GEOPHYSICAL RESEARCH LETTERS, VOL. 20, NO.18, PAGES 2003-2006, SEPTEMBER 15, 1993

NEW EVIDENCE FOR GEOMAGNETICALLY TRAPPED ANOMALOUS COSMIC RAYS

J. R. Cummings, A. C. Cummings, R. A. Mewaldt, R. S. Selesnick, E. C. Stone
California Institute of Technology

T. T. von Rosenvinge
NASA/Goddard Space Flight Center

Abstract. We report new observations of ≥ 15 MeV/nuc trapped heavy ions with Z ≥ 2, made on the polar-orbiting SAMPEX spacecraft in late 1992 and early 1993. A trapped population that includes He, N, O, and Ne is found to be located at L ≈ 2. We conclude that the observed N, O, and Ne ions are "anomalous" cosmic rays, trapped by the mechanism proposed by Blake and Friesen. While it is not expected that this mechanism would also trap anomalous He, the characteristics of the trapped He population are generally consistent with those of N, O, and Ne.

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 (Baker et al. 1993). SAMPEX includes 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 ~250 MeV/nuc (see Cook et al., 1993). 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 seven months of the mission.

There have been only scattered measurements of Z ≥ 6 ions with energy > 10 MeV/nuc in the magnetosphere (see, e.g., reviews by Spjeldvik and Fritz 1983 and by Biswas and Durgaprasad 1980). Because many of the observations have had limited temporal/spatial resolution, it has been difficult to separate the contributions of trapped ions from those of interplanetary ions accessible over parts of the orbit, and there has been no general agreement on the composition, intensity, distribution, or origin of > 10 MeV/nuc trapped heavy nuclei.

Recently, Grigorov et al. (1991) reported evidence for trapped nuclei originating from "anomalous cosmic rays". In interplanetary space, the anomalous cosmic ray (ACR) component 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 galactic cosmic ray (GCR) spectrum at energies < 50 MeV/nuc (Cummings and Stone 1987; Webber 1989). The 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 been accelerated to energies up to tens of MeV/nuc (Fisk, Kozlovsky, and Ramaty 1974), most likely at the solar wind termination shock (Pesses, Jokipii, and Eichler 1981). This model predicts that ACRs should be singly ionized (for recent evidence see Adams et al. 1991), in contrast to galactic cosmic rays, which are essentially fully stripped. 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 [1977; hereafter B&F] suggested a mechanism for trapping ACR nuclei in the magnetosphere (see also Blake 1990). Trapping can occur when a singly-charged ion with a rigidity somewhat above the geomagnetic cutoff penetrates 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 the study of Grigorov et al. (1991), 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 that was generally consistent with the ACR origin proposed by B&F. However, the passive detectors on COSMOS could not measure directly the ions' spatial distribution.

In this paper we report new observations of the spatial distribution and composition of trapped heavy ions from SAMPEX which show that trapped ACRs were also present in 1992, when the interplanetary cosmic ray flux was just recovering from solar maximum conditions. A preliminary account of this work appears in Cummings et al. (1993).

Observations

The MAST is composed of an array of silicon solid state detectors which determine the nuclear charge, mass, kinetic energy, and trajectory of particles which stop in the detector array (Cook et al. 1993). Figure 1 shows measured kinetic energy vs. magnetic latitude (Λ) for particles identified as oxygen. For comparison, nominal vertical geomagnetic cutoffs, estimated from the equation $P_c = 14.9 \cos^4(\Lambda)$, are shown for singly ionized and fully stripped oxygen. Three distinct particle populations are evident. At high latitudes (≥ 60°) there is a mixture of undifferentiated GCR and ACR oxygen. At mid-latitudes (~50° to 60°), fully stripped GCRs are not allowed, but there is evidence for > 15 MeV/nuc oxygen, presumably singly-ionized ACR oxygen. At low latitudes (≤ 50°), there is a low-energy grouping near and below the estimated cutoff for singly-charged oxygen.

