Highly Energetic Electron Environment in the Inner Magnetosphere

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ABSTRACT

Highly energetic electrons in the outer radiation disappear during the main phase of the magnetic storm, and rebuilding of the highly energetic electrons is made during the recovery phase of the magnetic storm. A distribution of the new peak of highly energetic electron flux with respect to the distance from the Earth is inversely proportional to the magnitude of the magnetic storm. In case of the super storm, the outer electron belt is pushed toward the Earth, filling so-called slot region. It is of interest to identify that the location of the intense low frequency plasma waves, which appear during the storm recovery phase, coincides with the location of the peak intensity of the highly energetic electrons in the outer radiation belt. This coincidence strongly suggests that an internal acceleration process takes place which leads to a large increase in the intensity of highly energetic electrons in the outer radiation belt during the storm recovery phase. A seasonal variation of the outer radiation belt is identified. The increase in the intensity of the highly energetic electrons is large both in spring and autumn seasons. The magnetic activity is also large both in spring and autumn seasons. Correlation of the increase in the intensity of highly energetic electrons with the magnetic activity is identified. A solar cycle variation of the outer radiation belt is identified. The location of the outer radiation belt was found closer to the Earth during the solar maximum periods and far from the Earth during the solar minimum periods. This variation is due to the evidence that large magnetic storms occur largely during the solar maximum periods, while small magnetic storms take place largely during the solar minimum periods, resulting a long-term solar cycle variation with respect to the distance from the Earth.

DYNAMIC BEHAVIOR OF THE HIGHLY ENERGETIC ELECTRON OUTER BELT DURING THE MAGNETIC STORM

Mission demonstration satellite 1 (MDS-1) was launched on Feb.4, 2002 into the geostationary transfer orbit (GTO) with an inclination of 28 degree and an orbital period of 10 hours. The MDS-1 satellite was renamed TSUBASA, meaning wings after launch. On this satellite a high energy particle detector was installed. The results are given in Fig.1. Top panel in the figure shows *L* - t diagram, where the vertical axis shows *L* - value ranging from *L* = 1 to 9 and the horizontal axis gives time covering three months with a start of April 1, 2002. We can see electron flux enhancements many times. These enhancements are caused by the magnetic storms. One example showing the dynamic variation of the electron outer radiation is given in Fig.2. Vertical axis shows the flux of 0.4-0.91 MeV electrons and horizontal axis is *L*-value. Around noon of April 17, a magnetic storm started and the *Dst* reached –120 nT early of April 18. The storm developed once again on April 19 and the *Dst* reached its minimum (-150nT) early on April 20 and then recovered gradually.

Individual measurements of MDS-1 are given in Fig. 2. Around 18UT on April 16, there was a peak of outer electron belt at $L = 5$ and it persisted till 09UT on April 17. The flux then decreased largely by 15UT on April 17; only a few hours after the commencement of the storm. The peak flux decreased more than one order of the

