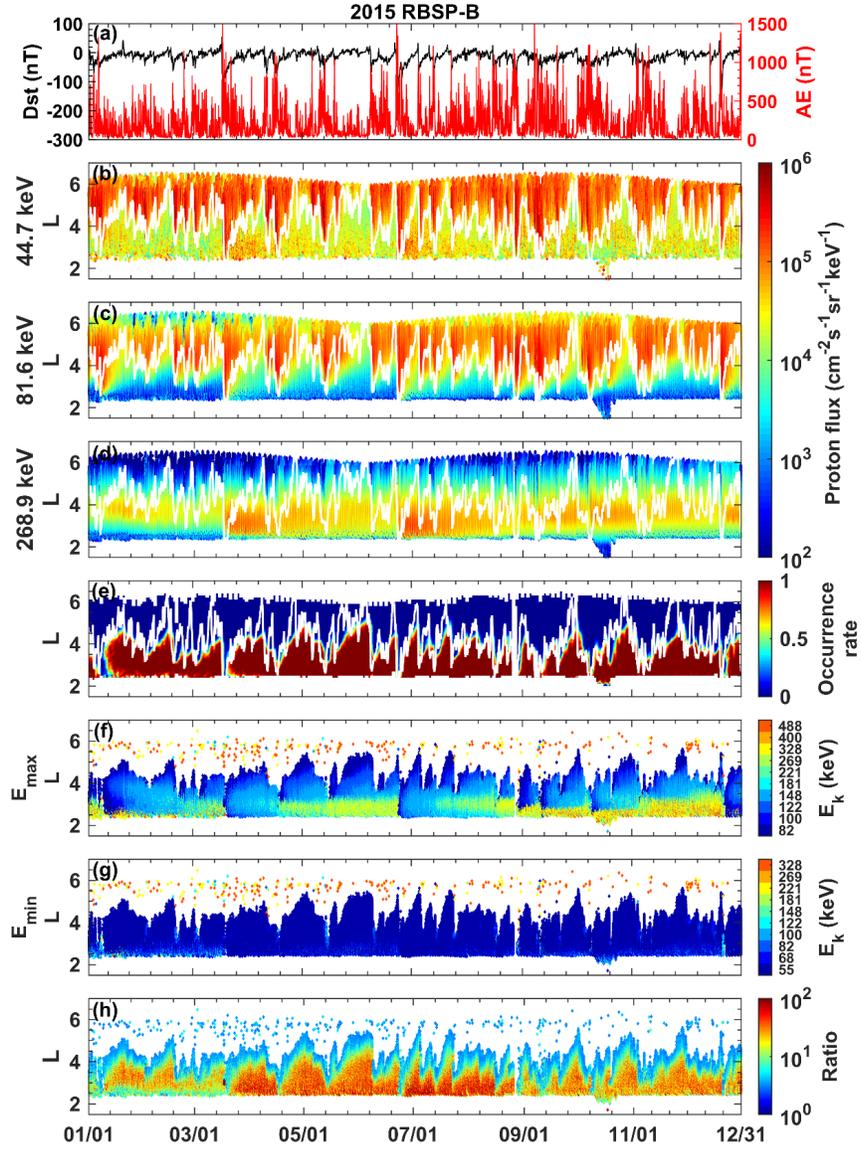


Figure 3. RBSPICE observations of proton fluxes during 2015 and the corresponding distributions of reversed proton energy spectra. (a) Dst and AE indices, (b-d) 90° pitch angle proton fluxes at energies of ~ 44.7 keV, ~ 81.6 keV, and ~ 268.9 keV, respectively, (e) occurrence rate of the reversed proton energy spectrum, (f) the proton energy of flux maximum, (g) the proton energy of flux minimum, and (h) the ratio of proton flux maximum to minimum. The white solid lines in (b-e) indicate the plasmapause location.

