SAMPEX Measurements of Heavy Ions Trapped in the Magnetosphere

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Abstract

New observations of >15 MeV/nuc trapped heavy ions with Z ≥ 2 have been made by the SAMPEX spacecraft in low polar orbit. The composition of these ions, which are located primarily around L = 2, is dominated by He, N, O, and Ne. The N, O, and Ne ions are apparently trapped "anomalous cosmic rays," while the origin of the trapped He flux is presently uncertain. These ions can affect the rate of single-event upsets (SEUs) in spacecraft hardware.

I. INTRODUCTION

The Solar, Anomalous, and Magnetospheric Particle Explorer (SAMPEX) was launched July 3, 1992 into an 82° inclination orbit with an apogee of ~670 km and a perigee of ~520 km [1]. SAMPEX carries four energetic-particle instruments, including a Mass Spectrometer Telescope (MAST) designed to measure the elemental and isotopic composition of nuclei from He to Ni (Z = 2 to 28) over the energy range from ~15 to ~200 MeV/nuc. Although MAST is designed primarily for studies of solar flare and cosmic-ray nuclei during its passage over the geomagnetic poles, trapped particles account for a significant fraction of the events with Z ≥ 6 observed during the first few months of the mission. The vast majority of the ions with Z ≥ 6 appear to be "anomalous cosmic rays" (ACRs) that have become trapped in the magnetosphere.

The interplanetary ACR component of the Galactic Cosmic Rays (GCRs) includes those elements (He, C, N, O, Ne, Ar, and perhaps H) whose solar-minimum energy spectra have shown anomalous increases in flux above the quiet time GCR spectrum at energies < 50 MeV/nuc (see, e.g., [2,3]). ACRs are thought to represent a sample of neutral interstellar particles that have drifted into the heliosphere, become ionized by the solar wind or UV radiation, and then accelerated to energies up to tens of MeV/nuc [4]. This model predicts that ACRs should be singly ionized (for which there is recent evidence), in contrast to galactic cosmic rays, which are essentially fully stripped. Experimental evidence confirms that the ACRs are singly ionized [5]. Because ACRs are especially sensitive to solar modulation, they are detectable at 1 AU only near solar minimum.

Soon after the discovery of ACRs, Blake and Friesen [6] suggested a mechanism for trapping ACR nuclei in the magnetosphere (see also Blake [7] and Schulz *et al.* [8]). Trapping can occur when a singly charged ion, with a rigidity somewhat above the geomagnetic cutoff, penetrates deeply into the magnetosphere and loses some or all of its remaining electrons in the upper atmosphere, such that its resulting rigidity is suddenly below the trapping limit. In 1991, Grigorov *et al.* [8] reported the first evidence for trapped ACRs. In that study, passive track detectors flown on COSMOS spacecraft during the 1985 to 1988 solar minimum observed ~5 to 30 MeV/nuc ions with a composition, angular distribution, and temporal behavior consistent with the origin proposed by Blake and Friesen. However, the passive detectors on COSMOS could not measure the ions' spatial distribution.

In this paper, we report on a new study of the spatial distribution, composition, and energy spectrum of trapped heavy ions that began with the launch of SAMPEX in mid-1992. Initial results from this study have been reported by Cummings *et al.* [10,11]. We summarize here the current status of this work and discuss possible implications of these observations for the single-event-upset environment experienced by orbiting spacecraft.

II. THE INSTRUMENT

MAST is composed of an array of silicon solid-state detectors that determine the nuclear charge, mass, kinetic energy, and trajectory of particles that stop in the detector array (for a complete description, see [11]). The threshold for particle identification ranges from 14 MeV/nuc for C, to 16 MeV/nuc for O, to 27 MeV/nuc for Fe, with a more limited response to He from ~7.5 to ~15 MeV/nuc. The MAST telescope has a full-angle field of view of ~101° and a typical geometry factor of ~12.5 cm^2sr, oriented approximately toward local zenith over most of the SAMPEX orbit. The arrival time of incident nuclei can be measured to an accuracy of ±1 s. Because nuclei with Z > 2 are given highest readout priority and because

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MAST is relatively insensitive to protons, it is capable of measuring heavy nuclei in the presence of a much greater flux of protons and/or electrons.

III. OBSERVATIONS

We describe below the essential features of trapped heavy nuclei observed by MAST over the period from 7/6/92 to 2/7/93.