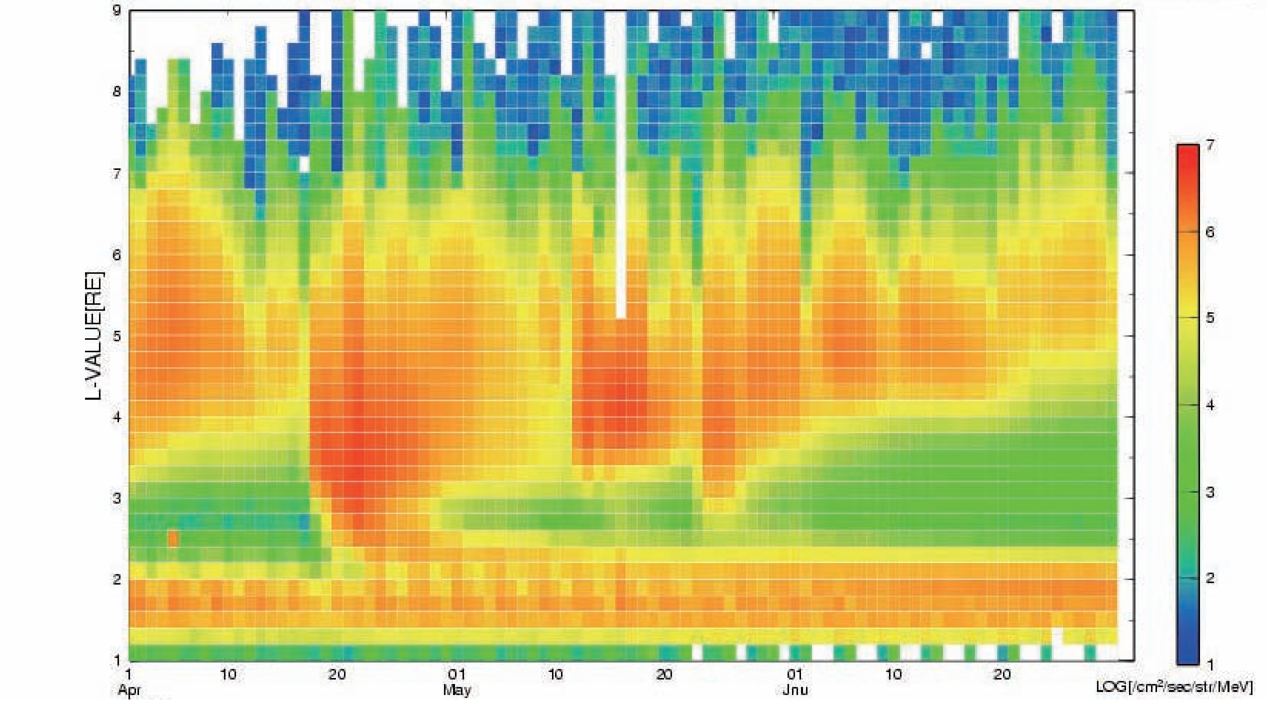

Fig.1. *L*-t diagram of 0.4 MeV to 0.91 MeV electrons and *Dst* index in 2002.