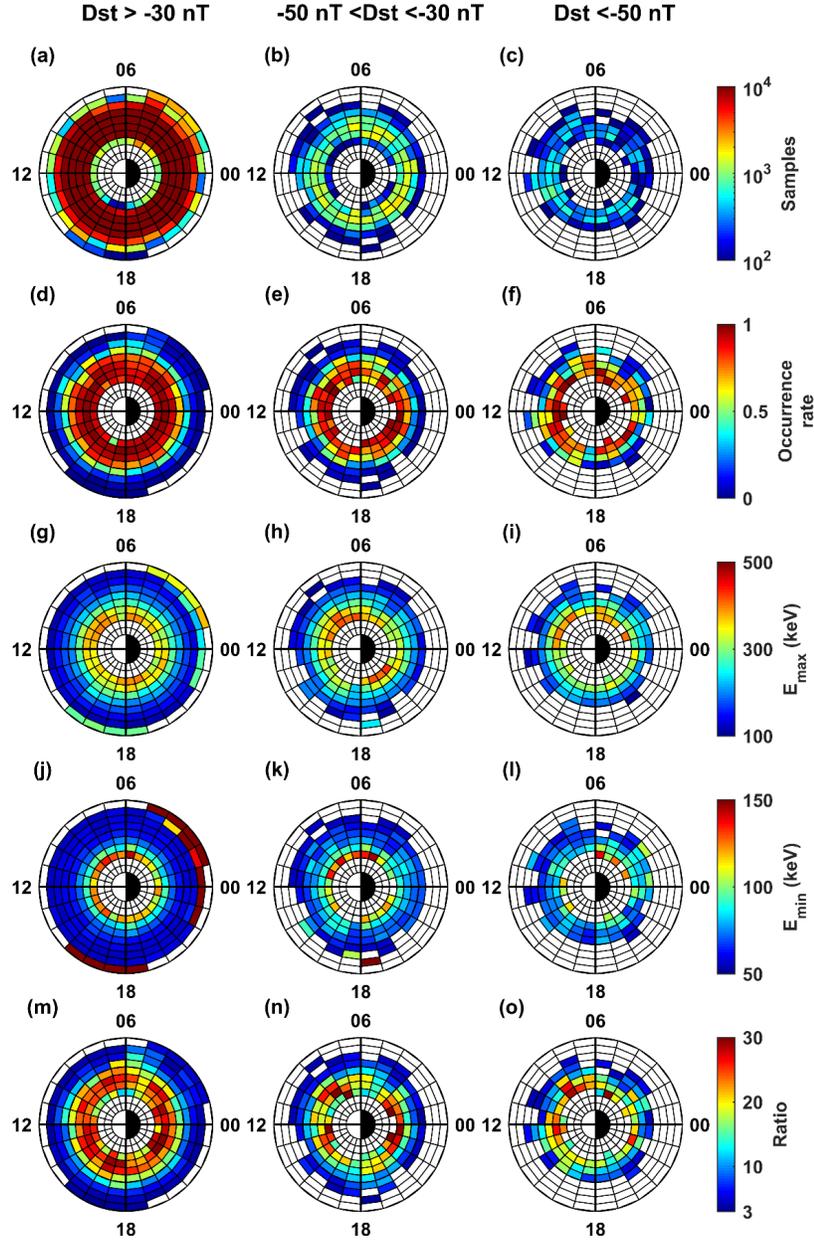


Figure 4. Statistical results of the global distribution of reversed proton energy spectrum during 2013-2016 under the indicated three geomagnetic conditions (from left to right: $Dst > -30$ nT, -50 nT $< Dst < -30$ nT, and $Dst < -50$ nT). (a-c) samples, (d-f) occurrence rate, (g-i) the proton energy of flux maximum, (j-l) the proton energy of flux minimum, and (m-o) the ratio of the proton flux maximum to minimum.

29

30 **Abstract**

31 Energy spectra of ring current protons are crucial to understanding the ring
32 current dynamics. Based on high-quality Van Allen Probes RBSPICE measurements,
33 we investigate the global distribution of the reversed proton energy spectra using the
34 2013-2016 RBSPICE datasets. The reversed proton energy spectra are characterized
35 by the distinct flux minima around 50 - 100 keV and flux maxima around 200 - 400
36 keV. Our results show that the reversed proton energy spectrum is prevalent inside the
37 plasmasphere, with the occurrence rates $> 90\%$ at $L \sim 2 - 4$ during geomagnetically
38 quiet periods. Its occurrence also manifests a significant decrease trend with
39 increasing L-shell and enhanced geomagnetic activity. It is indicated that the
40 substorm-associated processes are likely to lead to the disappearances of the reversed
41 spectra. These results provide important clues for exploring the underlying physical
42 mechanisms responsible for the formation and evolution of reversed proton energy
43 spectra.

44

45

46 **Plain language summary**

47 The energy spectra of ring current protons are significant for us to understand the
48 ring current dynamics. Several previous studies reported the reversed energy spectra
49 of ring current protons that represent flux minima at lower energies and flux maxima
50 at higher energies. In the literature, there is rather limited statistical investigation on
51 the global distribution features of such spectra. The availability of high quality Van
52 Allen Probes RBSPICE data enables a comprehensive study in this regard. Based on
53 RBSPICE measurements, we report the reversed energy spectra of ring current
54 protons particularly featured by the distinct flux minima around 50 - 100 keV and flux
55 maxima around 200 - 400 keV. We further adopt 4-year RBSPICE proton datasets
56 from 2013 to 2016 to investigate the occurrence rate, corresponding energies of flux
57 maximum and minimum, and the ratio of flux maximum to minimum as a function of

58 L shell, MLT and geomagnetic activity level. Our results demonstrate that these
59 reversed proton energy spectra are prevalent inside the plasmasphere, with the
60 occurrence rates $> 90\%$ at $L \sim 2 - 4$ during geomagnetically quiet periods. The strong
61 L and geomagnetic activity dependence imply the physical processes in association
62 with proton substorm injections.

63

64

65 **1. Introduction**

66 Energy spectrum distributions of energetic particles are an essential indicator for
67 understanding the underlying physics of magnetospheric particle dynamics. In
68 general, it is well recognized that both electron and proton energy spectra in space
69 plasmas follow a Kappa or Kappa-like profile having fluxes steeply falling with
70 increasing energy (e.g., Freden, 1965; Pizzella et al., 1962; Summers et al., 2009). In
71 contrast, a number of previous studies reported ‘reversed’ energy spectra of energetic
72 particles that do not follow monotonically decrease profiles of fluxes with increasing
73 energy but represent flux minima at lower energies and flux maxima at higher
74 energies. Based on the Molniya 1 measurements, Vakulov et al. (1975) observed a
75 flux maximum of the outer belt electron energy spectra at energy $\sim 1-2$ MeV. West et
76 al. (1981), using 60 keV to 3 MeV electron data from Ogo5, showed a flux maximum
77 at ~ 1.5 MeV and a minimum at ~ 500 keV. By analyzing the ring current proton
78 spectra (1 - 300 keV) observed by the Explorer 45, Williams et al. (1973) reported the
79 flux minima of proton energy spectra at energies $\sim 20 - 100$ keV over $L \sim 3.2 - 4.0$,
80 which they attributed to the ion-cyclotron instability. Based on the AMPET CCE
81 measurements, Krimigis et al. (1985) observed the flux maxima at energies $\sim 100 -$
82 300 keV during both the main and recovery phases of a geomagnetic storm.

83 Along with the launch of the twin Van Allen Probes mission in August 2012
84 (Mauk et al., 2012), the long-term accumulation of unprecedented, high quality
85 particle datasets with fine energy resolutions has fueled a resurgence in
86 magnetospheric particle dynamics studies. By combining the MagEIS and REPT

87 measurements, Zhao et al. (2019a) reported a reversed energy spectrum of radiation
88 belt electrons, which is featured by the flux maximum $\sim 1 - 2$ MeV and flux minimum
89 ~ 100 's keV and is reasonably accounted for energy-dependent electron losses
90 induced by hiss wave (e.g., Ni et al., 2019; Fu et al., 2020). A following statistical
91 analysis of Zhao et al. (2019b), on basis of the detailed analysis of reversed electron
92 energy spectra, found that reversed energy spectra dominate inside the plasmasphere
93 at $L < 2.5$.

