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The Possible Sources of the Relativistic Electrons in the Magnetosphere

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Abstract. Using data from ACE and low-altitude polar orbit satellite of NOAA, we investigate the possible sources of the enhancements of relativistic electrons in the magnetosphere. The observations from NOAA for the different geomagnetic activity periods show that substorms injections provide seed electrons for MeV electron enhancement associated with geomagnetic storms and the energetic electrons in the solar wind provide an alternative source for the relativistic electrons in the magnetosphere during the SEP events.

Keywords. Sun: coronal mass ejections (CMEs), particle emission, solar-terrestrial relations, solar wind

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1. Introduction

The magnetosphere is an efficient accelerator and effective trapping device for energetic electrons. The relativistic electron population has long been observed in the Earth's outer radiation belt. The fluxes of these electrons are highly variable and dynamics, showing enhancements of several orders of magnitude occurring on timescales of about one day in many storm periods (Baker *et al.* 1994). The trigger for the flux enhancement of high-energy electron associated with geomagnetic storms is known mostly to be the enhanced solar wind velocity and north-south changes of the interplanetary magnetic field (IMF). Relativistic electron flux enhancements were further often also shown strong recurrent tendencies with the 27-day rotation period of the sun, particularly in the years approaching solar minimum (e.g., Baker *et al.* 1979). These have led to the view that the MeV electron flux enhancements are linked to solar energetic particle (SEP), coronal mass ejections (CMEs), and corotating interaction regions (CIRs) associated with high-speed solar wind stream.

The sources, acceleration mechanisms and transport processes of relativistic electron are primary issues in the research field of magnetospheric physics and remain unsolved problems for further studies. It has been proposed that relativistic electrons in the solar wind, either from the sun or from Jupiter, may be a source of the relativistic electron in the magnetosphere (e.g., Baker *et al.* 1979; Baker *et al.* 1986). Although the acceleration mechanisms of relativistic electron have not fully understood, in the meantime a few mechanisms responsible for acceleration of relativistic electron population in the Earth's magnetosphere have been proposed: radial diffusion (Li, 1997), re-circulation (Fujimoto, 1990) and wave-particle interaction (Liu, 1999), etc. These acceleration mechanisms all need a source that provides seed electrons (approximately hundreds of keV to one or two MeV) to be accelerated to the range of a few to ten MeV. The origin of the MeV electrons in the magnetosphere remains an unsolved problem. Two notable possible sources have been noticed in the literature: the energetic electrons near the outer boundary of the inner magnetosphere and in the solar wind. It has been suggested that substorms may

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effectively produce the seed population of energetic electron that can be accelerated by a not yet defined process to be relativistic electrons (Baker *et al.* 1998). High-energy particles within in the Earth's radiation belt can be accelerated in the magnetosphere (Schulz and Lanzerotti, 1974). The seed population can also originate from source beyond the Earth's immediate influence (Scholer, 1979). It has been established that energetic protons and other ions from the sun can be penetrated into the terrestrial magnetosphere (Scholer, 1979; Fennel, 1973). In this paper we aim to identify the evidences for the sources of the relativistic electrons in the magnetosphere mainly based on the observations from low-altitude polar orbit NOAA satellite.

2. Data

NOAA/Polar Orbiting Environmental Satellites (POES) were launched into a nearly polar orbit with an altitude about 850km, an inclination of 98°. The spacecraft carry a suite of instruments that detect and monitor the flux of energetic ions and electrons into the atmosphere and the particle radiation environment at the altitude of the satellite. The present study examines the observations of electrons from the (Medium Energy Proton and Electron Detector) MEPED on board the NOAA-15 and NOAA-16. The MEPED instrument measures electrons at angle of 10° and 80° to the local vertical measurements of trapped electron in three differential energy channels E1(>30keV), E2(>100keV), E3(>300keV) at 80° angle were used in this study. It worthwhile to point that we have try to exclude the electron contamination by the proton based on the suggestion by the principle scientist of MEPED/NOAA. The ACE electron flux in the energy range of 175–315keV, proton flux with the energy greater than 10MeV, and the solar wind velocity are provided by the energy particle and solar wind instrument on board ACE spacecraft.

