Large enhancement of highly energetic electrons in the outer radiation belt and its transport into the inner radiation belt inferred from MDS-1 satellite observations

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Abstract We have examined a large increase of relativistic electrons in the outer radiation belt and its penetration into the inner radiation belt over slot region using the MDS-1 satellite observations. Result of analyses demonstrates that a large increase took place in the spring and autumn seasons, and we have newly confirmed that the penetration of outer belt electrons to the inner radiation zone took place during the big magnetic storms by examining a pitch angle distribution of the penetrating electrons.

Keywords:

Introduction

Large increase of relativistic electrons causes satellite malfunctions as well as anomalies. Japan aerospace exploration agency (JAXA) has installed space environment detectors on several JAXA satellites to monitor space radiation weather (Obara et al., 2005, Obara et al., 2012). One of the unique satellites was the MDS-1 (Mission Demonstration Satellite-1), which had a geostationary transfer orbit. The MDS-1 satellite was launched in 2002 to examine relativistic electron dynamics in the radiation belt. Besides the large increase of relativistic electrons in the outer radiation belt, interesting issue in the radiation belt science will be a coupling of the outer radiation belt and the inner radiation belt during the large enhancement of outer belt electrons. The MDS-1 satellite enabled us to study such subjects.

Historically there have been a few geostationary transfer orbit spacecraft. Explorer 45 and CRESS (Combined Release and Radiation Effect Satellite) are the best examples. Based on these observations, many studies have been made to investigate a large increase of relativistic electrons during the geomagnetic storms (Friedel et al., 2002). Increase of relativistic electron flux in the outer radiation belt during the storm recovery phase could be explained by the internal acceleration processes by the low frequency plasma waves as well as ULF waves (Obara et al., 2001, Miyoshi et al., 2003, and references therein). Such wave activities are expected to occur very frequently both in the spring and autumn seasons (Miyoshi et al., 2011) due to the large increase of substrom activities.

Relationship between substorm activities and large increases in the intensity of relativistic electrons has been one of the interesting issues in the radiation belt study. Obara et al. (2000) examined the effects of the southward IMF and substorm on the rapid enhancement of relativistic electrons in the outer radiation belt during storm recovery phase. They concluded that continuous southward IMF leads to substorm activities and large enhancement of relativistic electrons. If this will be the case, a large increase is expected to occur both in spring and autumn seasons. One of the aims of this paper is to confirm such tendency based on the MDS-1 and other JAXA satellite observations.

Historically, coupling between the outer radiation belt and the inner radiation belt has been investigated in various radiation belt studies. Lyons et al.(1972), Lyons and Williams (1975a, 1975b) studied the deep penetration of the relativistic electrons into the low *L* region based on Explorer 45 observations. They investigated pitch angle distribution of the relativistic electrons in the slot region both in quiet time and in storm time. The structure of the relativistic electrons in the storm time is greatly distorted from the quiet time equilibrium structure of the relativistic electrons

Cannon et al. (2007) investigated pitch angle distribution based on the CRRES data. They classified pitch angle distributions into three categories; i.e. 90^0-peaked, flat top, and butterfly. They also used approximation of the sine function; i.e. $\sin^N\theta$, where θ is a local pitch angle. They studied *N* number and found flat top distribution is rather common nature in the outer radiation belt. Even though they have studied moderate or slightly disturbed cases, flat top distribution appeared in low *L* region; i.e. *L*=3~4.

Very extensive studies with respect to the pitch angle distribution of relativistic electrons have been done by Zhao et al.(2014a, 2014b). They used the data from the Van Allen Probes, showing a peculiar 90°-minimum pitch angle distribution in the slot region as well as the inner radiation zone. It has been reported by Baker et al.(2007) that the injection of relativistic electrons in the slot region is rare and only occurs during strong storms. Zhao et al. (2014b) performed a systematic investigation of the pitch angle distribution for the injected electrons in the slot region, and found the bump distribution around 90^0 around *L*=3~4.

Purpose of this paper is to confirm the pitch angle distribution of electrons in the outer radiation belt and the inner radiation belt together with the slot region. By using the MDS-1 date, we will examine the transport processes of outer belt electrons into the inner radiation belt during the strong magnetic storms.

MDS-1 observations of outer belt electrons

In order to investigate short-term variations of radiation belt electrons together with seasonal variations, the MDS-1 satellite was launched on Feb. 4 in 2002 and the satellite renamed Tsubasa meaning wing (Obara et al., 2009). The MDS-1 satellite took a geostationary transfer orbit, whose apogee, perigee, inclination and orbital period were 35,204 km, 209 km, 29.1 deg. and 11 hours, respectively. The radiation belt, which is one of the threats for the safe operation of satellites in space, was successfully observed by the radiation particle monitor on board the MDS-1 satellite.