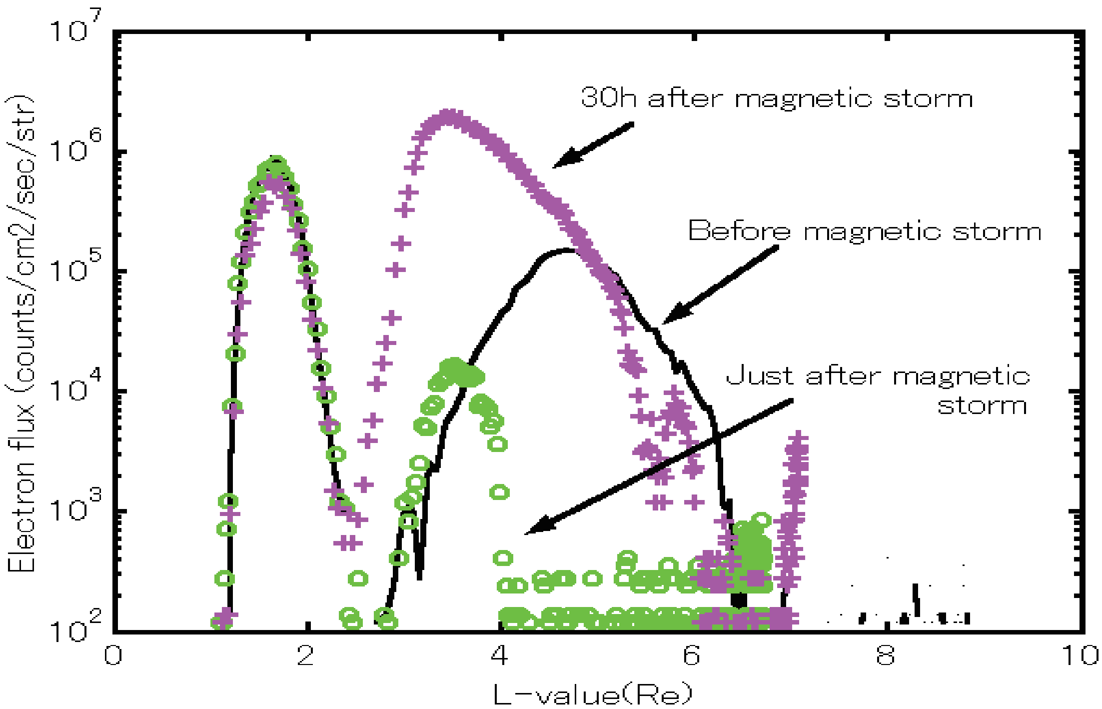

Fig.2. Variation of radiation belt profile measured by MDS-1 satellite. Each line demonstrates flux of electrons in the unit of $(cm^2 \text{ sec st. MeV})^{-1}$, covering three days from April 16 to April 18.

magnitude and the peak location approached the Earth: i.e. L = 3.5. The magnetic storm continued on April 18, keeping *Dst* index around –100 nT. There were prolonged magnetic activities over April 18 producing quasi-periodic substorm injections every three hours or so. First injection was identified around 3UT by the LANL satellite and strong disturbances of the magnetic field were seen by the ground-based magnetometer. Due to this prolonged magnetic activities the flux of outer belt electrons increased significantly, exceeding pre-storm level. It should be mentioned that a new peak location of the outer radiation belt shifted toward the Earth; i.e. L = 3.5, which is consistent with Akebono simultaneous measurements and also consistent with statistical result (Obara et al., 2000).

During the life-time of MDS-1 satellite; i.e. one year and half, there were almost 30 enhancements in the flux of outer belt electrons with energy of 0.4 – 0.95 MeV. The results are given in Fig. 3, in which a peak position of newly formed outer belt during the storm recovery phase is plotted as a function of minimum *Dst* of each storm. There seems to be a correlation of the peak position and *Dst* value; a large storm produces a new outer electron belt closer to the Earth. This result is largely consistent with Obara et al. (2000) and O'Brian et al. (2003).

