Comparison of trapped particle intensities in SAA region observed by two Japanese satellites, USERS and SERVIS-1

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***Abstract*— Particle data observed by two Japanese satellites, USERS and SERVIS-1 in the altitude of 600 km and 1000 km, respectively, are used to investigate the geographical and temporal variations of protons trapped in the South Atlantic Anomaly region during large two successive storms within several days. Both geographical boundary of the SAA after the storms in November 2004 obtained by the satellites did not show any changes from the one before the storms. The proton intensity at the centre of SAA increased rapidly at the beginning of the 2nd storm, while the one in the outer region of SAA increased gradually in the recovery phase of the 2nd storm. However, any intensity changes were not shown in the 1st storm.**

I. Introduction

The intensity of particles being trapped in the South Atlantic Anomaly, so-called SAA, over Brazil is much higher than that in any other region. The origin of the SAA is causally related to the anomalous distribution of geomagnetic field, the intensity of which is the lowest as compared with those in any other region, since it is much different from that as estimated from its dipole approximation.

Since the discovery of SAA, many ideas have been put forth to interpret on how the anomalous behavior observed for the temporal variation in both proton and electron intensities are originated (e.g., [1], [2], [3]). However, it has not been resolved as yet what mechanism is essentially responsible for the temporal behavior of the particles being trapped in the magnetosphere, in particular, the temporal variations of those particles inside SAA. In order to search for this mechanism, the observed results available from various satellites have been analyzed up to now. For instance, our group has reported the enhamcement by about five times of protons and electrons in the SAA region after the one of biggest magnetic storm at the end of October 2003 which was observed by the Japanese satellite, USERS [4], [5]. It seems that the temporal variations in the intensities of both protons and electrons being trapped in the inner magnetosphere before and after some large magnetic storms may give us some insight to get a clue to resolve the behavior of these particles inside SAA and its nearby region. We have tried to analyze the observed results available from two Japanese satellites, USERS and SERVIS-1, their orbiting altitudes of which were appropriate to investigate the temporal variation of both protons and electrons in and outside SAA of the inner magnetosphere. This paper mainly concentrates the behavior of protons in the SAA. The case of electrons in the SAA will be reported in the near future.

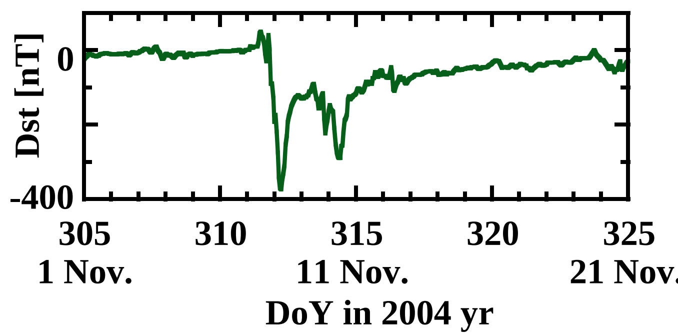

Fig. 1. The temporal variation of Dst index in November 2004. Two successive magnetic storms were observed on 7th and 10th November.

II. Observations

Using the data on trapped protons as observed by Japanese satellite, USERS and SERVIS-1, both of the geographical and temporal variations of these protons in the SAA region during magnetic storms were analyzed and compared with some parameters of geomagnetic storm during the period from October to November 2004 . Two *successive* large magnetic storms occurred on 7th and 10th November 2004 (hereafter called November storm), both of which were found during the period. The Dst indices which present the characteristics of geomagnetic disturbance near the equatorial region reached to about -400 nT and -300 nT, respectively (Fig.1). The first storm on 7th day caused an aurora at middle latitude area as Hokkaido in Japan (140°E, 45°N). A similar *successive* storms also happened at the end of October 2003 which is very famous storm called Halloween event [6].

The Japanese satellites, USERS and SERVIS-1, had been operated by the Institute for Unmanned Space Experiment Free Flyer (USEF) in Japan. These satellites observed trapped particles in similar energy range, but their orbital parameters are quite different from each other. The characteristics of these two satellites are briefly described as follows. The details of these satellites and the particle detectors onboard them have been reported earlier [4].