94 Comparatively, there remains lacking the systematic information about the global
95 distribution of the reversed energy spectra of ring current protons. The availability of
96 Van Allen Probes RBSPICE data enables a comprehensive study in this regard.
97 Therefore, this letter is dedicated to investigate the global distribution of reversed
98 proton energy spectra based upon multi-year RBSPICE data from Van Allen Probes.
99 By establishing an automatic identification criterion for the reversed proton energy
100 spectra, we intend to perform a statistical analysis to explore the global distribution
101 features of the reversed proton energy spectrum, its occurrence pattern, its dependence
102 on geomagnetic activity, and its profile characteristics in terms of the energy range of
103 local flux minimum and the ratio of local flux maximum to minimum.

104

105 **2. Instrumentation and Datasets**

106 The Van Allen Probes, launched in August 2012, consist of two identical
107 satellites and operate in almost same orbits with perigees of ~ 600 km, inclination of
108 $\sim 10^\circ$, apogees of ~ 5.8 Earth radii (R_E) and spin period of ~ 11 s (Mauk et al., 2012).
109 The Radiation Belt Storm Probes Ion Composition Experiment (RBSPICE)
110 instrument onboard the Van Allen Probes, which are designed to obtain a
111 comprehensive physical understanding of ring current, provides measurements of
112 protons in the energy range of $\sim 7 - 600$ keV (Mitchell et al., 2013). The level 3-PAP
113 data with pitch angle information are adopted in this study. Due to the high-voltage
114 issues during the early phase of the emission of RBSPICE-A, we only adopted the
115 data from RBSPICE-B in the present study (Summers et al., 2017). The L shell used

116 in this study is McIlwain L calculated with IGRF and OP77Q (Olson and Pfitzer,
117 1982) magnetic field model.

118

119 **3. Observations and Statistical Results**

120 Figure 1 displays the observations of proton fluxes during 16 - 30 March, 2015.
121 The solar wind parameters and geomagnetic indices obtained from the OMNIweb are
122 plotted in Figures 1a-b. On 17 March 2015 when an intense geomagnetic storm
123 occurred, the solar wind speed jumped from ~ 400 to ~ 600 km/s and the interplanetary
124 magnetic field (IMF) B_z turned quickly from northward (~ 15 nT) to southward (~ -15
125 nT). The Dst index dropped from ~ 30 to ~ -220 nT with the AE index increasing
126 significantly from ~ 100 to 1500 nT. At the same time, the RBSPICE onboard the Van
127 Allen Probe B observed evident proton flux increases at energies of 44.7 and 81.6
128 keV (Figures 1c-d). However, the enhancements of 268.9 keV proton fluxes did not
129 occur until 18 March. The black solid lines in Figures 1c-e indicate the plasmapause
130 location calculated using Liu et al., (2015) model. In Figures 1c-d, the proton fluxes
131 outside the plasmasphere are higher than those inside the plasmasphere during quiet
132 times. During the recovery phase after 18 March, 44.7 and 81.6 keV proton fluxes at
133 lower L ($\sim 2 - 4$) gradually decreased while the 268.9 keV proton fluxes increased and
134 then remained relatively stable. Figures 1f-h further show the proton energy spectra at
135 the indicated time intervals. As shown in Figure 1f, the proton fluxes generally
136 decreased monotonically with increasing energy over L $\sim 3.0 - 5.6$. However, several
137 days later (Figures 1g-h), the proton energy spectra at L $< \sim 5.2$ exhibited “reversed”
138 structures with fluxes decay more significantly at low energies $< \sim 200$ keV, leading to
139 flux minima at energies ~ 80 keV. These flux minima reduced with decreasing L
140 shells.

141 Figure 2 illustrates some key parameters of the reversed proton energy spectra.
142 This representative example occurred at 02:04:47 on 29 March 2015 at L = 3.15. In
143 this example, proton energy spectrum has a clear flux minimum (f_{\min}) at $E_{\min} \sim 82$ keV
144 and a flux maximum (f_{\max}) at $E_{\max} \sim 221$ keV with the ratio of flux maximum to

145 minimum reaching ~ 60 . To automatically identify the reversed proton energy spectra,
146 we adopted three criteria: (1) proton energy spectra show the existence of the
147 maximum and minimum, and the corresponding energy of flux maximum (E_{\max}) is
148 greater than that of flux minimum (E_{\min}), (2) $\frac{f_{\max}}{f_{\min}} > 3$, and (3) there must be at least one
149 energy channel between the E_{\max} and E_{\min} to avoid the misclassification.

150 To further investigate the relation between the geomagnetic activities and the
151 reversed proton spectra in a long period, we present the geomagnetic indices and
152 proton fluxes with three energy channels (44.7, 81.6 and 268.9 keV) during 2015 in
153 Figures 3a-d with the white solid lines representing plasmopause locations. When the
154 Dst index suddenly decreased and the AE index increased, the locations of
155 plasmopause were reduced to lower L ($\sim 2 - 3$). For 44.7 and 81.6 keV protons, the
156 fluxes outside the plasmasphere are ~ 1 order of the magnitude higher than those
157 inside the plasmasphere in most cases, yet this is opposite to the fluxes of 268.9 keV
158 protons. While inside the plasmasphere, the proton fluxes at energies 44.7 and 268.9
159 keV are generally 1~2 orders higher than those at energies 81.6 keV. With increasing
160 energy, the proton energy spectra are going to show the decreasing and then
161 increasing trend which is the reversed feature depicted in Figure 2. Figures 3e-h
162 demonstrate the key parameters of automatically selected reversed proton energy
163 spectra. The occurrence rate of the reversed proton energy spectra is calculated with
164 the grids of 0.1 L and one day. The locations of plasmapauses match well with the
165 upper boundaries of the region with the occurrence rate $> 90\%$. During quiet times,
166 the plasmapauses usually locate at $L > 4.5$ so that the reversed proton energy spectra
167 locate at $L \sim 2 - 4$. We find that the proton reversed energy spectra are likely to be
168 observed under active geomagnetic conditions ($Dst > -50$ nT and the AE > 1000 nT).
169 As shown in Figures 3f-h, the proton energies of flux maxima mostly lie in the range
170 of ~ 82 -400 keV, decreasing with increasing L shells. Similarly, the proton energies of
171 flux minima for reversed energy spectra are tens of keV. Note that there still are a few

172 events which distribute outside the plasmasphere at $L > \sim 4.5$ with $E_{\max} > 328$ keV and
173 $E_{\min} > 100$ keV. Figure 3f reveals that the flux maxima are ~ 10 to 30 times greater
174 than the flux minima at $L < 4$, while the ratios decrease from ~ 10 to 3 with increasing
175 L shells at $L > 4$.