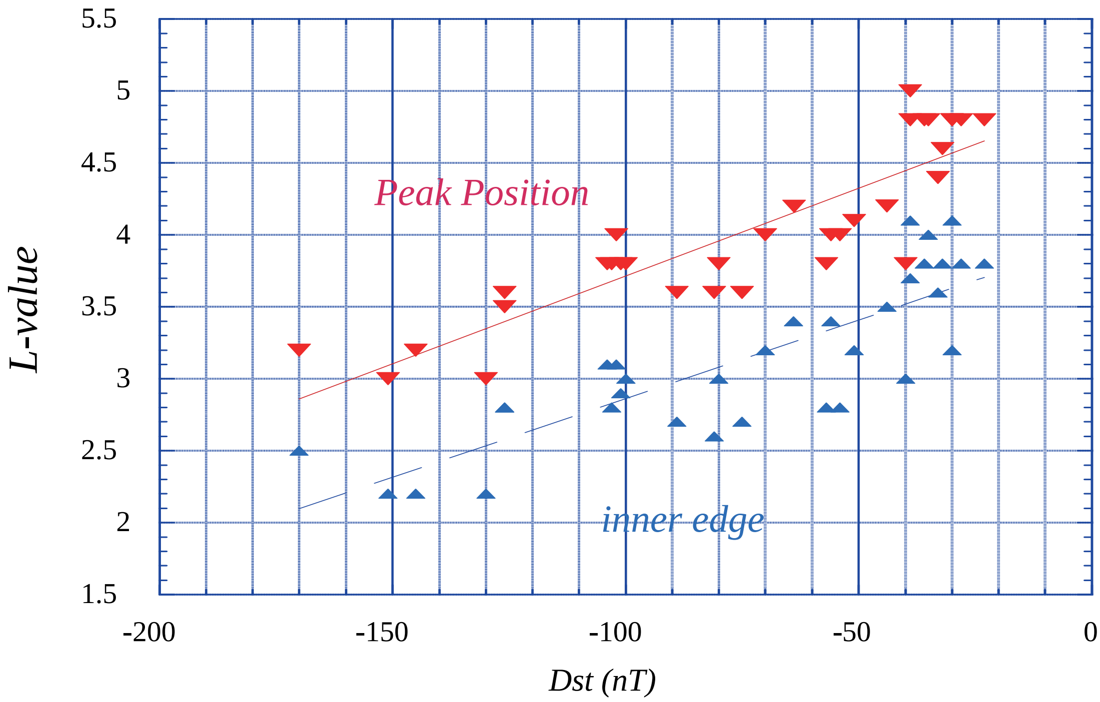

Fig. 3. Peak position of newly developed outer belt as a function of *Dst*. Inner edge of the newly formed belt is also plotted.

MDS-1 measurements show a clear relationship between the peak position of the energetic electron flux and *Dst* variations. This tendency is largely consistent with previous works Obara et al. (2000), O'Brian et al. (2003) and Tverskaya (2002). This is consistent with being caused by the transport of seed electrons during the main phase or early recovery phase (Obara et al., 2001). Advantage of MDS-1 measurement is that the observation has been made near the magnetic equator. We can clearly identify the inner edge of newly developed outer electron belt as given in Fig. 3. Location of inner edge is much closer to the Earth than that of peak location. This means that the transport of seed electrons is quite efficient near the Earth than as expected. Detail processes are however unclear at present. We need to investigate energetic electron transport mechanisms much more thoroughly.

The Akebono satellite measured VLF (very low frequency) chorus emissions along the orbit. The peak location of wave amplitude largely coincides with that of energetic electrons (Obara et al., 2006). Whistler mode chorus emission can accelerate seed electrons up to MeV range (Obara et al., 2000 and 2001, Miyoshi et al., 2003). MDS-1 and Akebono measurements show the coexistence of energetic electron enhancements and the VLF chorus emissions. These observations confirm many results found using the previous satellites in the different orbit. Next step will be the quantitative study how the VLF waves produce relativistic electrons in the outer radiation belt.

Important physics of the outer electron radiation belt includes injection or transportation of seed electrons, acceleration of electrons. We have examined these issues by investigating super storm events. Outer belt electrons are pushed toward the Earth very rapidly at the commencement of the super storms, filling the slot region. One example is given in Fig.4, where electron fluxes with energy of >300 keV is demonstrated in the top of the figure as a function of time. *Dst* index is given in the bottom panel. On day of 197 in 2000 an intense interplanetary shock wave hit the Earth, causing a terrible large magnetic storm. The *Dst* index reached down to –300 nT. NOAA satellite measured the >300 keV electrons on the morning-evening meridian plane with an orbital period of 90 min. With a development of the storm main phase, energetic electrons were pushed toward the Earth, forming a new radiation belt in the slot region. By day of 199 additional population of 300 keV electrons has been produced in the outer radiation zone; i.e. ranging up to *L*=5 or so. On day of 202 a slight but significant depletion of 300 keV electrons is identified around *L*=3, which became slot (Obara et al., 2005).