Figure 1 demonstrates the *L*-t diagram of 0.4 MeV electrons together with *Kp* and *Dst* indexes for the year 2002, where we can recognize temporal variations of electrons both in the outer belt zone and the slot region. Because an orbital plane of the satellite inclined a little bit (29 deg.), the inner belt shows a slow change. This is caused by the latitudinal change of the inner belt electron intensity, which has a peak at the magnetic equator. On the contrary, many changes were seen in the outer belt region; i.e. $3 < L < 6$. Actually, we see that a large enhancement of electron flux which exceeds 10^6 (/cm2 sec str MeV) occurred during the magnetic storms and that the magnetic storms occurred more frequently in spring and autumn seasons in the year 2002. This tendency continued to year 2003 (not shown here but will be shown later) and a significant increase was evident in the spring of 2003. Another feature, we see in the figure, is a transportation of the outer belt electrons into the inner radiation zone across the slot region. The transportation was evident around day 110, day 252 and day 275 of year 2002. *Dst* index for these days was less than -150 nT, which means big magnetic storms.

By integrating electron flux along the satellite path, we have obtained a total dose for year 2002 as shown in Figure 2(A), in which a vertical axis demonstrates a total dose (rad/24h) and a horizontal axis shows the day of year. We see two peaks both around day 110 and day 280, which correspond to spring and autumn. The figure also accommodates the data obtained from another satellite; i.e. MEO satellite. The MEO satellite is also a geostationary transfer orbit satellite, which is largely same with the MDS-1, but a no-inclined satellite. It has been said that the flux of relativistic electrons is higher near the magnetic equator. The flux from MEO satellite seems a little bit larger than that from the MDS-1 satellite. Since the cross calibration has not been yet, we can't discuss quantitatively. Figure 2(A), however, show almost same tendency that relativistic electron increases significantly both in spring and autumn seasons.

Since the MDS-1 observation is very much limited in one year and thus is not convincing enough. When more data are available, we can say more about the seasonal variation of relativistic electron in the outer radiation belt. Hence, we used DRTS (Data Relay Test Satellite) data to confirm the seasonal variation of outer radiation belt electrons. DRTS was launched by JAXA into the geostationary orbit altitude, whose inclination and location are 0 degree and 90 degree east, respectively. Monthly averaged relativistic electron flux for almost ten years has been plotted in Figure 2(B). Energy range of electrons is ranging from 0.58 MeV to 1.18 MeV. We see two peaks in spring and autumn seasons, which is likely to be consistent with the MDS-1 variation in a qualitative manner.

Connection of outer belt and inner belt

It was found in Figure 1 that relativistic electrons sometimes penetrated into the inner radiation belt at least three times; i.e. day 110, day 252 and day 275 of the year 2002. Comparing with magnetic activity intensity, we found the penetration occurred when the magnetic storm was very large; i.e. *Dst* < -150 nT (Obara et al., 2005). In order to demonstrate the penetration of outer belt electrons into the inner radiation zone, we have examined the pitch angle distribution of relativistic electrons. Since we expect that electrons in the radiation belts seem to have pancake distribution, we have tried to fit pitch angle distribution by sine function; i.e. $\sin^N\theta$, where θ is the local pitch angle.

Result of fitting for absolute flux is given in Figure 3(A), where a vertical axis shows *L*-value and a horizontal axis demonstrates orbit number after the launch. *N* value is demonstrated with a color and the color code is given in the right. We found that the *N* number in the outer radiation belt (*L* > 3) is close to 0.3 (lowest value), which means that the electron distribution is rather flat with respect to the pitch angle. On the contrary, electrons in the inner belt has a sharp peak at θ = 90°, keeping high value more than 3. We can, therefore, distinguish outer belt electrons and inner belt electrons by looking at the obtained *N* number.

On days 110, 252 and 275, which correspond to orbital numbers of 160, 480, and 550, respectively, relativistic electrons of the outer belt origin got penetrated into the inner radiation belt, keeping low *N* value and filled there. We also see such penetrations for orbit numbers of 825 and 1090 both in year 2003. We believe that number density of penetrating electrons seems to be high, exceeding that of pre-existing inner belt electrons, since we could fit electron distribution without problem. This tendency will be confirmed by looking at *L*-t diagram as shown in Figure 3(B). Our analysis suggests that outer belt electrons penetrate into the inner belt region during the large magnetic storms and become a significant source of the relativistic electrons in the inner radiation belt.