A. Invariant Latitude Distributions

Figure 1 shows the geographic distribution of oxygen nuclei with 16 to 200 MeV/nuc observed by MAST during solar quiet times. Over the magnetic poles, MAST can detect galactic cosmic rays mixed with a solar-cycle-dependent contribution from ~15 to ~40 MeV/nuc ACR nuclei. These high-latitude particles are present at all longitudes. Also evident in Figure 1 is a trapped population concentrated in the region south-east of the South Atlantic Anomaly (SAA), which extends to energies > 50 MeV/nuc. (The particles appear in the SAA region because the relatively low magnetic field in this region allows the ions to dip down to the SAMPEX altitude there; the mirror-point altitude follows a locus of constant magnetic field.) Tylka [13] has produced Monte Carlo models of trapped anomalous cosmic rays that bear an excellent resemblance to this plot. Figure 2 shows invariant latitude distributions for He and O, two of the species observed in this region. Note that the distribution of O is sharply peaked at $\Lambda = 45°$, corresponding to L = 2. The intensity of energetic oxygen nuclei in this region exceeds that over any portion of the SAMPEX orbit, except for those rare periods when very large solar-particle events are observed over the poles (Λ > 65°).

The location of the trapped oxygen fluxes is somewhat energy dependent, with higher-energy oxygen trapped on lower L shells. At a given energy/nucleon, E, more than ~ 90% of the oxygen events are within a region of L bounded by

$$L(E) = (2.0 \pm 0.3)(E/20\ \mathrm{MeV/nuc})^{-0.25}.$$

We also observe that the trapped N and Ne fluxes have a similar L-shell distribution.