176 Figure 4 shows the global distributions of reversed proton energy spectra as a
177 function of L shell and MLT for three indicated geomagnetic conditions ($Dst > -30$ nT,
178 $-50 \text{ nT} < Dst < -30$ nT and $Dst < -50$ nT) from January 2013 to December 2016. From top
179 to bottom, each row presents the number of total samples, occurrence rate, the
180 corresponding energies of flux maximum and minimum, and the ratio of flux
181 maximum to minimum. The region of our interest has been divided into smaller bins
182 with the resolution of $0.5 L \times 1$ MLT, and the blank bins means the observational
183 samples are less than 50. Both the E_{\max} , E_{\min} , and the ratio of flux maximum to
184 minimum in Figures 4g-o are valued by averaging the cases in one bin. Most samples
185 are observed during quiet times ($Dst > -30$ nT) at $L \sim 2.5 - 4.5$ (Figure 4a). The
186 reversed proton spectra almost persistently exist over $L \sim 2 - 4$ during quiet times,
187 with occurrence rates $> 90\%$. Besides, the occurrence rates decrease with increasing L
188 shells, which is consistent with the observations shown in Figure 1, and decreases
189 under more active geomagnetic activities. The upper boundary of higher occurrence
190 rate ($> 90\%$) regions shift from higher to lower L shells. Regarding to the MLT
191 dependence, we find that the occurrence rates on the dayside are slightly higher than
192 those of nightside, especially during the geomagnetically active periods ($Dst < -50$
193 nT). In Figures 4g-l, the statistical distributions of the E_{\max} and E_{\min} demonstrate that
194 the proton fluxes mostly reach the peaks at energies $\sim 200 - 400$ keV and drop to the
195 valleys at energies $\sim 50 - 100$ keV. Both E_{\max} and E_{\min} decrease first as the L shell
196 increases to ~ 5 , while they suddenly increase on two MLT sectors (15-19, 22-05) at
197 $L > 5$ with relatively small samples. In addition, the statistics of E_{\max} and E_{\min} show a
198 less geomagnetic activity dependence. The ratios decrease with the increasing L
199 shells, which are smaller under the more active geomagnetic conditions (Figures 4m-
200 o).

201

202 **4. Discussions**

203 Our results show that the reversed proton spectra are preferentially inside the
204 plasmasphere and show significant losses of lower energy ($\sim 50 - 100$ keV) protons
205 after the geomagnetic storm (Figures 1f-h). It is significant for us to further
206 understand the mechanisms that produce the reversed proton energy spectra. There are
207 several possible explanations for the formation of the reversed proton energy spectra.

208 Firstly, charge exchange is found to be the main loss process of ring current
209 protons by capturing electrons from neutral atoms (Ebihara & Ejiri, 2003; Dessler &
210 Parker, 1959; Smith & Bewtra, 1976). The lifetime of proton due to charge exchange
211 is shortest at energies around tens of keV with the value of $0.2 - 1$ day (Fok et al.,
212 1991). This energy range is consistent with our statistical distributions of E_{\min} in
213 reversed proton spectra. Furthermore, the densities of neutral hydrogen are higher at
214 lower L shells (Østgaard et al., 2003). Thus, the loss effect due to charge exchange is
215 stronger at lower L shells. We also find that the reversed proton energy spectra show a
216 high occurrence at low L shells ($L=2 - 4$). These agreements in spatial distribution
217 suggest that charge exchange plays an important role in the formation of reversed
218 proton energy spectral.

219 Another candidate for the loss of protons is Coulomb collision (Fok et al., 1996;
220 Jordanova et al., 1996, 1999). When particles travel through the plasma, they will loss
221 energy or change pitch angles due to collisions with other particles. Similar to charge
222 exchange, Coulomb collision also likes to occur in lower L shells (Fok et al., 1991).
223 However, this process is dominant in decreasing the proton fluxes at low-energies
224 (<10 keV) (Fok et al., 1996) and is not likely to produce the reversed proton energy
225 spectra with local minima at energies $\sim 50 - 100$ keV.

226 There are also two collisionless scattering mechanisms for the ring current
227 decay: wave-particle interactions and field line curvature (FLC) scattering. The
228 electromagnetic ion cyclotron (EMIC) waves can effectively scatter several keV to
229 hundreds of keV protons into the loss cone due to pitch angle diffusion with a time

230 scale of a few hours (Cao et al., 2019, 2020; Cornwall, 1977; Jordanova et al., 1997;
231 Xiao et al., 2011; Summers, 2005). The field line curvature scattering is of importance
232 for the ring current decay when the field line configuration is stretching (Chen et al.,
233 2019; Ebihara et al., 2011; Sergeev et al., 1993; Yu et al., 2020). Yu et al. (2020)
234 investigated the role of FLC scattering in ring current decay during the 17 March
235 2013 storm and found that the associated proton precipitation mainly occurs at $L > 5$
236 on the nightside. This finding is basically consistent with our observations that the
237 reversed proton energy spectra are distributed at $L > 5$ on two MLT sectors (15-19,
238 22-05). The formation mechanism of reversed energy spectra at $L > 5$ may be different
239 from those at $L < 5$.

240 Although several loss mechanisms have been proposed to explain the decay of
241 Earth's ring current. The relative contributions of difference mechanisms to the
242 formation of the reversed proton energy spectra still remain to be fully understood,
243 which however is outside the scope of this study and is left to a future study.

244

245 **5. Conclusions**

246 In this study, based on the high-resolution proton flux data from RBSPICE
247 onboard the Van Allen Probe B during 2013 – 2016, we have performed a detailed
248 statistical analysis of the global distribution of reversed energy spectra of ring current
249 protons. The major conclusions are summarized as follows:

250 (1) The reversed proton energy spectra are preferentially observed inside the
251 plasmasphere, with the occurrence rates $> 90\%$ at $L \sim 2 - 4$ during geomagnetically
252 quiet periods. As the geomagnetic activity intensifies, the preferential occurrence
253 region of the reversed proton energy spectra shrinks to lower L shells ($\sim 2.5 - 3.5$).