A. The USERS satellite

The USERS (Unmanned Space Experiment Recovery System) satellite was in operation from 10 September, 2002 to 25 February, 2005 at the altitude of 500 – 600 km with the inclination of 30 degrees. In order to observe the radiation environment, the satellite had the Environment Measurement System (EMS) onboard USERS, whose system consists of three light particle detectors (hereafter called LPDs) and a dose monitor. The LPDs facing sight angles to each other as anti-solarward, southward and eastward, respectively, made the observation on trapped protons for the energy range from 15 to 130 MeV, electrons from 0.7 to more than 18 MeV and α particles from 16 to 100 MeV. The proton data obtained by the LPD for anti-solarward direction was made in use for investigating the SAA in this report.

B. SERVIS-1 satellite

The SERVIS-1 (Space Environment Reliability Verification Integrated System 1) satellite had been flown in dawn-dusk plane with the inclination of 100 degrees in the altitude of 1000 km. The satellite carried an EMS package consisted of an LPD, two single event upset monitors, three dose monitors and three shield dose monitors. The LPD aligned to anti-solar direction had also observed protons in the energy range 1.2 – 150 MeV, electrons in 0.3 – 10 MeV, α particles in 7 – 640 MeV and heavy ions in 2 – 160 MeV/nucleon during the period from 1st December 2003 to 31st October 2005. This report only focuses on the proton data available from the LPD for the SERVIS-1 satellite.

III. Observed Results

A. Geographical distributions

The geographical distributions of the counting rate for trapped protons before and after the November storm are displayed in Fig.2 for the USERS satellite and Fig.3 for the SERVIS-1 satellite. Both upper and bottom panels in each figure show the distribution before and after the storm, respectively. The energy ranges are similar from each other which are 15.9 – 44.1 MeV for the USERS satellite and 12.5 – 24.5 MeV for the SERVIS-1 satellite. The geomagnetic strength distributions based on IGRF2005 model are also expressed by red line in these figures.

The enhancement of proton intensities in the SAA region above Brazil is clearly seen for each of these distributions. In particular, as the location approaches to the centre of the SAA, which corresponds to low geomagnetic strength, the proton intensity becomes higher. The SAA region observed by the

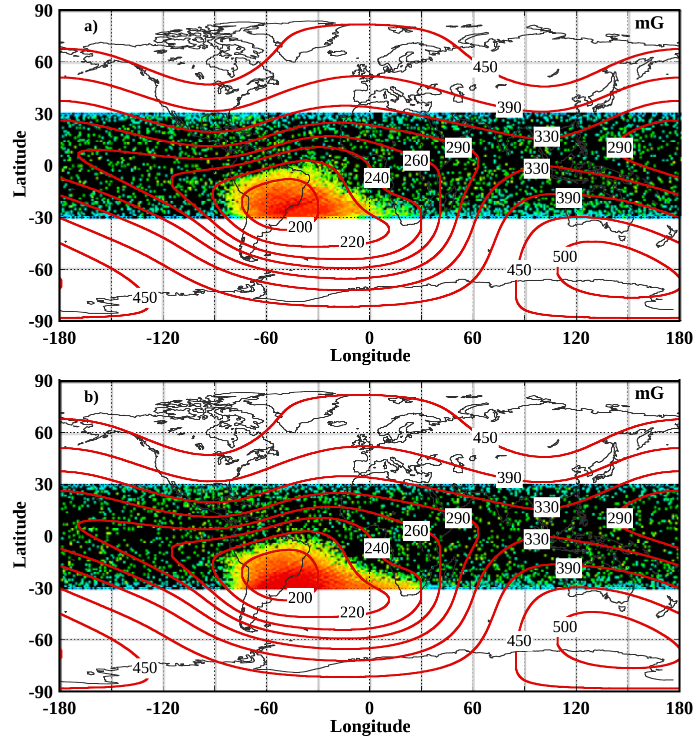

Fig. 2. Geographical distributions of proton counting rate with 15.9–44.1 MeV obtained by USERS satellite. The observation periods for top and bottom panels are 20 days before and after the November storm, respectively. Red linse contour in a map show geomagnetic strength in mG unit.