3. Energetic electron source in the solar wind

On Oct. 28, 2003 the sun produced an extreme large flares X17/4B peaking at 1110 UT. A very fast (near 2000km/s) earthward coronal mass ejection (CME) was observed on SOHO/LASCO. Successively at 1150UT after X-ray burst, beginning of a strong SEP event was, detected by GOES spacecraft at the geosynchronous orbit. Two fast-moving magnetic clouds from the sun swept past Earth and produced extreme geomagnetic storms. The storm suddenly commenced at 0611UT on Oct. 29 and at 1637UT on Oct. 30, respectively. Figure 1 shows the counts rate of >0.3MeV electrons of Oct. 27–30 from MEPED instrument on NOAA-16. This figure is color-coded spectrogram showing the logarithm of counts rate, the scale being indicated by the color bar on right. The data are binned in 0.1 L-values. The total L range 1<L<15 is shown in the figure. The time between adjacent columns of pixels is 2 hours. The electron counts rate had been relatively low until an enhancement across a wide range from high L-values to low L-value occurred around 1200 UT on Oct. 28. This enhancement stared before the magnetic storm on Oct. 29 and was directly correlated with the SEP event in the upstream solar wind. The observation by the NOAA satellite shows that the abrupt electron enhancement extends across all high L-value (L>6) without notable time difference. Figure 2 shows the variation of energetic electron (175–315 keV) and proton (>10MeV) flux of Oct. 28–29 measured by the ACE. Measurements by ACE indicated that the massive solar energetic electrons with energy being a few hundreds keV could be produced during the period of the SEP event. The increases of the solar energetic electron beginning around 1200

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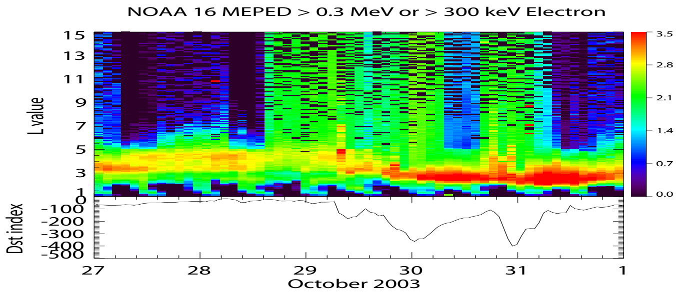

Figure 1. The counts rate of >0.3MeV electrons as a function of time and L-shell. The Dst index is shown below.

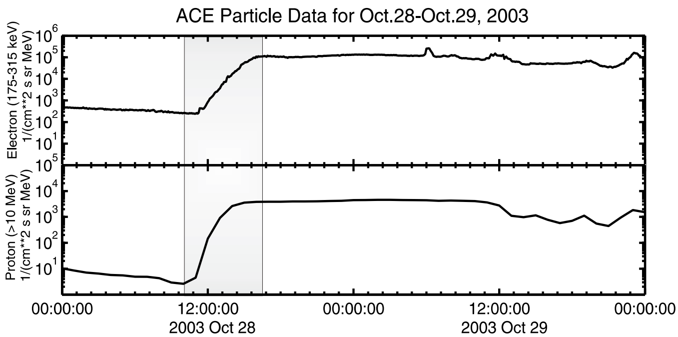

Figure 2. The variation of energetic electron (175–315keV) and proton (>10MeV) flux of Oct. 28–29 measured by the ACE.

UT are coincident with the enhancement of relativistic electrons in the magnetosphere observed by NOAA.

Following up on the above observations, a question arises as to whether solar energetic electron population during the SEPs is a significant source of MeV electron enhancement in the magnetosphere? Figure 3 plot the NOAA data of Oct. 28–29, 2003. The measurements were made in the north polar cap region with a selection criterion applied such that magnetic latitude was greater than 70°. In the open magnetosphere model, this criterion would imply that at such high latitudes NOAA was sampling essentially interplanetary-connected field lines (Baker *et al.* 1997) As is seen in Figure 3(a), the >0.3MeV electrons measured by MEPED /NOAA enhanced rapidly above background levels around 0600UT on 28 October. Simultaneously an increase of energetic electrons was detected by ACE. The intensities of electrons remained high level for more than one day. This observation suggests that massive solar energetic electrons can be seen in the polar cap region. Figure 3(b) plots data of the electron counts rate in the energy range Of >0.3 MeV at L = 6.6 for the same time period as figure 3(a). In Figure 3(b) an enhancement of electrons in the inner magnetosphere observed while strong access of solar electrons to the polar cap was seen. In Figure 4, we show the measurement of spin average integral electron rates with energy >0.3MeV of measured by POLAR for the same time period. Similar enhancement can be seen in this figure. All these electrons require a channel to penetrate into the magnetosphere. It has been suggested that solar particles would have rather directed access to polar cap region following the open magnetic filed lines (Fennel, 1973). Sheldon *et al.* (1998) also presented the POLAR observation of MeV electrons population in the cusp region. The following solar wind electron entry scenario

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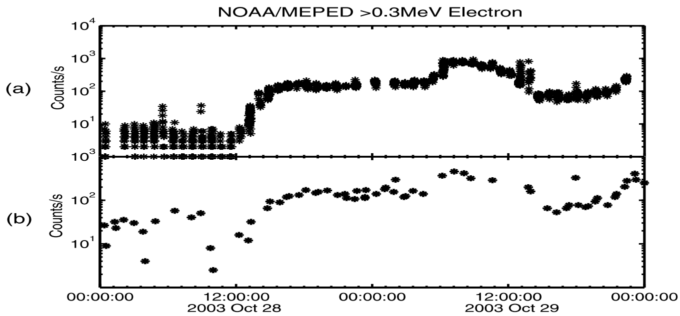