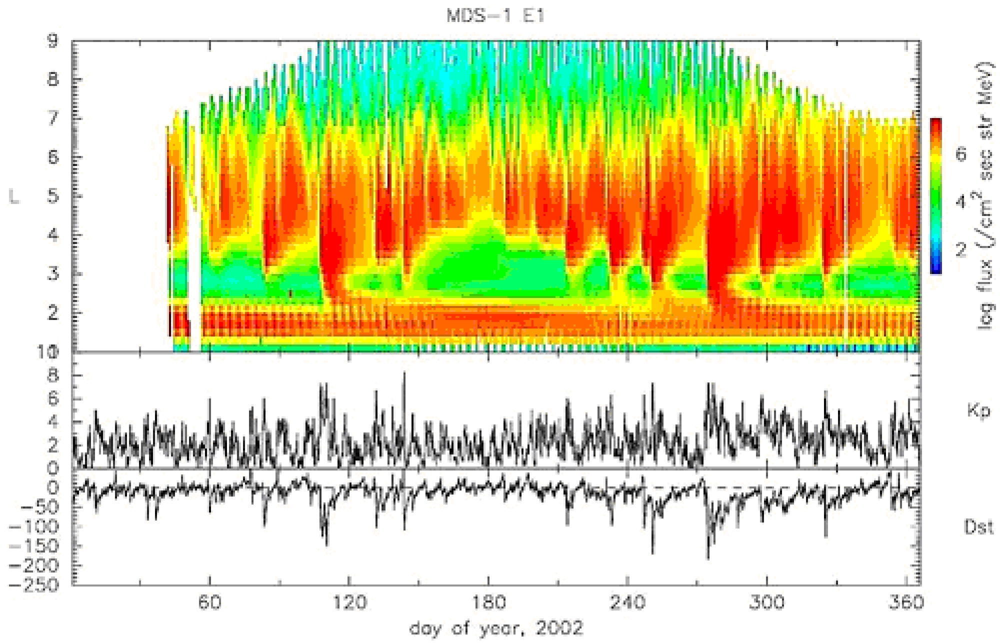

Figure 1: Spatial and temporal variations of radiation belt electrons with energy of 0.4MeV obtained by the MDS-1 satellite (top), *Kp* index (middle) and *Dst* index (bottom) are given as a function of day of year 2002. We see large increases of electron flux which exceed 10^6 (/cm2 sec str MeV) during the magnetic storms.

The figure also tells that it took one or two days for outer belt electrons to move from L = 3 to L = 2.5 and took about ten days from L = 2.5 to L = 2. This means that diffusion coefficient is getting smaller with a decrease of L-value.

Discussion and concluding remark

We have demonstrated space-based observations which have been conducted by the MDS-1 satellite from February 2012 to September 2013. By using these data, penetration of outer belt electrons into the inner belt zone over the slot region was confirmed. There have been several data to show pitch angle distribution of penetrating electrons as given in the introduction of this paper: i.e. Lyons et al.(1972), Lyons and Williams (1975a, 1975b), Cannon et al. (2007), and Zhao, H.(2014a,2014b). They pointed that penetration of outer belt electrons into the inner belt zone and Zhao, H.(2014a,2014b) demonstrated new findings relating to the local dip of 90^0 deg pitch angle electrons. The MDS-1 satellite was fortunately a spin type satellite, which enabled us to obtain a pitch angle distribution of the radiation belt electrons. Results of the MDS-1 observations for one year and half confirmed relativistic electron penetrations which have been shown in the previous studied and such penetration occurred during strong magnetic storm cases.

Results demonstrated that a large amount of electrons went into the inner radiation belt keeping the signature of outer belt electrons over slot region, and survived for significant time in the inner radiation belt. Even though it needs more careful studies to examine life time of newly transported electrons into the inner radiation zone, this paper could demonstrate the evidence of the supply of electrons into the inner radiation belt region during large magnetic storms.

Even though the evidence that shows the difference of pitch angle distribution between the outer belt and inner belt is evident, we still have little knowledge how the electrons have more pancake-like distribution during the transport. In the outer belt, electrons show rather flat nature almost all the time even when the intensity of electron flux increases. Our data suggests that the pitch angle scattering is more effective in the outer radiation belt. When the outer belt electrons move inward, they might be expected to be more pancake-like distribution due to hold the adiabatic invariants. Actually we see this tendency by comparing color code in Figure 3(A). This paper, we think, is just to report our first step of the pitch angle study at around the slot region, and more comprehensive analyses should be needed to understand acceleration processes, transport process and, of course, loss process. We will do follow us study shortly.