254 (2) The proton energies corresponding to the flux maxima and minima of the
255 reversed energy spectra decrease with the increase of L shell in the region of $L < 5$.
256 The flux minima of the reversed proton spectra mainly occur at $\sim 50 - 100$ keV, while
257 the flux maxima are generally present at $\sim 200 - 400$ keV.

258 (3) Similar to the global distribution of the reversed spectrum occurrence rate,

259 the ratios between flux maxima and minima are strongly L shell and geomagnetic
260 activity dependent, showing that the ratios during active times and at higher L shells
261 are smaller than those during quiet times and at lower L shells.

262

263 **Acknowledgments**

264 This work was supported by the National Natural Science Foundation of China
265 (grant nos. 42025404, 41674163, 41704162, 41974186, 41674162, 41904144,
266 41904143), the B-type Strategic Priority Program of the Chinese Academy of
267 Sciences (grant no. XDB41000000), the pre-research projects on Civil Aerospace
268 Technologies (grant nos. D020303, D020308, D020104) funded by the China
269 National Space Administration, the National Key R&D Program of China
270 (2018YFC1407303) and the China Postdoctoral Science Foundation Project (grant no.
271 2019M662700). We also acknowledge the Van Allen Probes mission, particularly the
272 RBSPICE team, for providing particle data. at <http://rbspice.ftecs.com>. Profiles of the
273 solar wind parameters and geomagnetic indices are from the OMNI website
274 (<http://omniweb.gsfc.nasa.gov>).

275

276 **References**

- 277 Cao, X., Ni, B., Summers, D., Shprits, Y. Y., Gu, X., Fu, S., Lou, Y., Zhang, Y., Ma,
278 X., Zhang, W., Huang, H., & Yi, J. (2019). Sensitivity of EMIC wave-driven
279 scattering loss of ring current protons to wave normal angle distribution.
280 *Geophysical Research Letters*, 46, 590–598.
281 <https://doi.org/10.1029/2018GL081550>
- 282 Cao, X., Ni, B., Summers, D., Shprits, Y. Y., & Lou, Y. (2020). Effects of polarization
283 reversal on the pitch angle scattering of radiation belt electrons and ring current
284 protons by EMIC waves. *Geophysical Research Letters*, 47, e2020GL089718.
285 <https://doi.org/10.1029/2020GL089718>
- 286 Fok, M.-C., Kozyra, J. U., Nagy, A. F., & Cravens, T. E. (1991). Lifetime of ring
287 current particles due to coulomb collisions in the plasmasphere. *Journal of*

288 Geophysical Research, 96(A5), 7861– 7867. <https://doi.org/10.1029/90JA02620>

289 Fok, M.-C., Moore, T. E., & Greenspan, M. E. (1996). Ring current development
290 during storm main phase. *Journal of Geophysical Research*, 101(A7), 15,311–
291 15,322. <https://doi.org/10.1029/96JA01274>

292 Fu, S., Yi, J., Ni, B., Zhou, R., Hu, Z., Cao, X., et al. (2020). Combined scattering of
293 radiation belt electrons by low frequency hiss: Cyclotron, Landau, and bounce
294 resonances. *Geophysical Research Letters*, 47, e2020GL086963.
295 <https://doi.org/10.1029/2020GL086963>

296 Freden, S. C., Blake, J. B., & Paulikas, G. A. (1965). Spatial variation of the inner
297 zone trapped proton spectrum. *Journal of Geophysical Research*, 70(13), 3113–
298 3116. <https://doi.org/10.1029/JZ070i013p03113>

299 Jordanova, V. K., Kozyra, J., Nagy, A., & Khazanov, G. (1997). Kinetic model of the
300 ring current-atmosphere interactions. *Journal of Geophysical Research*, 102(A7),
301 14,279–14,291. <https://doi.org/10.1029/96JA03699>

302 Krimigis, S. M., McEntire, R. W., Potemra, T. A., Gloeckler, G., Scarf, F. L., &
303 Shelley, E. G. (1985). Magnetic storm of September 4, 1984—A synthesis of
304 ring current spectra and energy densities measured with AMPTE/CCE.
305 *Geophysical Research Letters* (ISSN 0094-8276), 12, 329-332.
306 <http://doi.org/10.1029/GL012i005p00329>

307 Liu, X., Liu, W., Cao, J. B., Fu, H. S., Yu, J., & Li, X. (2015). Dynamic plasmopause
308 model based on THEMIS measurements. *Journal of Geophysical Research:*
309 *Space Physics*, 120, 10,543–10,556. <https://doi.org/10.1002/2015JA021801>

310 Mauk, B. H., Fox, N. J., Kanekal, S. G., Kessel, R. L., Sibeck, D. G., & Ukhorskiy, A.
311 (2012). Science objectives and rationale for the Radiation Belt Storm Probes
312 mission. *Space Science Reviews*, 1–15. [https://doi.org/10.1007/s11214-012-](https://doi.org/10.1007/s11214-012-9908-y)
313 [9908-y](https://doi.org/10.1007/s11214-012-9908-y)

314 Mitchell, D. G., Lanzerotti, L. J., Kim, C. K., Stokes, M., Ho, G., Cooper, S., ...

315 Kerem, S. (2013). Radiation belt storm probes ion composition experiment
316 (RBSPICE). *Space Science Reviews*, 179. [https://doi.org/10.1007/s11214-013-](https://doi.org/10.1007/s11214-013-9995-4)
317 [9995-4](https://doi.org/10.1007/s11214-013-9995-4)

318 Ni, B., Huang, H., Zhang, W., Gu, X., Zhao, H., Li, X., Baker, D. N., Fu, S., Xiang,
319 Z., & Cao, X. (2019). Parametric sensitivity of the formation of reversed electron
320 energy spectrum caused by plasmaspheric hiss. *Geophysical Research Letters*,
321 46, 4134–4143. <https://doi.org/10.1029/2019GL082032>

322 Olson, W. P., & Pfizter, K. A. (1982). A dynamic model of the magnetospheric
323 magnetic and electric fields for July 29, 1977. *Journal of Geophysical Research*,
324 87, 5943–5948. <https://doi.org/10.1029/JA087iA08p05943>

325 Ostgaard, N., Mende, S. B., Frey, H. U., Gladstone, G. R., & Lauche, H. (2000).
326 Neutral hydrogen density profiles derived from geocoronal imaging. *Journal of*
327 *Geophysical Research Space Physics*, 108, 1300.