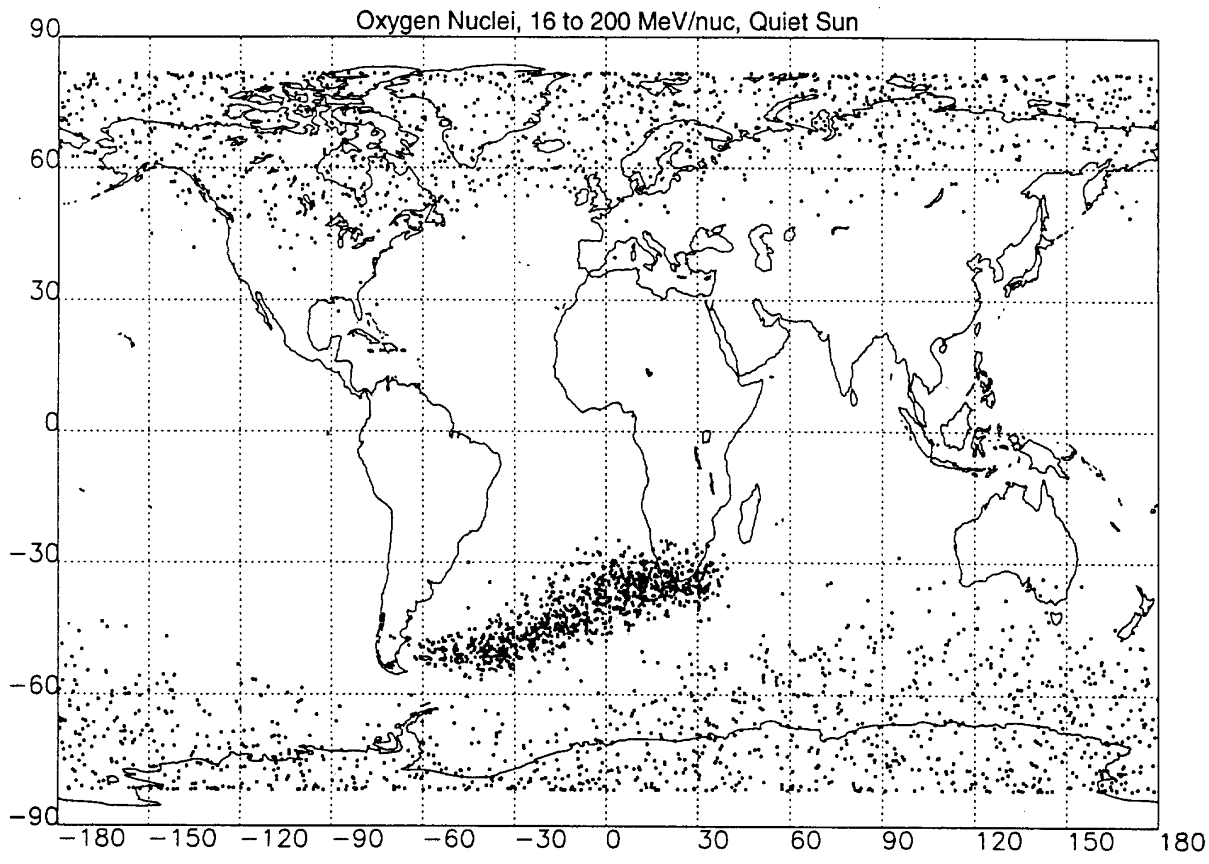

Fig. 1. Geographic distribution of quiet-time oxygen nuclei with 16 to 200 MeV/nuc observed by MAST during the period from 7/6/92 to 2/6/93. For comparison, the SAA is centered approximately at ~30° South Latitude and ~315° degrees Longitude.

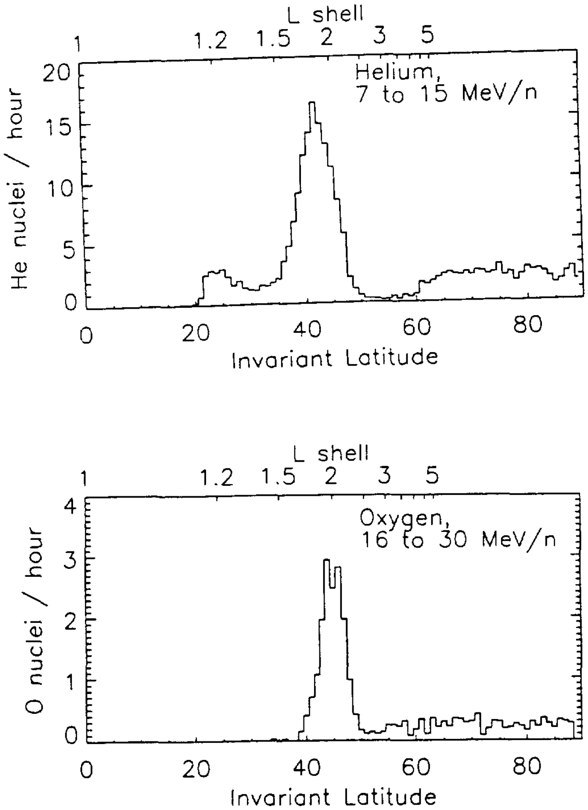

Fig. 2. Invariant latitude distribution of quiet-time He and O observed by MAST.

The trapped He observed by MAST has a somewhat different latitude distribution than that of heavier ions, with a peak at L = 1.8, approximately independent of energy, and a somewhat smaller intensity peaked at L = 1.2, in the region of the SAA. Note that the MAST instrument is sensitive to He only over the energy range from ~7.5 to ~15 MeV/nuc, much lower in energy than its response to heavier nuclei [11].

B. Composition

As Figure 3 indicates, the composition of trapped nuclei with $Z \geq 6$ that is observed at $L \approx 2$ is dominated by N, O, and Ne (see also [14]). In addition, one event each have been observed of B and C (along with a single event having Z = 23). It should be pointed out that the composition is somewhat energy dependent (see below), which may explain why the COSMOS observations at somewhat lower energy [9] include less N and somewhat more Ne.

C. Pitch-angle Distributions

As the orbit of SAMPEX precesses, the angle of the MAST telescope with respect to the local magnetic field in the L = 2 region varies with a period of 3 months. Figure 4 shows that the particles at L = 2 are observed primarily when the MAST telescope is viewing nearly perpendicular to the local magnetic-field line, implying that these are indeed trapped particles with pitch angles of ~90°.

