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Charge and Mass Composition of Heavy Ions in the Earth's Radiation Belt

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Abstract: Energetic heavy ions with 20∼200 MeV/nucleon in the radiation belts have been observed by Heavy Ion Telescope (HIT) onboard TSUBASA satellite. The data observed during quiet periods in the outer region of radiation belt indicate that the relative abundance for major elements are similar to that of primary nuclei in galactic cosmic rays obtained by ACE/CRIS experiment, in particular for the ratio of ^{22}Ne/^{20}Ne, while the absolute intensities there were less than that obtained by ACE/CRIS. On the other hand, in the inner region of radiation belt near the earth, both energetic ^{3}He and ^{4}He isotopes were enhanced, in particular for ^{3}He, however, no energetic heavy ions except for energetic nuclei as Li-B, N and Ar were observed. Thus the charge and mass composition of heavy ions is essential to our consideration of possible sources and behavior of energetic heavy ions trapped in the radiation belt.

Introduction

Energetic protons and electrons trapped in the Earth's radiation belt have been observed by various satellites, while energetic heavy ions trapped there have not been precisely observed. Several satellites reported some anomalous components of heavy ions in the radiation belt near the Earth, which were observed by the SAMPEX[1] satellite as anomalous cosmic rays of oxygen at $L \sim 2$ and by CRRES[2], SAMPEX[3] and NINA[4] satellites as the ratio of ^{3}He/^{4}He enhancement at $L < 2$ as compared with that of solar system. However, there are few report on elemental and mass abundances of heavy ions trapped there.

Although the total intensity of heavy ions is much less than those of protons and electrons, the relative abundance of heavy ions may indicate some feature to be remarked. For instance, in case of galactic cosmic rays (hereafter cited as GCRs), the abundances of secondary nuclei as Li, Be, B, sub-iron and odd nuclei are higher than those in solar system. Therefore, some suggestions in considering the source of trapped particles will be given by the precise observation of abundance of heavy ions trapped in the radiation belt.

A Japanese satellite, TSUBASA, carried a heavy ion detector called Heavy Ion Telescope (HIT) which observed heavy ions from helium to iron with 20∼200 MeV/nucleon trapped in the radiation belt with good elemental and mass resolution[5]. It was in the geostationary transfer orbit with a perigee of 500 km and an apogee of 36000 km with the inclination of $28.5°$ during the period from February, 2002 to September, 2003.

This report discusses possible sources of heavy ions trapped in the inner and outer region of radiation belt based on the observed results obtained from TSUBASA satellite.

Observed Results

The spatial distribution of energetic heavy ion intensities in the radiation belt as a function of L-value is shown in Fig.1. The intensities of each element are almost constant in the region of $L > 5$, while those decrease gradually in the region of

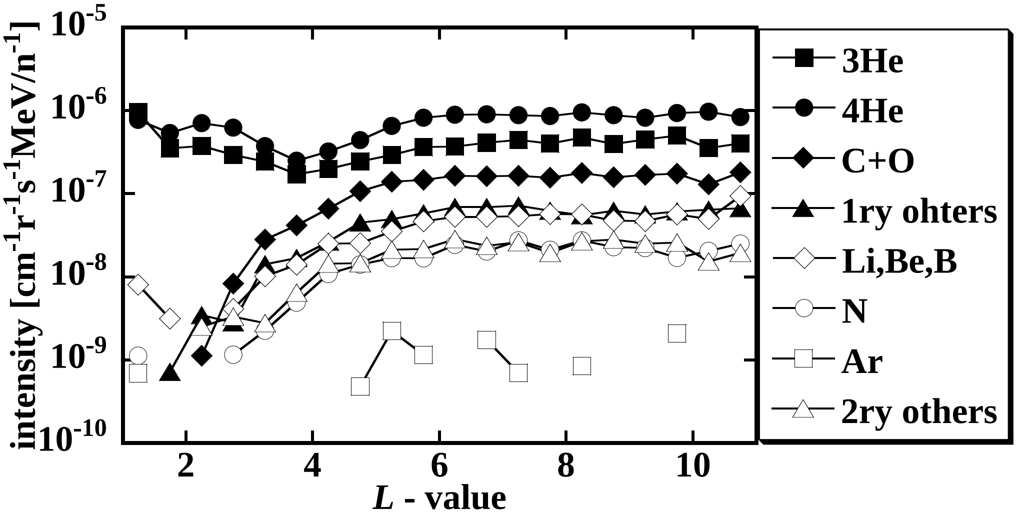

Figure 1: Intensity distribution of trapped heavy ions as functioned by L-value obtained from TSUBASA satellite. The terms of ‘1ry others’ and ‘2ry others’ mean elements as Ne, Si, Mg, S and Fe, and F, Na, Al, P, Cl and sub-Fe from K to Mn.