328 Pizzella, G., Laughlin, C. D., & O'Brien, B. J. (1962). Note on the electron energy
329 spectrum in the inner Van Allen Belt. *Journal of Geophysical Research*, 67(9),
330 3281–3287. <https://doi.org/10.1029/JZ067i009p03281>

331 Summers, D. (2005). Quasi-linear diffusion coefficients for field-aligned
332 electromagnetic waves with applications to the magnetosphere. *Journal of*
333 *Geophysical Research*, 110, A08213. <https://doi.org/10.1029/2005JA011159>

334 Summers, D., Tang, R., & Thorne, R. M. (2009). Limit on stably trapped particle
335 fluxes in planetary magnetospheres. *Journal of Geophysical Research*, 114,
336 A10210. <https://doi.org/10.1029/2009JA014428>

337 Summers, D., Shi, R., Engebretson, M. J., Oksavik, K., Manweiler, J. W., & Mitchell,
338 D. G. (2017). Energetic proton spectra measured by the Van Allen Probes.
339 *Journal of Geophysical Research: Space Physics*, 122, 10,129–10,144.
340 <https://doi.org/10.1002/2017JA024484>

341 Vakulov, P. V., Kovrygina, L. M., Mineev, I. V., & Tverskaia, L. V. (1975). Dynamics
342 of the outer belt of energetic electrons during moderate magnetic disturbances.
343 *Geomagnetizm I Aeronomiia*, 15, 1028–1032.

344 West, H. I. Jr., Buck, R. M., & Davidson, G. T. (1981). The dynamics of energetic

345 electrons in the Earth's outer radiation belt during 1968 as observed by the
346 Lawrence Livermore National Laboratory's spectrometer on Ogo 5. *Journal of*
347 *Geophysical Research*, 86(A4), 2111–2142.
348 <https://doi.org/10.1029/JA086iA04p02111>

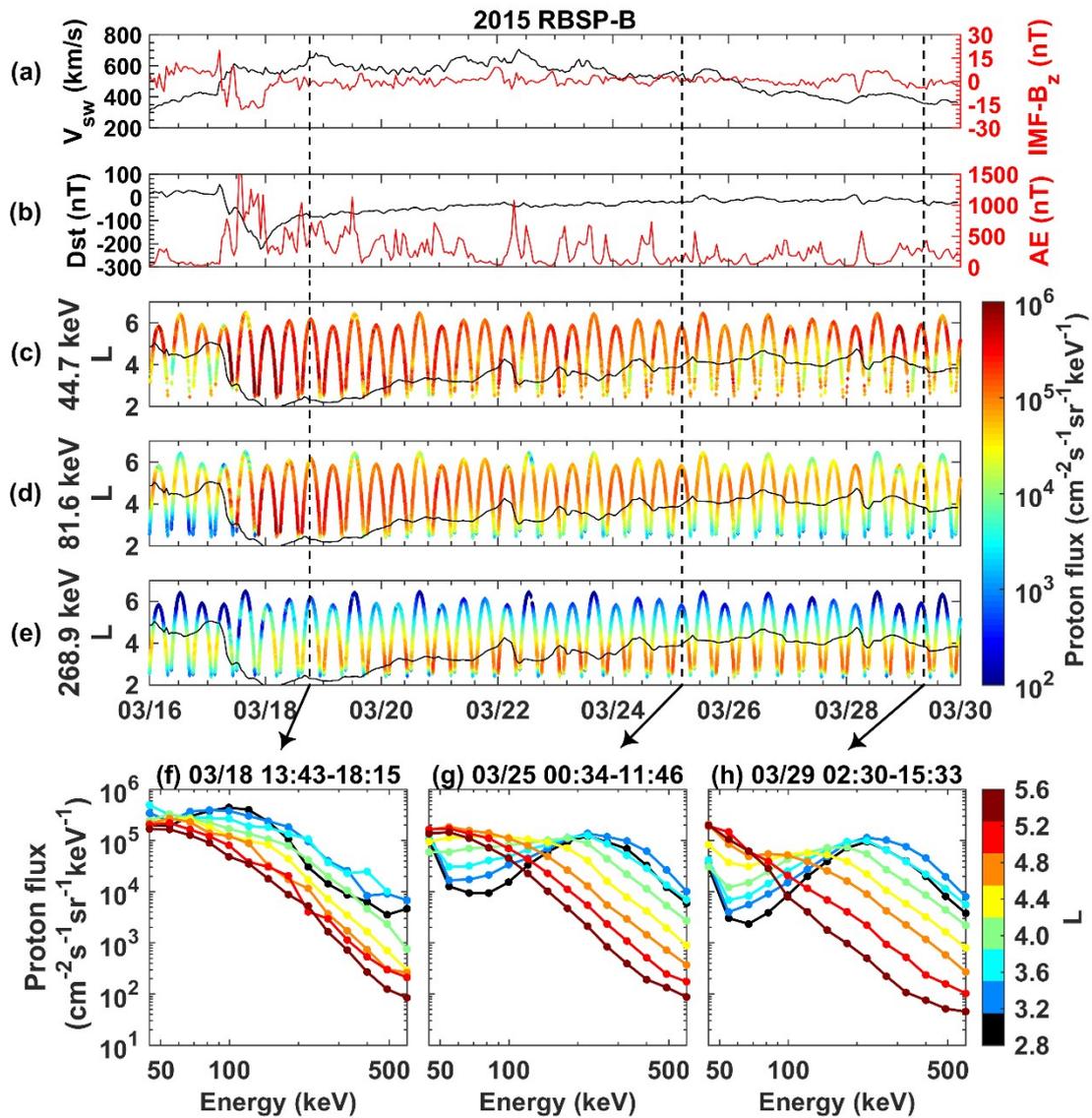
349 Williams, D. J., Fritz, T. A., & Konradi, A. (1973). Observations of proton spectra (1.0
350 $\leq E_p \leq 300$ keV) and fluxes at the plasmopause. *Journal of Geophysical*
351 *Research*, 78, 4751–4755. <https://doi.org/10.1029/JA078i022p04751>