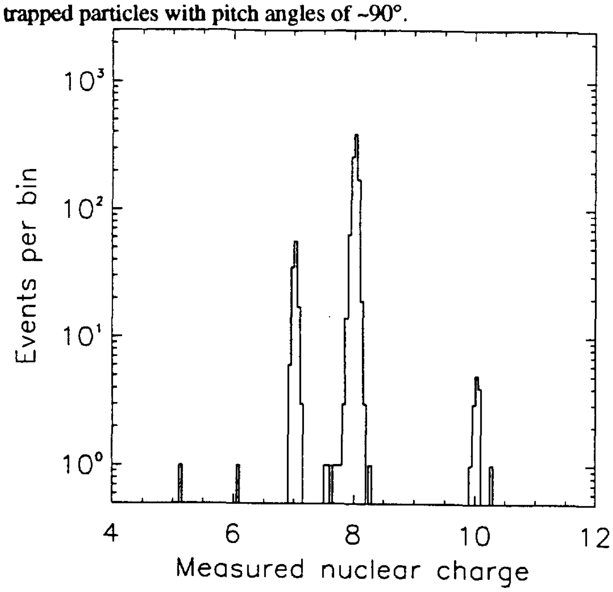

Fig. 3. Observed composition of trapped nuclei with Z > 4 at L = 2.05 ± 0.60, including all days from 7/6/92 to 2/7/93. Detection thresholds in MAST range from ~14 MeV/nuc for C, to ~16 MeV/nuc for O, to ~18 MeV/nuc for Ne. In addition, one event with Z = 23 was observed.

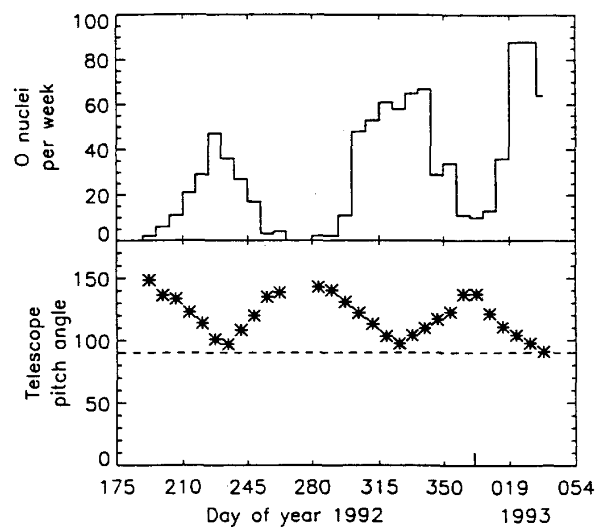

Fig. 4. Top Panel: Rate at which MAST detects O nuclei in the region Southeast of the SAA, delimited here by L = 2.05±0.60 and restricted to the Southern Hemisphere. Bottom Panel: Average angle of the MAST telescope axis to the local magnetic field (calculated from the 1990 IGRF, updated with secular variations) for events included in the top panel. This angle evolves with a ~3-month period as the SAMPEX orbit precesses. The MAST telescope has a full opening angle of ~101°. Similar results are obtained for He, N, and Ne.

D. Time Variations

Grigorov *et al.* [9] found that the intensity of the trapped oxygen fluxes measured over the years from 1985 to 1988 varied by a factor of ~10, in good correlation with the interplanetary intensity of ACR oxygen measured by IMP-8. Over the course of the SAMPEX mission, the ACR fluxes at L = 2 have increased by a factor of ~2 (see Figure 4), consistent with the interplanetary ACR flux measured by MAST as it passes over the geomagnetic poles [15]. Since the interplanetary ACR fluxes are the source of these trapped nuclei, we would expect the intensity of the trapped fluxes to continue building up as solar minimum approaches over the next few years. During the 1987 solar minimum, Bobrovska *et al.* [14] concluded that the flux of trapped ACRs at ~ 200 to 400 km was ~ 500 times greater than the interplanetary intensity

IV. Origin of the Trapped Heavy Ions

Both Grigorov *et al.* [9] and Cummings *et al.* [9,10] argued that on the basis of the observed composition, angular distribution, and time variations, the trapped heavy nuclei observed first by COSMOS satellites and now by SAMPEX must represent trapped anomalous cosmic rays, presumably trapped by the mechanism proposed by Blake and Friesen [6]. Although the observations to date are generally consistent with that model, the SAMPEX observations now show that there are differences in detail. In particular, we find that the trapped ACRs are located closer to Earth than was predicted.