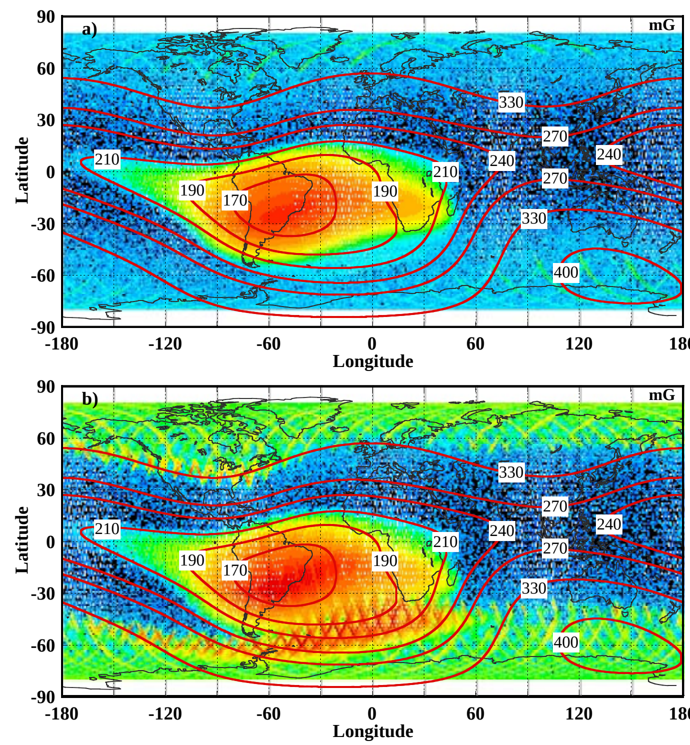

Fig. 3. Geographical distributions of proton counting rate with 12.1–24.5 MeV obtained by SERVIS-1 satellite. The period and the contour are the same as Fig.2.

SERVIS-1 satellite is much larger than the one observed by the USERS satellite. The SAA obtained by the USERS covers the area from the east sea of Chile to the east sea of the South Africa, while the one obtained by SERVIS-1 is located in a vast region from the Easter island to the Madagascar island. As compared with the geomagnetic strength contour, the boundary of SAA produced by protons consistent with the geomagnetic contour line of about 210 mG in these four figures despite that the observation altitude is different between the USERS and the SERVIS-1 satellite and the different observational period is also different: the one is before and the other is after the November storm. However, the boundaries around the south-eastern region of the SAA obtained by the SERVIS-1 satellite are not aligned with the line of 210 mG in strength. Moreover, a new proton belt appeared below the south-eastern region of SAA. This belt is aligned to the L-shell of 3.

In the SAA, the clear increase of the proton intensity were observed by both satellite data after the onset of the storm as compared with that before the storm, while the fringe of the SAA region did not show any expansion, except for the east region of SAA observed by the USERS.

B. Temporal variations

Temporal variations of proton intensities in the SAA region during the November storm are shown in Fig.4. Top four panels are divided by referring to total geomagnetic strength, B_t, and each color line is distinguished by L-shell. Basically, the region at a small B_t and a small L-shell is close to the centre of SAA. In the lowest panel of the figure, the Dst index is shown and measured with left axis and the magnetic strength of north component in interplanetary magnetic field (IMF), B_z, observed by the ACE/MAM is indexed with right axis. It should be noted that the top four figures are made by referring to the data of the SERVIS-1 satellite only. The USERS satellite did not give us any temporal variation in a specifically small region as done by the SERVIS-1 satellite, because of its complicated orbital motion. However, the variations obtained by the USERS are roughly similar to those of the SERVIS-1.

It is clear that the intensity increased at the beginning of the second disturbance of the November storm, but there was no increase at the first disturbance. The timing of flux increase is different between the centre and the outer region of the SAA. In detailed comparison, the proton intensity increased rapidly near the centre of SAA when strong northward component of the disturbed IMF in the 2nd disturbance reached to the earth, but not in the case of the southward IMF disturbance. Based on the outer region of SAA, the proton increase began in the recovery phase of the 2nd disturbance. The increasing rate of proton intensity in the centre of SAA is larger than that in the outer of SAA, except for the south-eastern region of SAA corresponding to the green lines in Fig.4(c) and (d).