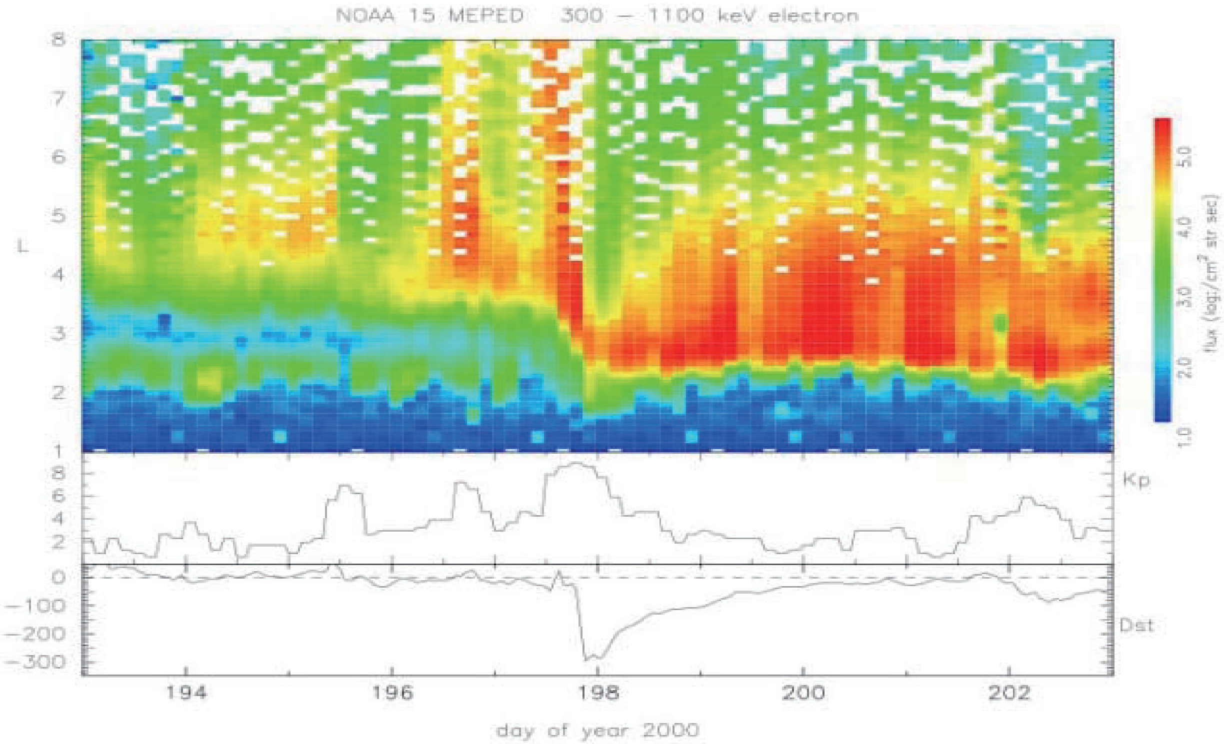

Fig. 4. *L*-t diagram for electrons with energies of >300keV (top), *Kp* index (middle) and *Dst* index (bottom) for the Bastille day super storm. Electron data were measured by NOAA 15 satellite.

Large transport of outer radiation belt electrons might be caused by the enhanced convection which reaches down to *L*=2.5 during the main phase of the super storm. Several satellites such as DMSP and Akebono have observed such enhanced convection in a subauroral and middle latitude zone. We believe the transport is made by this enhanced convection rather than the SC induced electric field proposed by Hudson et al. (1997), since it took several hours for the movement of the inner edge of outer electron belt to the slot region. During the recovery phase of the super storm, a large enhancement in the intensity of energetic electrons around *L*=4 was seen. By analyzing Akebono radiation electron data we have obtained a large increase of phase space density, which means additional internal acceleration actually took place in the heart of outer radiation belt (Obara et al., 2005).

LONG-TERM VARIATIONS IN THE OUTER RADIATION BELT ELECTRONS

Interesting feature of the outer electron radiation belt in a long-time scale has been identified in the MDS-1 data. Fig. 5 demonstrates observations of highly energetic electrons by the MDS-1 together with MEO. MED is a geostationary transfer orbit satellite which is largely same with MDS-1 but one difference is inclination of the orbit.