Figure 2 shows the geographic distribution of these particles at SAMPEX altitude. Note that the high-latitude and mid-latitude particles are present at all longitudes, while the third population is concentrated in an ~8000 km long band southeast of the South Atlantic Anomaly (SAA), with a smaller number distributed around the boundary of the polar regions (possibly including a tail from the mid-latitude particles). As indicated in Figure 3, the L-shell distribution of the observed oxygen ions

Paper number 93GL01961
0094-8534/93/93GL-01961$03.00

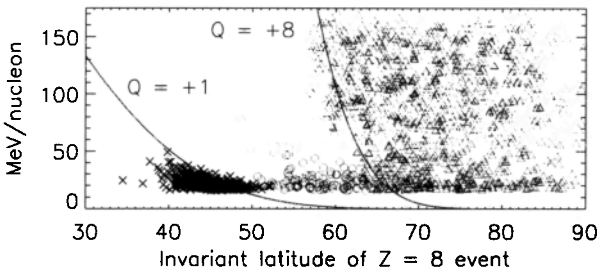

Fig. 1: Measured energy/nuc vs. invariant latitude (Λ) for oxygen ions observed during solar-quiet days from 7/6/92 to 2/7/93. Calculated vertical rigidity cutoffs (estimated from $P_C = 14.9 \cos^4\Lambda$) are shown for singly-ionized (Q = +1) and fully stripped O (Q = +8). Triangles: events with a energy above that estimated for vertical O with Q = +6; Crosses: those with an energy less than estimated for Q = +1.5; and Circles: those with intermediate energies. The same symbols are used for the corresponding data in Fig. 2.

is sharply peaked at L ≈ 2, with 90% of the 16 to 30 MeV/nuc oxygen having L = 2.04 ± 0.26

The composition of 4 ≤ Z ≤ 12 particles observed at L ≈ 2 is shown in Figure 4. In addition to O and N, which were detected by Grigorov et al. (1991; see also Bobrovskaya et al. 1993), Ne ions are concentrated at L ≈ 2. We find (somewhat energy dependent) preliminary abundances of N/O ≈ 0.11 ± 0.01, and Ne/O ≈ 0.025 ± 0.008, after approximate corrections for differences in detection threshold for different elements. There is very little C present, with an upper limit of C/O < 0.004 at L ≈ 2. The MAST instrument is sensitive to He with ~7 to ~15 MeV/nuc. The observed trapped He has a somewhat different geographic distribution than O. As shown in Figure 5, there is a concentration of ~7 to 15 MeV/nuc He at L ≈ 1.85, and also a separate, smaller population in the region of the SAA at L ≈ 1.2.

As the SAMPEX orbit precesses, the angle of the MAST telescope with respect to the local magnetic field in the L = 2 region varies with a 3-month period. Figure 6 indicates that the particles at L ≈ 2 are observed primarily when MAST is viewing near 90° to the local magnetic field line. We conclude that these are trapped particles with pitch angles of ~90°.

Although the characteristics of this trapped population are generally consistent with those deduced by Grigorov et al. (1991) from observations during the last solar minimum, there are some differences. Based on Monte Carlo simulations Grigorov et al. deduced that their observed angular distribution of tracks was consistent with a trapped population at L = 2 to 3, with poorer agreement obtained for particles distributed throughout the SAA, or at L = 1.2 to 1.5. We find a narrow distribution at L ≈ 2.0 (see Figure 3). The COSMOS data give N/O = 0.045 ± .008 and C/O < a "few percent" for 10 to 20 MeV/nuc ions (Grigorov et al. 1991; Bobrovskaya et al. 1993). In addition, we observe trapped He and Ne at L ≈ 2.

Discussion

One key to understanding the origin of trapped heavy ions is their composition. In particular, the ions near L ≈ 2 have a C/O ratio of < 0.004, significantly less than that of most interplanetary particle populations, including GCRs (C/O ~ 1), solar energetic particles (C/O ~ 0.5), and solar wind (C/O ~ 0.5). The appreciable abundance of Ne argues against an atmospheric origin, where Ne/O ≈ 5 x 10^{-5}. The observed composition is generally consistent with that of interplanetary ACRs (see also Grigorov et al. 1991), for which we find N/O ≈ 0.2, and Ne/O ≈ 0.1 in late 1992 with this instrument (Mewaldt et al. 1993), and for which Voyagers 1 and 2 found C/O ≈ 0.01, N/O ≈ 0.17 and Ne/O ≈ 0.055 at ~23 AU in 1987 (Cummings and Stone, 1990).

With only a single event at boron (Z = 5) we can only speculate on whether there might be a population of trapped 3 ≤ Z ≤ 5 nuclei resulting from the breakup of ACR N, O, and Ne nuclei as they are stripped in the upper atmosphere. Such a mechanism would also produce He, but it is unlikely to account for the He observed at L ≈ 2, since we find no evidence for ^{3}He as might be expected from fragmentation.

