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Low Energy Anomalous Cosmic Rays Trapped in the Earth's Magnetosphere: 6 years of SAMPEX Observations

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Abstract

We summarize over 6 years of observations of ~1-4 MeV/nucleon heavy ions trapped in the Earth's magnetosphere on L shells of 1.7 to 3. We obtained these new results in low-Earth orbit with the SAMPEX spacecraft; they extend the observations of trapped ACR species to much lower energies than previously examined in detail. The low energy O and Ne originate from continual energy loss of higher energy trapped anomalous cosmic rays in the residual atmosphere, producing energy spectra that level-off below a few MeV/nucleon. We find that the trapped anomalous Ar flux is ~200 times more intense than interplanetary Ar at ~3 MeV/nucleon; this is an enhancement ~2 times greater than that of the trapped anomalous O or Ne. We have also detected trapped ions with low first ionization potential (Mg-S and Fe) in addition to the anomalous species C, O, Ne, and Ar, although at much lower intensities. The presence of these rare elements in the low energy trapped population is consistent with an interplanetary component of energetic Mg-S and Fe that is singly charged.

1 Introduction

The bulk of the anomalous cosmic rays (ACR) are a sample of the local interstellar medium. Interstellar gas atoms with first ionization potential greater than that of H are neutral (e.g. He, N, O, Ne, and Ar), flow unimpeded into the heliosphere, and can become singly ionized from solar ultraviolet photons or through charge exchange collisions with the solar wind. Once convected out to the solar wind termination shock, these singly charged ions are a seed population for shock acceleration; they then propagate back into the solar system as energetic ACR. Below ~10 MeV/nucleon the bulk of the ACR are singly ionized [Mewaldt et al. 1996; Klecker & Mewaldt 1998] and can penetrate to low altitudes within the Earth's magnetosphere because of their high magnetic rigidity. Blake & Friesen [1977] pointed out that if an ACR ion loses its remaining electrons in a collision with the upper atmosphere, the sudden rigidity change can lead to stable trapping and the formation of a belt of interstellar material readily accessible to spacecraft in low-Earth orbit.

The trapped ACR elemental & isotopic composition, time dependence, and spatial dependence above ~10 MeV/nucleon have been studied in detail with instrumentation on board the SAMPEX satellite (e.g., Selesnick et al. 1995a; Looper et al. 1996). Here we summarize over 6 years of continuous measurements of the trapped ACR down to ~ 1 MeV/nucleon that has only been briefly reported before using SAMPEX measurements (Selesnick et al. 1995b). The low energy trapped O spectrum has been measured down to ~4 MeV/nucleon with track detectors on Cosmos satellites (e.g. Grigorov et al. 1995; Tylka et al. 1996). With the relatively long lifetime of the SAMPEX spacecraft we have been able to continuously track the time dependence of the trapped ACR population to much lower energies through the decrease of solar cycle 22, at solar minimum, and the rise of cycle 23. This long observation time has also been necessary in order to detect the signatures of trapped minor ACR species such as Ar whose interplanetary abundance is less than 1% of ACR O.

2 Observations and Data Analysis

The observations presented here are from the Solar, Anomalous, and Magnetospheric Particle Explorer (SAMPEX) spacecraft, launched into a 512 x 675 km, 82° inclination Earth orbit in July 1992. The Low energy Ion Composition Analyzer (LICA) sensor on SAMPEX is a time-of-flight mass spectrometer whose energy range (~0.5 – 8 MeV/nuc for ^{16}O) overlaps with the peaks of the incident, interplanetary ACR spectra at 1 AU. The trapped ACR spectra are peaked at the energies corresponding to the geomagnetic cutoff rigidities for singly charged ACR incident from the west (e.g. Looper et al. 1996). For O and Ne the western cutoff energies are above the energy range of LICA for the range of L shells of this study, but the cutoff energy for singly charged Ar is within LICA's energy range.

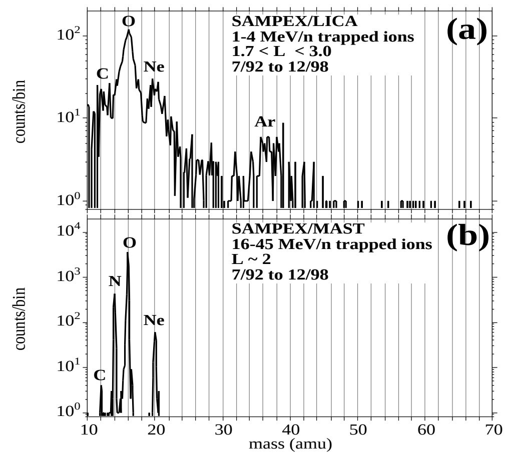

Figure 1. Trapped ion mass spectra at low & high energies.