SAMPEX observations of interplanetary cosmic rays [15] verify that there is an interplanetary source of anomalous N, O, and Ne in late 1992 with sufficient energy to exceed the geomagnetic cutoff for particles arriving at L = 2 from the west. As discussed by Cummings *et al.* [11], the appearance of trapped He at L = 2 is somewhat surprising because He is not expected to be trapped by the Blake and Friesen mechanism [6]. To reach L = 1.8 where it is observed, (see Figure 2) singly ionized He arriving from the west would require >300 MeV/nuc, well above the maximum energy to which it is observed in interplanetary space. If the trapped He is of ACR origin, there must be some other mechanism by which it is trapped. On the other hand, Adams [16] and Blake [17] have suggested that the observed He ions might be a remnant of a presumably solar particle population injected by the unusually strong and temporally narrow shock that struck the Earth's magnetosphere at 03:42 UT on 24 March 1991. The results of the injection were observed by CRRES [18,19,20]. In this case, the He intensity should decrease with time, while the intensity of trapped ACR species is expected to increase with time as the interplanetary intensity of the ACRs increases during the approach to solar minimum. Preliminary results indicate that the trapped He flux is decreasing with time.

V. Radiation Effects of Trapped ACRs

The potential of trapped ACRs to cause SEUs in spacecraft hardware will of course depend on the spacecraft orbit and the degree to which sensitive electronics are shielded. We consider here only trapped ACR oxygen and limit our attention to the SAMPEX orbit. In Figure 5, we show the quiet-time energy spectrum of oxygen observed by MAST, averaged over the entire orbit, including galactic cosmic rays, interplanetary anomalous cosmic rays, and trapped anomalous cosmic rays. Since MAST is oriented perpendicularly to the local magnetic field at L ~ 2 only 1/3 of the time, an omnidirectional detector would show a greater countrate. It is clear that trapped and interplanetary ACRs can contribute a significant fraction of the linear energy transfer (LET) distribution due to GCRs, although they are rather easily shielded against because of their low energies. However, magnetospheric processes such as radial diffusion may increase the energy of the geomagnetically trapped GCRs. The temporal behavior of the trapped GCRs needs to be carefully followed over the next several years by SAMPEX, with special emphasis upon the effects of major geomagnetic storms upon the trapped ions.

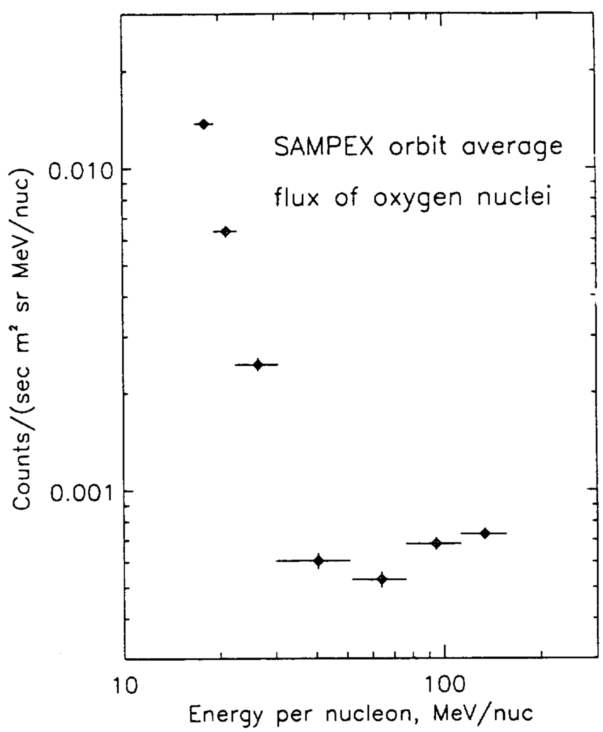

Fig. 5. Oxygen spectra averaged over the SAMPEX orbit during solar quiet times from 92:187 to 93:038. All event totals have been divided by the live time of the instrument, summed over the MAST orbit. Approximately 75% of the events in the rising portion of the spectrum are trapped ACRs.

It also should be noted that in other orbits that spend more time around L = 2, i.e., lower inclination orbits, the integrated trapped ACR exposure could be an order of magnitude or more larger. In addition, it is expected, based upon previous solar cycles, that the trapped ACR intensity will increase by up to a factor of ~ 10 over the next few years. SAMPEX measurements over the next few years will, therefore, be important in order to monitor the magnitude of SEU hazard that these trapped heavy nuclei may present to orbiting spacecraft. The energies of the trapped anomalous ions are relatively low. Shielding of the order of 100 mil of aluminum is adequate to protect vulnerable electronic components, cf. Adams, Jr. and Partridge [21].

VI. ACKNOWLEDGMENTS

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