The B&F mechanism requires an interplanetary source of singly-ionized ACR nuclei. In addition to previous studies that have concluded that ACR nuclei are singly ionized (e.g., Adams et al. 1991), there is evidence for partially-ionized oxygen penetrating to mid-latitudes at this time (see Figure 1). While it may seem surprising that there is a sufficient source of ACRs in the interplanetary medium at this phase of the solar cycle, we find that the interplanetary flux of ≥ 15 MeV/nuc ACRs had already recovered to ~20% of its solar minimum

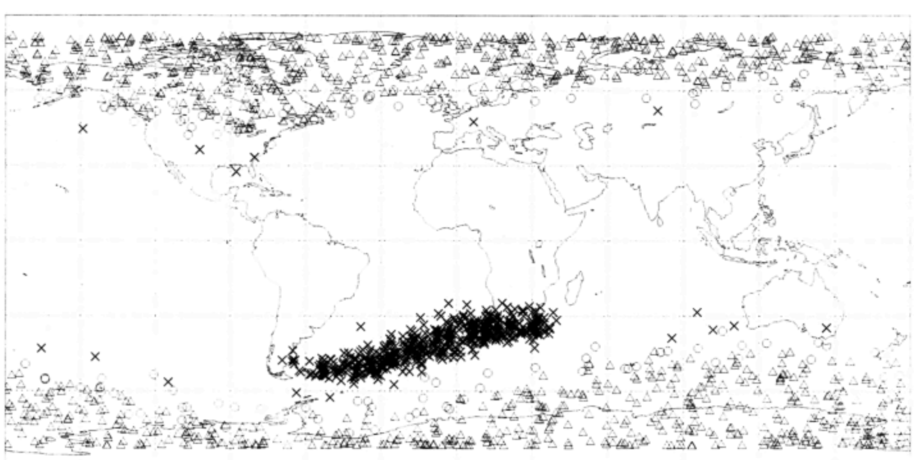

Fig. 2: The geographic distribution of observed oxygen ions is indicated, using the same symbols as in Fig. 1. For comparison, note that the SAA is centered approximately at -30° latitude and 315° longitude.

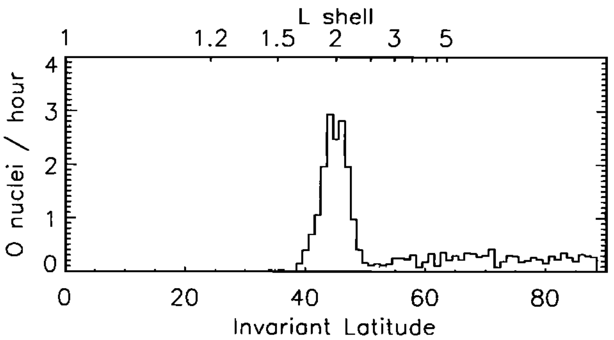

Fig. 3: Measured counting rates for 16 to 30 MeV/nuc oxygen ions as a function of Λ. The L value is also indicated [$L = 1/\cos^2(\Lambda)$]. Only solar quiet days are included.

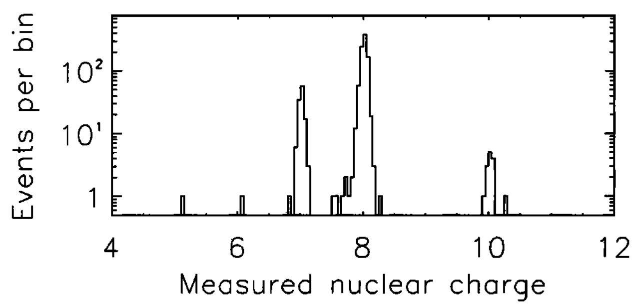

Fig. 4: Observed composition of $Z \geq 4$ nuclei at $L = 2.05 \pm 0.60$, including all days from 7/6/92 to 2/7/93. Detection thresholds in MAST range from ~14 MeV/nuc for C, to ~16 MeV/nuc for O, to ~18 MeV/nuc for Ne. In addition, one event with $Z = 23$ was observed.

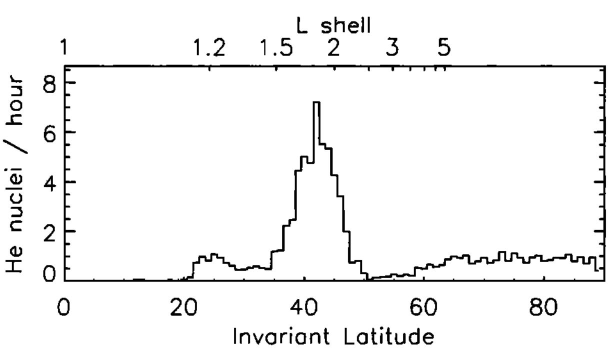

Fig. 5: Counting rates for 7 to 15 MeV/nuc He ions as a function of Λ. Only solar quiet days are included. The smaller peak at $\Lambda \approx 25°$ includes He in the region of the SAA.