The trapped ACR belt lies between about L=2 and L=3; SAMPEX has access to these trapped ions in the weaker magnetic field region of the South Atlantic Anomaly. We selected an energy range of 1-4 MeV/nucleon and an L range from L=1.7 to L=3 in order to maximize the number of low energy trapped ions and to minimize the lower energy background in LICA from penetrating protons in the inner zone. Even though the mass resolution of the sensor is best near 0.8 MeV/nucleon, from 1 – 4 MeV/nucleon the instrument resolves the most abundant elements with a resolution of ~0.64 amu at mass 16. Figure 1a shows the mass spectrum of 1-4 MeV/nucleon trapped ions accumulated in L=1.7 to L=3 from 7/92 to 12/98 corrected for the instrumental efficiency of LICA. Figure 1b plots the mass spectrum of 16-45 MeV/nucleon trapped ACR ions measured with the SAMPEX/MAST instrument.

One outstanding difference between the trapped ion mass spectra of Figure 1a & 1b is the higher relative abundance of trapped Ar in the 1-4 MeV/nucleon sample not detected in previous studies of trapped ACR near 10 MeV/nucleon (note no events heavier than Ne were detected with SAMPEX/MAST). Compared to measurements above ~10 MeV/nucleon, this low energy sample of the trapped ACR is enhanced in C and Ne as well. Table 1 lists the relative abundances of trapped ACR at low and high energies compared with their interplanetary values. Because of the mass resolution of the instrument in this

Element	FIP (eV)	Trapped 1-4 MeV/nucleon	Trapped 16-45 MeV/nucleon [b,c]	Geomag. filtered Q=1[b] ~8-20 MeV/nucleon	Interplanetary quiet-time [d] ~5 MeV/nucleon
C	11.26	124 ± 28	0.8 ± 0.3	9 ± 5	7 ± 7
N	14.53	<140	90 ± 10	10.2 ± 0.7	139 ± 2
O	13.61	1000 ± 46	1000	1000	1000 ± 6
Ne	21.56	285 ± 21	30 ± 2.5	35 ± 3	74 ± 2
Mg+Si+S	7.64-10.36	88 ± 17	< 15	~ 0.7	3.5 ± 0.5
Ar	15.76	73 ± 9	< 11	< 0.2	3.7 ± 4
Fe (group)	7.87	17 ± 4	< 23	< 0.2	0.8 ± 0.2

Table 1. Abundances of trapped ions near 1 MeV/nucleon and 10 MeV/nucleon compared to interplanetary abundances. Notes: (a) this work, L=1.7-3; (b) Klecker & Mewaldt et al. 1998; (c) Selesnick et al. 1995a; (d) Reames 1999.

energy range, we used a maximum likelihood technique to fit gaussians and a linear background to the mass spectrum of Figure 1b to derive relative abundances. We list the best-fit abundance plus 1σ for N since we observed no clear N track in this energy range.

The relative abundances of the trapped ions are energy-dependent. Figure 2 plots the energy spectra of O, Ne, and Ar, both trapped between L=1.7 to 3 and in interplanetary space at 1 AU. The interplanetary O and Ne ACR spectra above ~10 MeV/nucleon were measured with the SAMPEX/HILT sensor in late 1995 and here were scaled to the average flux of ~20 MeV/nuc O and Ne also measured on SAMPEX from 7/92 to 12/98. The interplanetary ACR spectra below 10 MeV/nuc were corrected for quiet-time solar & interplanetary contributions by subtracting power laws proportional to (MeV/nucleon) $^{-2.7}$. We show the 1 AU quiet-time Ar spectrum averaged from 11/94 to 4/98 with instrumentation on board the Wind satellite (Reames 1999). Compared to the interplanetary spectra, the trapped O and Ne spectra level off below ~ 3 MeV/nucleon, since these ions originate from a continual energy loss of higher energy trapped ions in the residual atmosphere (e. g. Blake 1990). The leveling off of the spectra yields a Ne/O ratio that increases toward lower energies and is ~7 times larger at 2 MeV/nucleon than above 10 MeV/nucleon. In the case of Ar, the average western cutoff energy is ~2.8 MeV/nucleon for this L range and the low energy level off would be expected to occur below our selection threshold of 1 MeV/nucleon.