Enhancement in the intensity of outer radiation belt electrons during the recovery phase of the magnetic storms was large for large magnetic storms. Obara et al.(2000) compared substrorm effect on the large enhancement of the outer belt electrons and demonstrated such activity was large both in spring and autumn seasons. For the semiannual variation of substrom activities several hypotheses have been proposed. Investigation of semiannual variation of the relativistic electrons in the outer radiation belt is one of the outstanding questions in the field of radiation belt study, more comprehensive observation should be needed, since JAXA MDS-1 satellite has no wave measurements.

The institute of space and astronautical science (ISAS) in JAXA is now manufacturing ERG satellite, which will be launce middle of next year 2016. The ERG satellite will measure highly energetic particles with sufficient pitch angle information, magnetic field and wave signatures. From the analysis of the data from the ERG satellite, we will be able to improve models which have been proposed to explain dynamical behavior of radiation belts especially in the slot region.

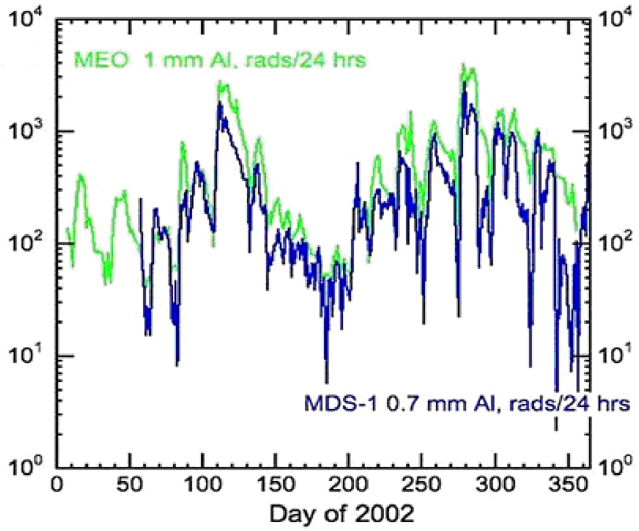

Figure 2(A): Variation of the total dose (rads/24h) obtained from MDS-1 and MEO satellites. Large increase is seen both in spring and autumn seasons.

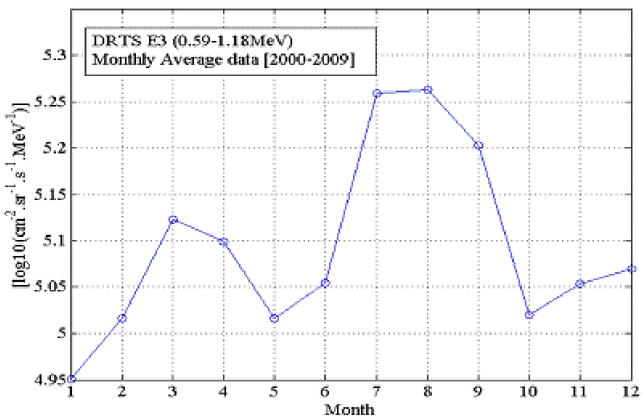

Figure 2(B): Variation of relativistic electron flux from DRTS satellite. Increase is seen both in spring and autumn seasons.

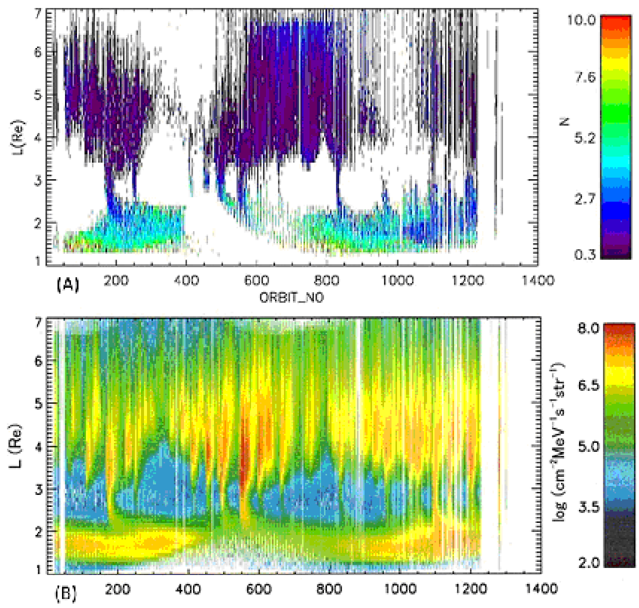

Figure 3: (A) Variation of the N number for pitch angle distribution evaluated from the MDS-1 data is given. We can see evidently that electrons with rather flat nature with respect to the pitch angle penetrate into the inner radiation zone. (B) *L*-t diagram for electrons is shown, just for reference.

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