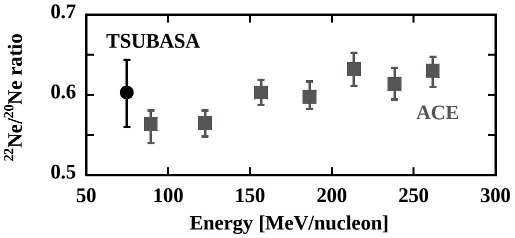

Figure 2: The ratio of Ne isotopes inside ($L > 5$) and outside the radiation belt observed by TSUBASA and ACE[6], respectively.

$L < 5$ with L decreasing due to the cutoff rigidity of geomagnetic effect. The ratio of ^{3}He/^{4}He in $L > 5$ of the radiatio belt is about 0.3 and similar to that of GCRs as $0.1 \sim 0.2$. For Ne isotopes as shown in Fig.2, both ratios obtained by TSUBASA inside and ACE/CRIS outside there agree with each other. It should be noted that the ratio of ^{22}Ne/^{20}Ne is considered as one of features in GCRs being higher by a factor of 5 times than that in the solar system.

On the other hand, the intensities of energetic helium in $L < 4$ show an anomalous behavior in contrast to the other elements. Both intensities of He isotope as ^{3}He and ^{4}He increase with L decreasing in the region of $L < 4$. At $L < 1.5$, in particular, the flux of ^{3}He is higher than that of ^{4}He. In generally, the ratio of ^{3}He/^{4}He is $0.1 \sim 0.2$ in GCRs and $< 10^{-4}$ in solar abundance, respectively. The anomaly has been already reported by previous observations such as CRRES[2], SAMPEX[3] and NINA[4]. The results obtained by TSUBASA satellite [7] confirmed previous observations.

Discussion

These results obtained by TSUBASA satellite suggest the existence of the different sources for trapped heavy ions between the regions of $L > 5$ and $L < 4$.

First, we consider the source of trapped heavy ions in $L > 5$ of the radiation belt. The observed results of isotope ratios as ^{3}He/^{4}He and ^{22}Ne/^{20}Ne indicate that a main source of heavy ions trapped there is GCR components. The intensity of individual heavy ion inside and beyond the radiation belt is presented in Fig.3. The data obtained from TSUBASA denoted as trapped particles was observed in $L > 5$ region inside there. The data (level2 data) obtained from ACE/CRIS defined as GCRs were observed at Lagrange point (L1) beyond there. For the major elements as C, O, Ne, Mg, Si and Fe, which are considered as primary nuclei in GCRs, both relative abundances are consistent with each other, although the absolute inten-

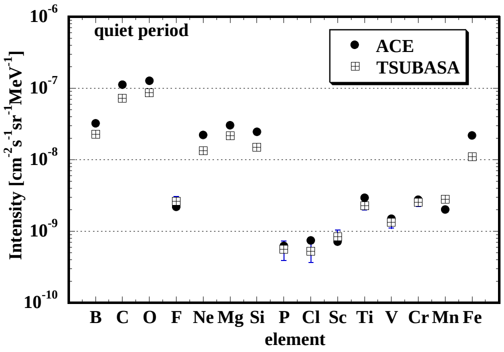

Figure 3: The intensities of elements inside and outside the magnetosphere and its ratios observed by TSUBASA and ACE, respectively.

sities inside there are about 60% flux as compared with those outside there. For the minor elements as F, P, Cl and sub-iron group which are considered as secondary nuclei in GCRs, both data inside and outside there have shown similar intensities. Such effects should be considered as the interaction of trapped ions with the upper residual atmospheric atoms as shown in Fig.4.

In case of the orbital path of TSUBASA satellite, the region at $L > 5$ corresponds to the altitude of 15,000 km and more. There are several hundreds of hydrogen atoms per cm^3 in the altitude more than 10,000 km, though this model of atmospheric compositions is applicable in the altitude of about 1000 km or less [8]. If trapped particles are in mirror motion along the geomagnetic field, those particles are possible to come down to the altitude of several hundreds km. According to our estimation under an assumption of the interaction of trapped GCR with the residual atmosphere in the report [9], the fluxes of sub-irons estimated at $L > 5$ inside the radiation belt based on the data obtained by ACE/CRIS outside there were in good agreement with the observed fluxes by TSUBASA satellite inside there. The path length of iron in the upper atmosphere was also calculated based on both iron intensities inside and outside there obtained by TSUBASA and ACE, respectively. It was consistent with path length of GCR propagation in the Galaxy, if trapped particle moved mirroring. In fact, secondary/primary ratios observed by TSUBASA in the magnetosphere are almost 2 times higher than those observed by ACE outside there.