352 Xiao, F., Chen, L., He, Y., Su, Z., & Zheng, H. (2011). Modeling of precipitation loss
353 of ring current protons by electromagnetic ion cyclotron waves. *Journal of*
354 *Atmospheric and Solar - Terrestrial Physics*, 73, 106–111.
355 <https://doi.org/10.1016/j.jastp.2010.01.007>

356 Zhao, H., Ni, B., Li, X., Baker, D. N., Johnston, W. R., Zhang, W., et al. (2019a).
357 Plasmaspheric hiss waves generate a reversed energy spectrum of radiation belt
358 electrons. *Nature Physics*, 15(4), 367–372. [https://doi.org/10.1038/s41567-018-](https://doi.org/10.1038/s41567-018-0391-6)
359 [0391-6](https://doi.org/10.1038/s41567-018-0391-6)

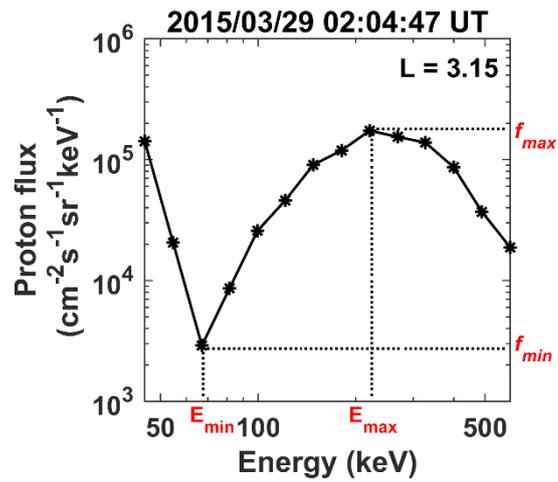
360 Zhao, H., Johnston, W. R., Baker, D. N., Li, X., Ni, B., Jaynes, A. N., Kanekal, S. G.,
361 Blake, J. B., Claudepierre, S. G., Reeves, G. D., & Boyd, A. J. (2019).
362 Characterization and evolution of radiation belt electron energy spectra based on
363 the Van Allen Probes measurements. *Journal of Geophysical Research: Space*
364 *Physics*, 124, 4217–4232. <https://doi.org/10.1029/2019JA026697>

365



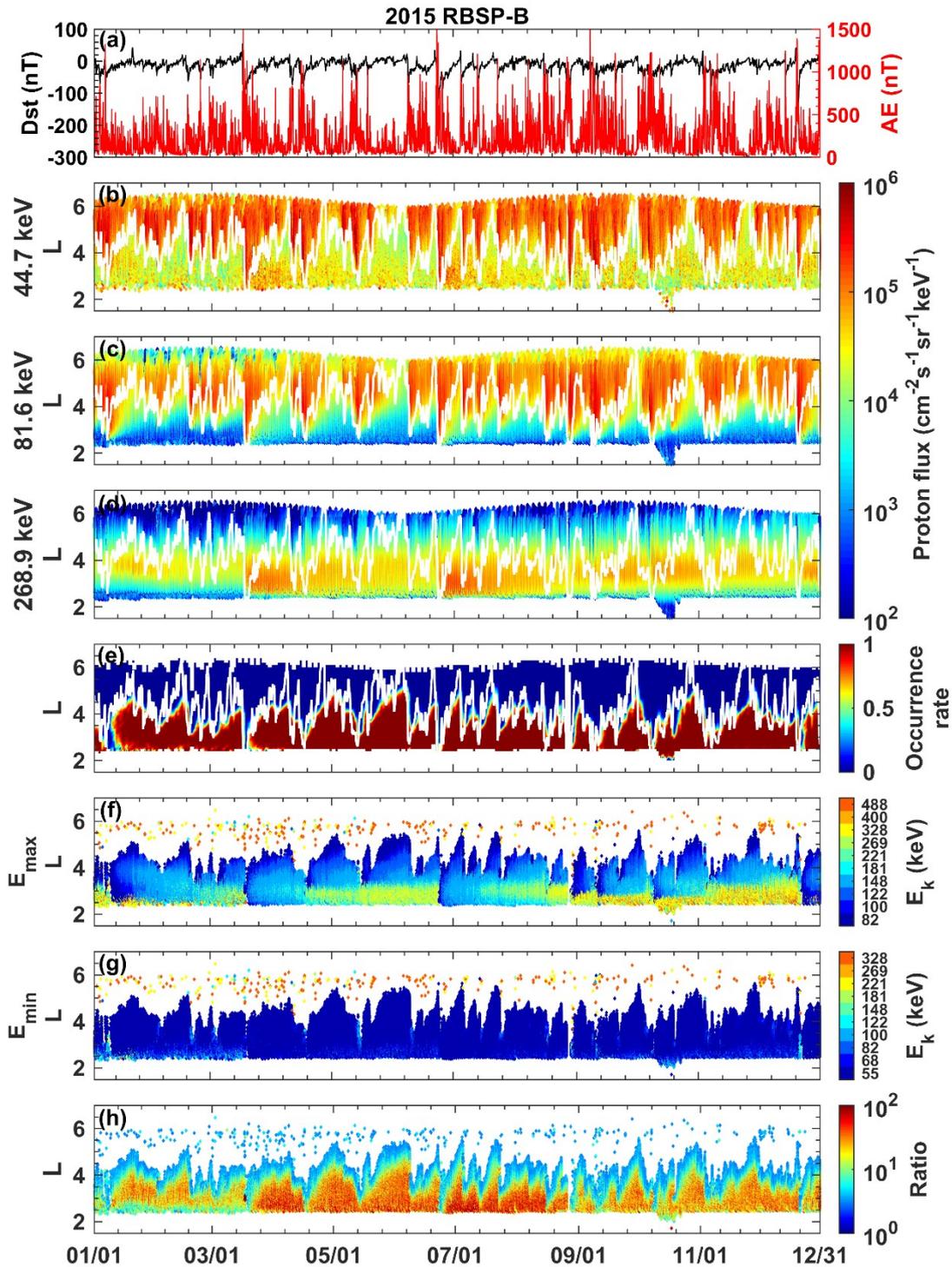
366

367 **Figure 1.** An overview of the 17 March 2015 strong geomagnetic storm. (a) solar
 368 wind speed (V_{sw}) and interplanetary magnetic field (IMF) B_z , (b) Dst and AE indices,
 369 (c-e) 90° pitch angle proton fluxes at energies of ~ 44.7 keV, ~ 81.6 keV, and ~ 268.9
 370 keV, respectively, with the black solid lines indicating the plasmopause location. (f-h)
 371 The proton energy spectra at $L \sim 2.8 - 5.6$ during three indicated time intervals of the
 372 storm.