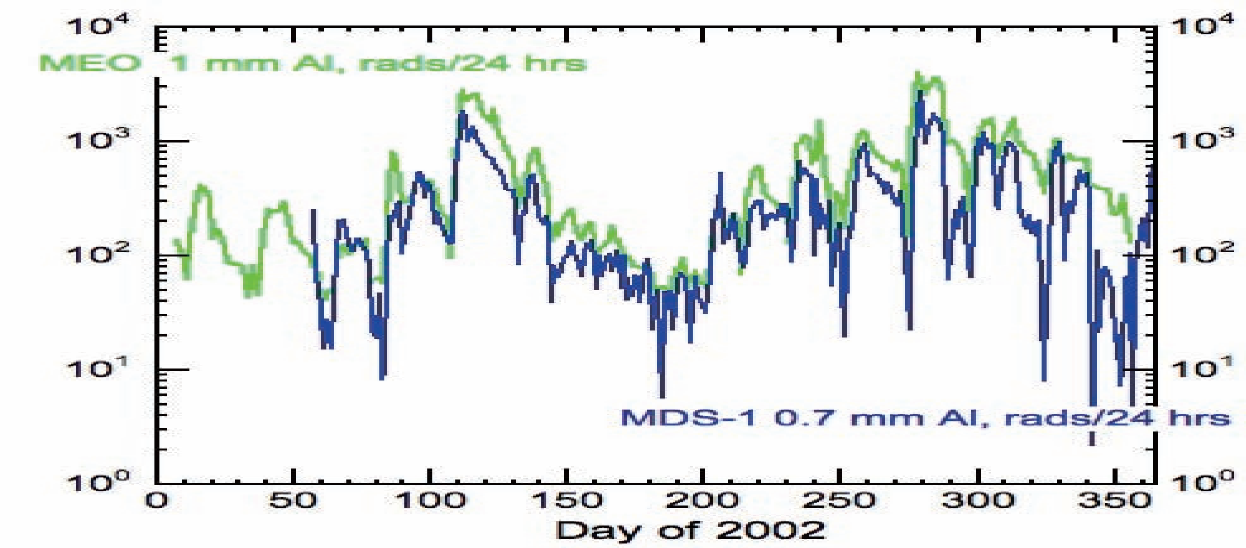

Fig. 5. Variation of total dose form MDS-1 and MEO satellites. Large increase is seen both in spring and autumn seasons.

We can see two peaks in the intensity of total dose. Peak appears both in spring and autumn seasons. Though inclinations of both satellites are differ, two lines in Fig. 5 show almost same intensity. This means that highly energetic electrons have isotropic nature, and this is consistent with pitch angle measurements by MDS-1 (Obara et al., 2006). Why the magnetic activities are high both in spring and autumn is the effect of the tilting of the Earth's magnetic field. If the intensity of highly energetic electrons increases due to the large magnetic activities, this evidence supports the internal acceleration model proposed by Obara et al. (2001).

Interesting feature of the outer electron radiation belt in a long-time scale has been identified in the NOAA data. Fig. 6 demonstrates observations of >300 keV electrons for more than 20 years. A location of the outer radiation belt was found to be closer to the Earth during the solar maximum periods and far from the Earth during the solar minimum periods. Location of the outer radiation belt is decided by the magnitude of magnetic storm (Obara et al., 2000) and the occurrence probability of the large magnetic storm is high during the solar maximum periods. Portions with red circles in Fig.6 demonstrate the periods when the big magnetic storms actually took place.