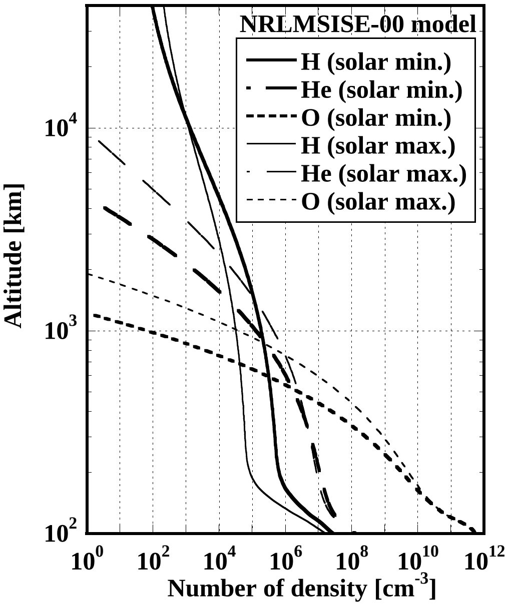

Figure 4: The composition of number density of atmospheric H, He and O atom in the upper atmosphere between the solar maximum (thin lines) and solar minimum (thick lines) based on the NRLMSISE-00 model [8].

On the other hand, the enhancement of helium isotopes in the region of $L < 3$, in particular for ^{3}He, is quite strange. As clarified from Fig.1, it is difficult for trapped helium ions in the inner region of radiation belt to consider a possible source as GCR component because of geomagnetic cutoff of energetic charged particles penetrating to the earth. Selesnick and Mewaldt suggested that He isotopes originated from the interaction of protons trapped there with residual atmosphere [10]. As shown in Fig.4, the number density of atmospheric helium and oxygen atom in the solar minimum are less than those in the solar maximum. In contrast, that of atmospheric hydrogen atoms makes an opposite variation. If a source of energetic helium nuclei in the inner region is the suggestion by Selesnick and Mewaldt, the fluxes of helium isotopes trapped there will be variated depending on the solar cycle activity. In other words, the fluxes of helium isotopes produced by the interactions of trapped particles with residual atmosphere will be decreased due to the decreasing of atmospheric helium and oxygen densities toward the solar minimum. The comparison of helium intensities between the maximum and the decreasing phases of solar cycle is

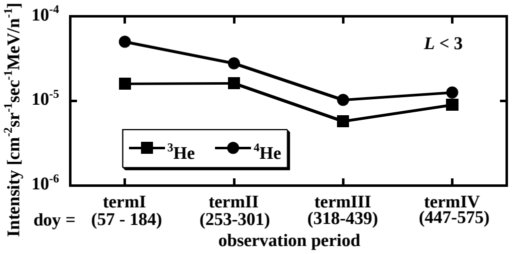

Figure 5: Temporal variation of He isotope intensities at $L < 3$ observed by TSUBASA satellite. Term I corresponds to the maximum phase of solar activity and term IV corresponds to the middle of decreasing phase of that.

displayed in Fig.5. The helium intensities in the decreasing phase denoted as term IV were less than those in the maximum phase denoted as term I. Furthermore, energetic Li-B, N and Ar nuclei were also observed by TSUBASA satellite at $L < 1.5$, but not the other heavy nuclei as shown in Fig.1. These light nuclei as Li, Be and B are able to be produced from the fragmentations of atmospheric oxygen atoms by the interaction of trapped particles. The existence of energetic nitrogen and argon nuclei, though an event was detected, respectively, was also possible to be explaicable with an idea that trapped particles interact with these air nitrogen and argons, because there are only small amounts of nitrogen and argon atoms in the upper atmosphere [8]. However, because there is no atom except for H, He N, O and Ar in the air, the other energetic heavy ions were not produced by the interaction of trapped particles with upper atmospheric atoms.

Summary

The data on variation nuclei as obtained from the Japanese satellite, TSUBASA, indicated the source of heavy ions trapped inside the radiation belt. At $L > 5$ inside there, the absolute fluxes of major elements were by about 40% less than those of GCR components beyond there, while the relative abundance, in particular for ^{3}He/^{4}He and ^{22}Ne/^{20}Ne, was in good agreement with each other. The fluxes of minor elements inside there were comparable with those outside there, while the relative abundance inside it was 2 times higher than those of GCRs. In the region of $L < 4$ of the radiation belt, energetic helium ions were enhanced, in particular for ^{3}He nuclei, but no other energetic heavy ions except for a small amount of Li-B, N and Ar nuclei. And the intensities of helium isotopes were changed depending on solar cycle activity. These results suggested two possible sources of trapped heavy ions for each region. For the outer radiation belt, the main source is GCRs and those trapped there interacted with the residual atmospheric atoms. For the inner radiation belt, the main source is energetic heavy ions produced from upper atmospheric atoms interacted by particles trapped there.

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