Figure 3. (a) Polar cap electron counts rates (>0.3MeV) measured by NOAA during October 28-29 2003. (b) Same as (a) but showing electron counts rate at low latitudes for L=6.6

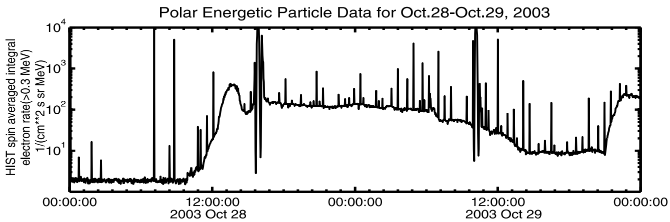

Figure 4. Spin average integral electron rates with energy >0.3MeV of POLAR for the same period of time as in Figure 4.

is then suggested in the present paper: When the solar wind energetic electrons in arrived at the Earth, they penetrate into the terrestrial magnetosphere along the open magnetic filed lines through the cusp and polar cap regions. With this scenario and based on the observations in Figures 3 and 4, we postulate that the solar wind energetic electrons in the solar wind may provide a source for the relativistic electrons in the magnetosphere during the period of the SEP events.

4. Energetic electron source near the Outer boundary of the magnetosphere

In the late 2000, two successive geomagnetic storms began on Nov 6 and 10. Figure 5(a) and (b) show the NOAA observations of >0.3MeV and 30-300keV electrons, respectively, for the interval from November 4 to 13. There was strong substorm activities during the storm time. Figure 5(b) shows a number of substorm particle injections during the storm time. In Figure 5(a)we see a numbers reduction of relativistic electrons at 3<L<6 during the main phase of the storm and an enhancement during the recover phase.

What is the source population of MeV electron filling the outer belt during the storm recover phase? In Figure 5(b) we see substorm produced intense injections of energetic electrons in the storm main phase (as well as in the recovery phase) before the increase of relativistic electrons in the inner magnetosphere. The substorm energetic electrons provided by substorm can be accelerated up to MeV by local energization mechanisms, such as wave-particle interaction, etc. Observations in Figure 5(a) and (b) thus strongly support the view that substorms can provide seed electrons for MeV electron enhancement associated with geomagnetic storms.

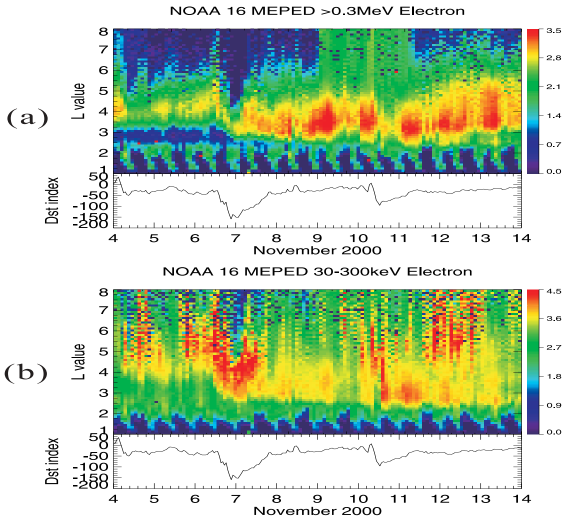

Figure 5. The counts rate of >0.3MeV electrons as a function of time and L-shell. The Dst index is shown below.

5. Conclusions

In the present paper we investigate the source of enhancement of relativistic electrons in the magnetosphere based on NOAA measurements. Upon all the observations we address the following views: (1) Substorm injections provide seed electrons for MeV electron enhancement associated with geomagnetic storms. (2) The Energetic electrons in the solar wind provide an alternative source for the relativistic electrons in the magnetosphere during the SEP events.

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Discussion

YOUSEF: It is very interesting that you found those relativistic electron. I have been looking for such events in order to test my model of acceleration found in this volume. Have you found other relativistic nuclei(ions) also during such events?

XIE: I didn't focus on the other relativistic ions during the SEP events. I only research the relativistic electron enhancement during the SEPs.

(NAME NOT WRITTEN): Do the relativistic electrons in the solar wind follow Parker's spiral?

XIE: The spacecraft used to measure relativistic electrons inside the Earth are NOAA, Polar, Sampex etc. We do not think electron detector onboard these satellites can tell us whether or not these electrons are along Parker's spiral.

KOUTCHMY: Can you say of your relativistic electron follow or not the Archimedes spiral (Parker) of the magnetic field coming from the sun? What is the angle of arrival at the Earth?

XIE: I think the relativistic electrons perhaps coming from the sun following the Parker orbit, but we have not directly observations. The angle of MeV electron measured by NOAA satellite is isotropic.