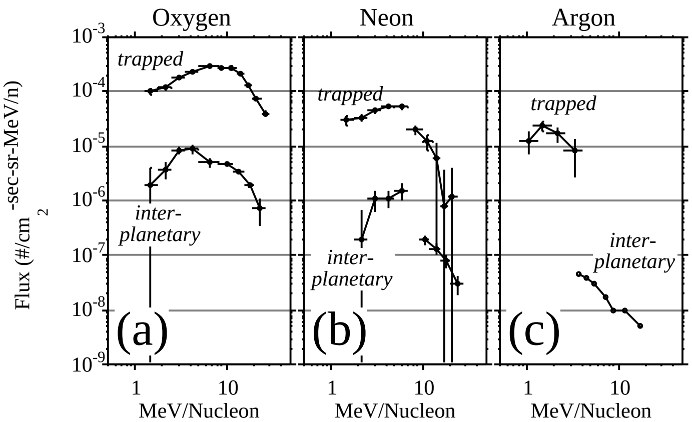

Figure 2. Trapped vs. interplanetary O, Ne, and Ar energy spectra.

4 Discussion

The new measurements presented here extend the observations of trapped ACR species to much lower energies than previously available. At the altitude of SAMPEX, the most abundant trapped heavy ions (O and Ne) below ~10 MeV/nucleon are at too low an energy to have had direct access as singly ionized incident ACR. The trapped energy spectra level-off below a few MeV/nucleon as expected due to the energy loss of higher energy trapped ions in the residual atmosphere. We observed a spectral peak for Ar between 1 and 2 MeV/nucleon that is consistent with the western cutoff energy for Ar^{+1}, suggesting that at 1-4 MeV/nucleon the interplanetary Ar is mostly singly ionized. We would expect lower energy Ar to be mostly singly ionized based on the observation that the energy per nucleon below which interplanetary ACR N, O, and Ne are mostly singly ionized decreases with increasing mass (e.g. Klecker & Mewaldt et al. 1998).

The fluxes of the trapped ACR O and Ne are enhanced relative to the interplanetary fluxes by factors of ~50-100 depending on energy. This first measurement of the trapped Ar spectrum shows that the enhancement factor is ~200 at ~3.5 MeV/nucleon where there is overlap between the trapped and interplanetary Ar spectra. A stripping cross section for Ar^{+1} that is twice as large as that of O^{+1} (Klecker and Mewaldt et al. 1998) and a correspondingly larger trapping probability (Blake 1990) may account for the relatively larger enhancement of trapped Ar.

At 1-4 MeV/nucleon we might expect to see the same trapped species observed above 10 MeV/nucleon because the trapped ions continually lose energy in the residual atmosphere. Table 1 shows that given the mass resolution of LICA this is the case for C, O, and Ne. However, for these species the 1-4 MeV/nucleon *abundances* relative to O are larger than the trapped abundances at higher energies by widely varying amounts (a factor of 155 for C/O and 9.5 for Ne/O). Selesnick et al. [1995a] found that above 16 MeV/nucleon the trapped ion spectra are softer for increasing Z, implying a higher Ne/O at lower energies in agreement with the trends of the O and Ne spectra of Figure 2. If the O spectrum is indeed softer than that of C, then the C/O ratio at 1-4 MeV/nucleon would be lower that the ratio above 10 MeV/nucleon; this is opposite to the observed trend. In fact, the low energy trapped population has larger C/O and Ne/O compared to the interplanetary singly ionized population as well as the quiet-time abundances at 5 MeV/nucleon. The origin of these large abundance differences is not known. It is possible that a detailed model of the trapping, energy loss, and eventual charge exchange loss processes may shed some light into the cause for the low energy enhancements of trapped C/O and Ne/O.

In addition to C we observe other species with FIP less than 12 eV in the low energy trapped population: Mg-S and Fe. Singly charged ions of these species would have western access to SAMPEX between L=1.7 to 3 within the LICA energy range but not above ~10 MeV/nucleon. We may suppose that these low energy trapped particles indicate that a singly-ionized population of energetic Mg-S and Fe exists at 1 AU that has participated in the pickup and ACR acceleration processes just at the more abundant, high-FIP interstellar ions. The Blake & Friesen [1977] process might then account for their presence in the trapped population. Indeed, Reames [1999] found ACR-like turn-ups in the Mg, Si, and S spectra at 1 AU that were significantly above the quiet-time levels of these species only below ~5 MeV/nucleon. The combination of low energy spectral features and western cutoff energies below ~10 MeV/nucleon may account for the presence of such low-FIP ions in this study and their relatively lower abundances seen in the trapped population above 10 MeV/nucleon. Geiss et al. [1995] identified an inner heliospheric source of pick-up ion C^{+1} that they attributed to interstellar dust, and it is possible that solar wind ions may be absorbed then re-emitted from such grains with +1 charge states (Klecker, pers. comm. 1999). The low energy trapped population might indicate that other inner heliosphere sources for ions with FIP below 12 eV may indeed exist. Observations with SAMPEX through the upcoming solar maximum will shed light on the dynamics of the processes that degrade the trapped ACR belt, while detailed modeling of the trapping of singly charged interplanetary C, Mg-S and Fe can test whether such a population can account for the low energy trapped composition.

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