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ScienceDirect

Advances in Space Research 58 (2016) 587–597

ADVANCES IN SPACE RESEARCH (a COSPAR publication)

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Study on geomagnetic storms driving motion of 0.1–2 MeV radiation belt electrons

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Received 29 October 2015; received in revised form 5 May 2016; accepted 6 May 2016
Available online 24 May 2016

Abstract

Using more than five years' worth of data observed by the Instrument for the Detection of Particles (IDP) spectrometer onboard the Detection of Electro-Magnetic Emissions Transmitted from Earthquake Regions (DEMETER) satellite, we studied the motion characteristics of energetic electrons in different regions, i.e., the inner radiation belt, the outer radiation belt, and the slot region in geomagnetic storms. We investigated the flux change of 0.1–2.4 MeV electrons and the energy change of 0.1–1.0 MeV electrons in these different regions. By cross correlation analysis, we came to the following conclusions. First, when Dst < -50, the correlation coefficient (c.c.) of the electron flux and Dst index ranges from -0.63 to -0.86, and the enhancement of the electron flux generally occurs during the storm's main and recovery phases. Second, the storms greatly influence the lower energy region of the electron energy spectrum in the inner radiation belt, while the enhancement in the higher energy region is more significant in the outer radiation belt and the slot region. Third, the effects of geomagnetic storms on electrons are not distinguished significantly between in the day and night, and independent of the timing of the events. For storms with $-50 <$ Dst < -30, there is a negative correlation of -0.51 to -0.57 between the Dst index and the electron flux in the outer radiation belt. Our analysis suggests that strong storms cause energetic electron ejections across a wide range, and the ejection level is affected by the storm intensity. Furthermore, the electron energy region influenced by the strong geomagnetic storms is opposite in the inner and outer radiation belts. The proportion of electrons accelerated to relativistic energies is greater in the outer radiation and slot regions, while the ejection energetic electrons are more concentrated in the low energy region of the inner radiation belt. This phenomenon reflects the different electron injection mechanisms and accelerating processes responsible for spectral index variations in different L regions during geomagnetic storms.

Keywords: Geomagnetic storms; Energetic electrons; Spectral index; Flux; Cross correlation

1. Introduction

Since Reeves et al. (2003) studied the statistical behavior of 1.2–3.5 MeV electron fluxes during geomagnetic storms, researchers have realized that the effects of relativistic electron flux by storms are quite different from those traditionally assumed. About 53% of geomagnetic storms increase the energetic electron flux, about 19% storms decrease the flux, and the remaining 28% do not cause the flux to vary significantly.

Most research thus far has focused on the influence of geomagnetic storms on the outer radiation belt. Cyamukungu (1999) analyzed the detection data from the Scintillating Fiber Detector (SFD) onboard the EQUATOR-S mission collected over a six-month period from the end of 1997 to 1998. They pointed out that the increases in electron flux over 400 keV in the outer radiation belt with $L > 3$ may be caused by the in situ accelera-

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http://dx.doi.org/10.1016/j.asr.2016.05.006
0273-1177/

tion of the electrons in the radiation belt. Horne et al. (2009), making use of the data from NOAA 15-18, studied the energetic electron precipitation phenomenon of the outer radiation belt during geomagnetic storms. They suggested that the electron precipitation of >300 keV peaks occurred during the main phase of the geomagnetic storms and the >1 MeV electron peaks occurred during the recovery phase. They thought that whistler mode chorus waves accelerate electrons up to the order of megaelectronvolts during the recovery phase, and then Electromagnetic Ion Cyclotron (EMIC) waves precipitate them. Using the data from 15 spacecraft detectors, Turner et al. (2014) studied the effects of the magnetic storm occurring between 30 September and 3 October 2012. They found that the electron flux of the outer radiation belt dropped by over an order of magnitude in less than 4 h, and explained this event by wave particle coupling theory. Based on the data of the Solar Anomalous and Magnetospheric Particle Explorer (SAMPEX), Zhao and Li (2013) observed the injection of relativistic electrons into the outer radiation belt during magnetic storms deep in the slot region L:2-3. Xiao et al. (2014) analyzed data of 2–4.5 MeV electrons during the magnetic storm of 12–19 March 2013 detected by Van Allen probes. They studied the electron flux change of the relativistic electrons during the main and recovery phases. The large flux increase of electrons is explained by numerical simulation.