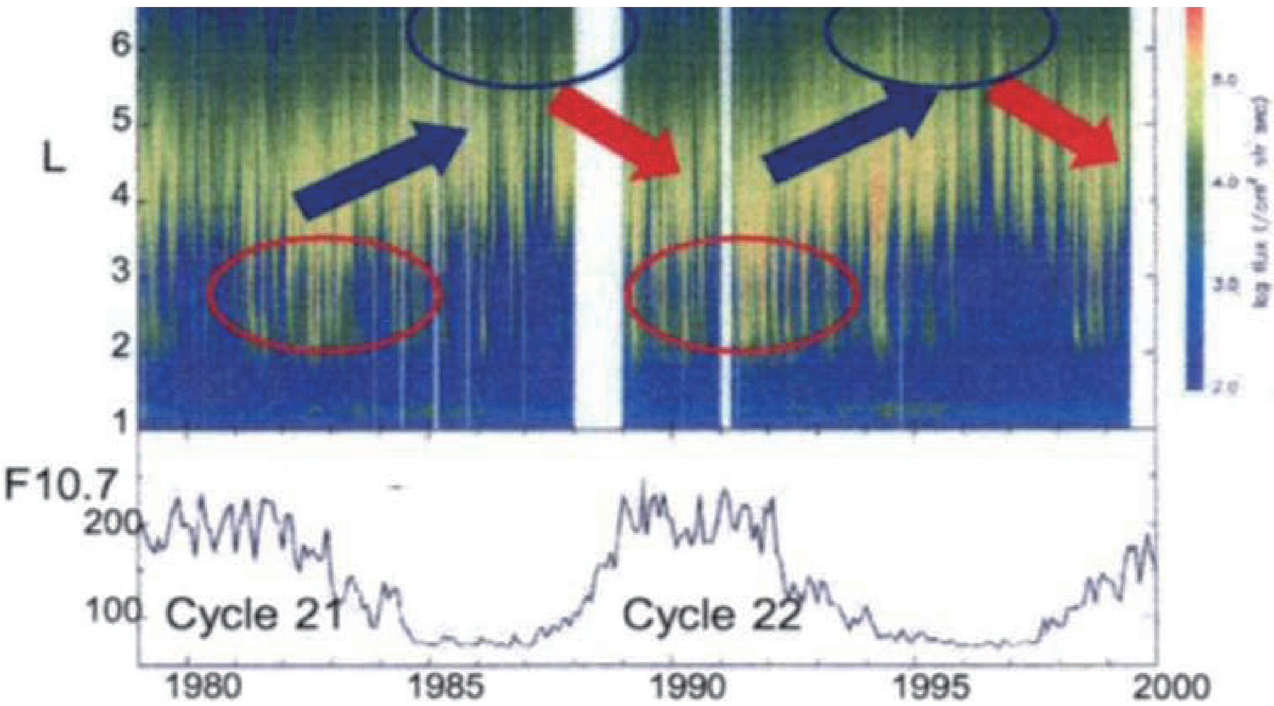

Fig. 6. Lon-term variation of >300keV electrons fort he last two decades. Bottom panel shows F10.7 flux. Enhancement of the electrons in the slot region is evident during the solar maximum periods (Miyoshi et al., 2004).

A highly energetic electron at geostationary orbit altitude is enhanced during the high-speed solar wind velocity periods. The high-speed solar wind is mainly caused by the coronal holes and they are evident during the declining phase of the solar activity. With the lack of the large magnetic storms during the solar minimum periods, the outer radiation belt moves outward compared with the solar maximum periods. Miyoshi et al. (2004) also demonstrated that there is a good coincidence between the plasma pause location and the peak location of >300 keV electrons. This evidence suggests that plasma pause takes an important role in making strong VLF emissions during the magnetic storm and the electron acceleration is possible to make highly energetic electrons there.

Non-adiabatic acceleration by VLF waves (Obara et al., 2001 and Miyoshi et al., 2003) is still one explanation in making relativistic electrons in the outer radiation belt during the storm recovery phase and we should like to confirm this by an international array of geostationary transfer orbit (GTO) satellites such as ERG satellite by ISAS/JAXA, ORBITALS satellite by CAS, RBSP satellites by NASA and RESONANCE satellite by IKI in very near future.

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