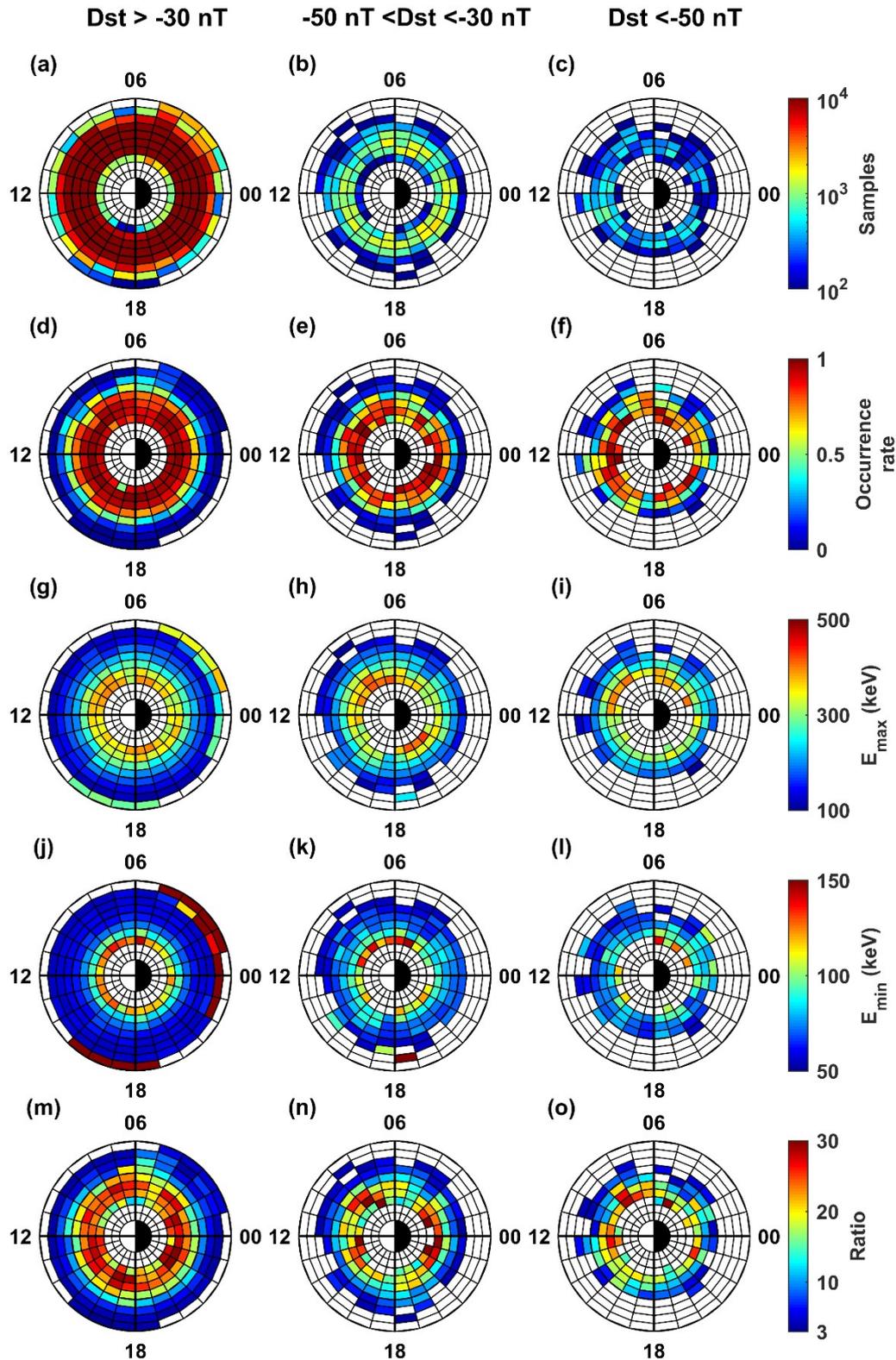
373

374 **Figure 2.** A representative example of the reversed proton energy spectrum at L =
 375 3.15 based on the RBSPICE measurements at 02:04:47 UT on 29 March 2015. Four
 376 characteristic parameters of the reversed energy spectrum, i.e., flux maximum (f_{\max}),
 377 flux minimum(f_{\min}), the energy of flux maximum (E_{\max}), and the energy of flux
 378 minimum (E_{\min}), are defined on the plot.



379

380 **Figure 3.** RBSPICE observations of proton fluxes during 2015 and the corresponding
 381 distributions of reversed proton energy spectra. (a) Dst and AE indices, (b-d) 90° pitch
 382 angle proton fluxes at energies of ~44.7 keV, ~81.6 keV, and ~268.9 keV, respectively,
 383 (e) occurrence rate of the reversed proton energy spectrum, (f) the proton energy of flux
 384 maximum, (g) the proton energy of flux minimum, and (h) the ratio of proton
 385 flux maximum to minimum. The white solid lines in (b-e) indicate the plasmapause
 386 location.



387

388 **Figure 4.** Statistical results of the global distribution of reversed proton energy
 389 spectrum during 2013-2016 under the indicated three geomagnetic conditions (from
 390 left to right: $Dst > -30$ nT, -50 nT $< Dst < -30$ nT, and $Dst < -50$ nT). (a-c) samples,
 391 (d-f) occurrence rate, (g-i) the proton energy of flux maximum, (j-l) the proton energy

392 of flux minimum, and (m-o) the ratio of the proton flux maximum to minimum.