Electrons of moderate energy (less than 1 MeV) often populate the inner radiation belt and the outer radiation belt. As the first evidence for a nearly impenetrable barrier for very high-energy electrons ($\sim$ 7.2 MeV) at an equatorial radial distance near 2.8 RE, from the Van Allen probe, Baker et al. (2014)'s study implies that almost no electrons at these energies are seen inside this limiting boundary maintained by an interplay of slow inward radial diffusion balanced by more rapid precipitation losses due to pitch angle diffusion driven by VLF hiss. There are some reports about the effects of magnetic storms on the inner radiation belt and the slot region. Using the particle detector onboard the National Oceanic and Atmospheric Administration (NOAA) satellite, Tadokoro et al. (2007) studied the influence of the medium magnetic storms with Dst index: -100 to -30 nT on 0.3–1 MeV electron flux. The electron flux increases by one order of magnitude during the main phase. Tadokoro et al. (2007) believe that this enhancement in electron flux is not from the electron ejection from the outer radiation belt. Xiao et al. (2009) analyzed the Imaging Electron Spectrometer (IES) data from the Polar spacecraft to study the pitch angle and flux evolvement of 30–500 keV electrons during the magnetic storm of 31 October 2003. They found that pitch-angle diffusion can primarily account for the evolution of the pitch-angle distribution of electrons in the innermost radiation belt near $L = 1.7$ and the slot region $2 < L < 3$. The obtained time scale for this pitch-angle distribution evolution was found to be from a few hours to tens of hours. In addition, using SAC-C and DEMETER data, Benck et al. (2010) studied the energetic electron lifetimes and compare the decay rates to those observed at high altitude when the magnetic activity calms down and the fluxes decay to quiet-time levels.

The studies of the effects of geomagnetic storms on energetic electron motion have mainly focused on flux change. By analyzing electron flux change during different phases of geomagnetic storms, the works discussed above investigate the driving process of magnetic storms on electron motion, and mainly focus on the outer radiation belt and some local areas of the inner radiation belt. Since these studies are limited in that the particle detectors have very few energy channels, a detailed comparative study on the influence of magnetic storms on the energetic electron spectrum has not been implemented. In addition, the previous study about the electron acceleration mechanism during magnetic storms is confined to analyzing the electron flux change in a certain energy range (Cyamukungu, 1999). In fact, the flux enhancement itself is not enough to explain the electron acceleration. Other explanations for electron acceleration include electron deceleration from higher energies and the ejection of electrons from other regions. Therefore, combining an energy spectrum analysis with the flux evolution analysis on large spatial scales could prove to be an effective method for describing the response process of energetic electrons during magnetic storms.

The energetic particle detector Instrument for the Detection of Particles (IDP) is one of the payloads onboard the Detection of Electro-Magnetic Emissions Transmitted from Earthquake Regions (DEMETER) micro-satellite (Sauvaud et al., 2006a). IDP has the ability to detect both flux and energy spectra for 0.1–2.4-MeV electrons. In orbit for more than five years with the DEMETER satellite, IDP provides us an opportunity to study the spectral evolution of energetic electrons during magnetic storms.

Using more than 5.5 years' worth of data from DEMETER/IDP, Whittaker et al. (2013) fit the electron spectrum during magnetic storms and compared power law, kappa and exponential shapes. They found that the power law provides the best fit. In addition, they found that the outer belt softened at the storm onset relative to the quiet period and then hardened during the main and recovery phase in the outer belt, while the inner belt hardened at storm onset relative to the quiet time.

In this paper, we use the DEMETER/IDP (Sauvaud et al., 2006a) data to analyze the relation between the flux and the spectra of energetic electrons (Clilverd et al., 2010; Rodger et al., 2010) and the Dst index in different L regions. Further, we discuss the energy transfer and the motions of energetic electrons over a large spatial scale during magnetic storms. This paper builds upon Whittaker's work (2013) as follows: (1) Both survey data and burst data, as opposed to 128 channels survey-mode data used in Whittaker's analysis, are used in this paper. (2) Three different shapes are compared in Whittaker's work, while the current work compares four shapes in which two different equations are considered. (3) The Kp index