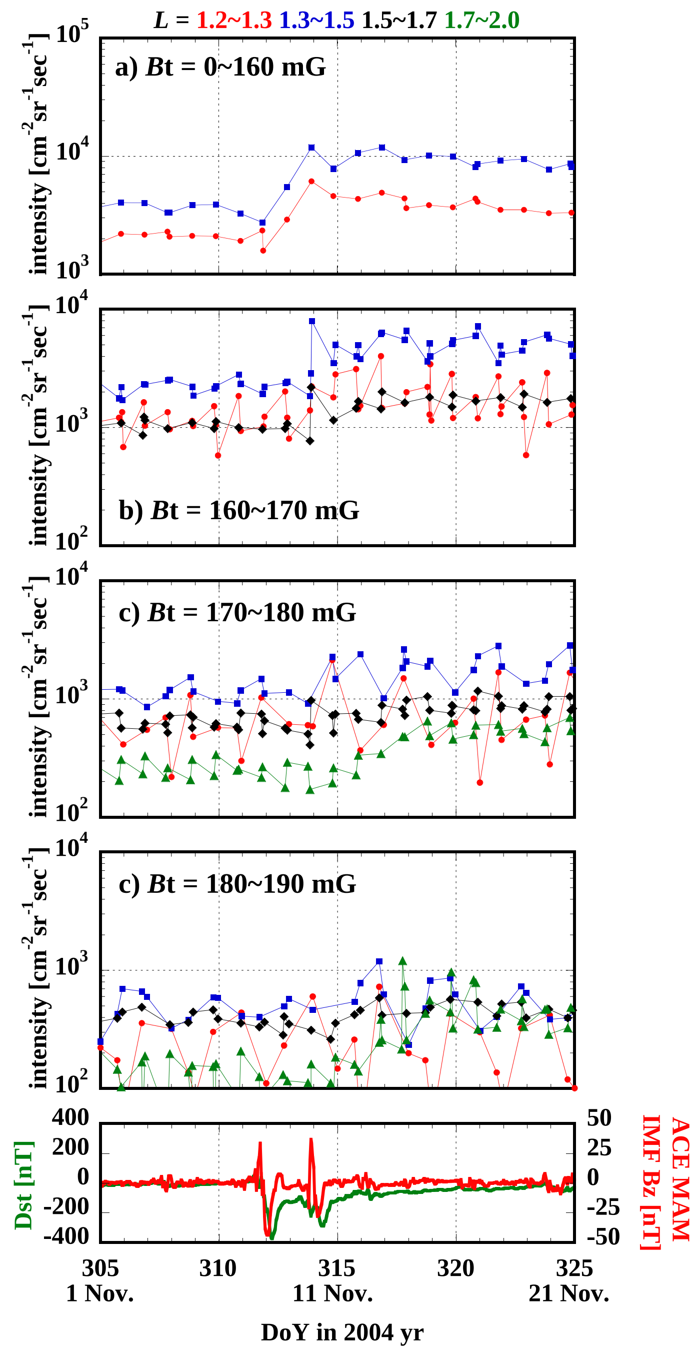

Fig. 4. Temporal variations of proton intensity in the SAA region during the November storm observed by SERVIS-1 satellite. Top four panels show the temporal variation distinguished by B_t. The color lines are also distinguished by L-shell. The bottom panel shows the Dst index with the left axis and the IMF B_z component obtained by ACE/MAM level 2 data.

IV. Discussions

A. The boundary of SAA

In the previous section, the boundary of the SAA as found from the observations by the USERS and the SERVIS-1 satellites is coincident with about 210 mG contour of total geomagnetic strength. According to the Alfven criteria, the maximum energy of ions trapped in magnetic field is determined as follows:

$$\frac{\rho_L}{\rho_m} \ll 1, \qquad (1)$$

where ρ_L is the particle Larmor radius and ρ_m is the curvature radius of magnetic field line. However, the curvature of geomagnetic field must be different between the observation altitudes of the USERS and the SERVIS-1, despite that the total geomagnetic strength is same from each other. And that will be also different between the different edge regions at the same total magnetic strength. If it were the case, the boundary of proton SAA could be determined by some other mechanisms except for Alfven criteria, although it is necessary for some more detailed analyses to clarify the structure by taking into consideration such as numerical analyses and data analyses in other energy region, other particles and so on.

B. Anomaly in the south-east region of SAA

The boundary structure and temporal variations of protons around the south-eastern region of SAA are different from those of the other region in the SAA. The geographical distributions of trapped protons before the November storm are compared with the contours of L-shell and the horizontal component of geomagnetic strength, $B_{\rm xy}$, in top and bottom panels of Fig.5, respectively. The boundary of anomaly region in the SAA is aligned with L-shell of 2.0. As compared to $B_{\rm xy}$ contour, the anomaly region coincident clearly with the anomaly of $B_{\rm xy}$ component. The declination of geomagnetic field is about 80 degrees and the $B_{\rm t}$ is small as 210 mG in this $B_{\rm xy}$ anomaly. In this area known as the drift loss cone or the bounce loss cone [7], [8],drifting protons and electrons in L-shell of $2.0 \sim 3.0$ at 1000 km will penetrate to the deep atmosphere without magnetic mirroring and then be absorbed over there. Therefore, the boundary at the south-east region of SAA is aligned to L-shell of 2.0. The new belt of protons appeared below the anomaly in the SAA is also thought to be caused by the anomaly of geomagnetic horizontal component. Trapped flare particles drifting around L-shell of 3 will be concentrated to this anomaly region after the November storm [9].

C. The variation of proton intensity in SAA

The proton intensity had increased in the 2nd storm, but not in the 1st storm. And its increasing ratio is higher in small strength of total geomagnetic field than that in the large strength. In order to clarify this variation, the correlation between the intensity and total geomagnetic strength related to L-shell is shown in Fig.6. The intensities before and after the November storm are shown by filled circle and square with left axis and their ratios are shown by diamond with right axis. The clear correlations are seen for the intensities and its increasing ratio is high in the region with low strength of total geomagnetic field than those in the region with high geomagnetic strength except for the region of $L = 1.7 \sim$

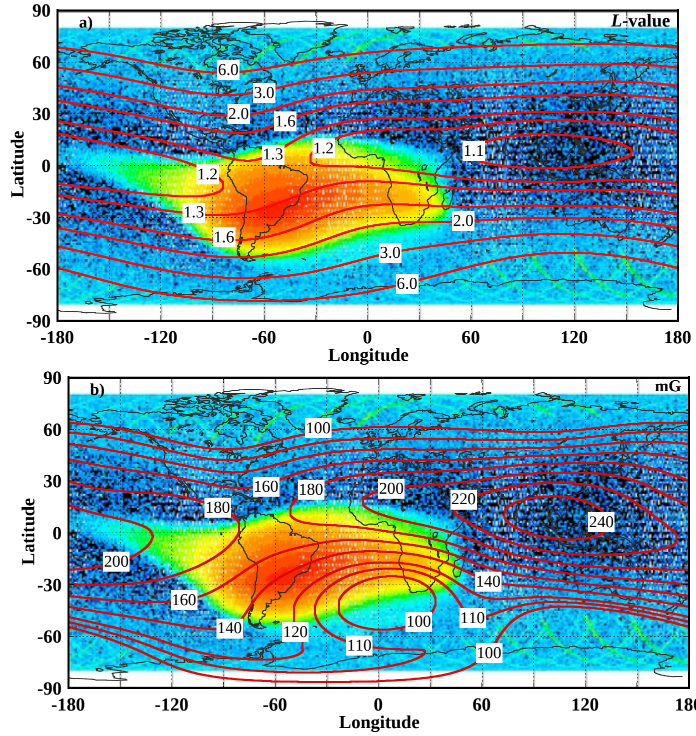

Fig. 5. Geographical distributions of proton counting rate with 15.9–44.1 MeV obtained by the SERVIS-1 satellite with L-shell contour (top) and $B_{\rm xy}$ contour (bottom).

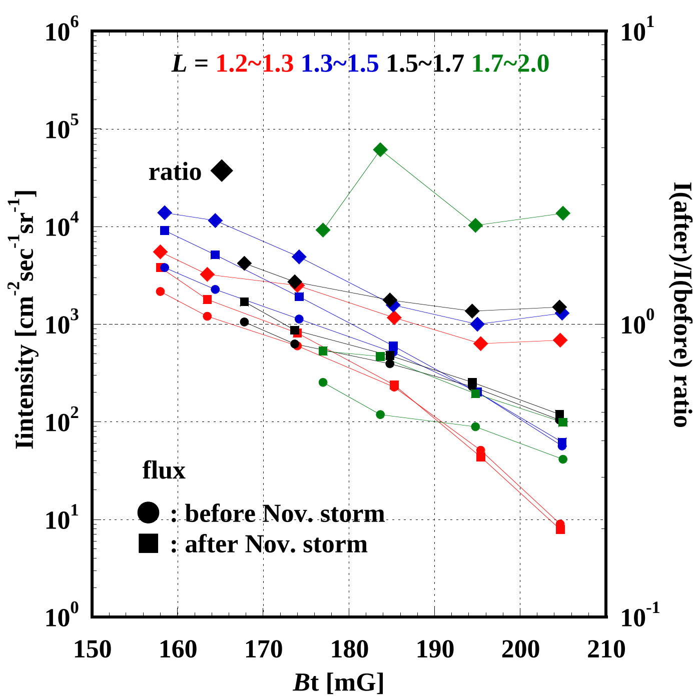

Fig. 6. The correlation between $B_{\rm t}$ and the proton intensity. The color lines are distinguished by L-shell as same as Filled circle and square show the intensity before and after the storm, respectively, with the left axis. Filled diamond shows the increased ratio as intensity after the storm over one before the storm with the right axis.

2.0 corresponding to the anomaly in the SAA discussed in previous section. Comparing precisely the variations between the intensity and B_{z} component of IMF, the proton intensity rapidly increased at the centre of SAA, when strong northward IMF to the earth just before the 2nd Dst disturbance reached, while the proton intensity at the outer region of SAA increased gradually in the recovery phase of the 2nd disturbance. These results give us an idea of variation of proton intensities in SAA.

It is generally known that solar flare particles can penetrate into outer magnetosphere corresponding to around 4 in L-shell, but not inner magnetosphere less than $4L$. Baker at al.[6] have reported that the plasmapause was suppressed during the Halloween storm in October 2003, being similar to the November storm. A strong northward IMF might have been able to suppress the magnetosphere. In the case of the November storm, flare particles might have been able to penetrate into the $4L$ region at the first storm. Then, it seems that these trapped flare particles precipitated to inner magnetosphere passing through the *tunnel* of small B_{t} region corresponding to the centre of SAA by magnetosphere suppression when second strong northward IMF reached. Finally, the trapped protons in SAA might have been either diffused or drifted to large B_{t} region through some mechanism as their absorption by collision and energy loss in the atmosphere at very high altitude during the recovery phase of 2nd storm.

V. Conclusion

The geographical and temporal variations of trapped proton intensity in the SAA region during the November storm were observed by two Japanese satellites, USERS and SERVIS-1, which had different orbital parameters from each other. Both boundaries of the SAA before and after the November storm obtained by the satellites were coincident with 210 mG contour in total geomagnetic strength. However, the boundary of south-eastern region of the SAA aligned with L-shell of 2, but not with 210 mG line in total geomagnetic strength, because of the effect of the drift loss cone originated by the anomaly of geomagnetic horizontal component. In the temporal variation of proton intensity, the proton intensity at the centre of SAA increased rapidly at the northward IMF disturbance of the beginning of the 2nd storm, while the one in the fringe region of SAA increased gradually in the recovery phase of the 2nd storm. These results show the behavior of trapped proton intensity in the SAA that the solar flare particles being trapped in outer radiation belt higer than $4L$ region at the 1st storm might have been precipitated into the central SAA at the beginning of 2nd storm and then diffused to the outer region of SAA.

Acknowledgments

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