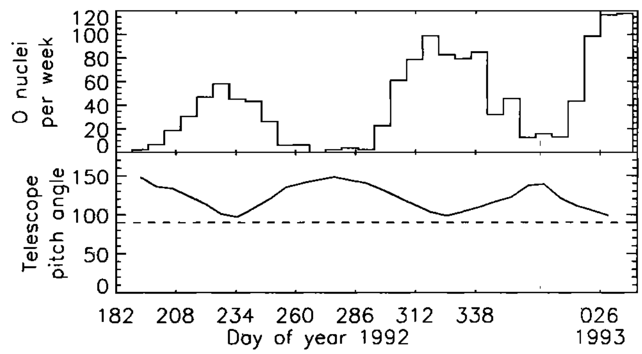

Fig. 6: Top Panel: Rate at which MAST detects O nuclei in the region southeast of the SAA, delimited here by $L = 2.05 \pm 0.60$ and restricted to the southern hemisphere. Bottom Panel: Average angle of the MAST telescope axis to the local magnetic field (calculated from the 1990 IGRF field, updated with secular variations) for events included in the top panel. This angle evolves with a ~3-month period as the SAMPEX orbit precesses. MAST has a full opening angle of ~101°. Similar results are obtained for N and Ne.

level by late 1992 (Mewaldt et al. 1993). The increase in intensity that is evident in Figure 6 is approximately consistent with the change in the interplanetary ACR flux over this time period as measured by SAMPEX.

Blake and Friesen (1977; see also Blake 1990) predicted that trapped ACR oxygen would be located at $L \approx 2.5$ to 3.5, somewhat greater than we observe. In their model the maximum L-shell that allows stable trapping is specified by the "adiabaticity" parameter (ε), defined as $\varepsilon = \rho/|B/\nabla B|$, where B is the magnetic field strength and ρ the ion's Larmor radius. They used

$$\varepsilon = 0.049\,(A/Z)L^2\,[\gamma^2 - 1]^{1/2}, \qquad (1)$$

where γ is the particle's Lorentz factor, and suggested that ions with $\varepsilon < 1/3$ (and the proper pitch angle) at the time of stripping would be stably trapped. Our observations of the L-shell distribution of N and O from ~15 to ~50 MeV/nuc suggest that $\varepsilon < 1/10$ is a more appropriate limit if Eqn. (1) is assumed to be correct. Tylka (1993) has modeled trapped ACRs at 600 km for $\varepsilon < 1/9$ and obtains reasonable agreement with the geographical distribution in Figure 2. In the B&F model the lowest energy ACR nuclei that have access to a given L-shell was assumed to be given by the vertical geomagnetic cutoff $P_c = (14.9\ \text{GV})/L^2$, in which case singly ionized N, O, and Ne with kinetic energies > 38, 29, and 19 MeV/nuc, respectively, can be trapped at $L = 2$. Our observations suggest that a more appropriate limit is the somewhat lower cutoff from the west (e.g. Rossi and Olbert 1970), in which case singly ionized N, O, and Ne with > 27, 21, and 14 MeV/nuc have access to $L = 2$. SAMPEX observations verify that there is a interplanetary source of ACR N, O, and Ne above these energies in late 1992 (Mewaldt et al. 1993).

The appearance of trapped He at $L \approx 2$ is somewhat surprising, as anomalous He is not expected to be trapped by the B&F mechanism because the change in rigidity that occurs upon stripping is only a factor of 2, compared to a factor of 8 for ACR oxygen. In addition, singly-charged He ions arriving from the west must have energies > 294 MeV/nuc to reach $L = 2$, several times greater than the observed maximum energy of ACR He (e.g., McDonald et al. 1992). Therfore, if the observed He is of ACR origin, there must be another mechanism by which He nuclei with energies < 30 MeV/nuc are trapped at $L \approx 2$.

It is also possible that there is an additional source of trapped heavy ions at $L \approx 2$, and Adams (1993) and Blake (1993) have independently suggested to us that the observed He may be a remnant of a solar particle population trapped during the substorm of 3/24/91 and observed by CRRES (Blake et al. 1992). We plan to investigate this and other possibilities by looking for evidence of other trapped solar particles at this location.

We conclude that we are observing ACR N, O, and Ne that have been trapped by the B&F mechanism (or some variation of this mechanism), and that the observed He at $L \approx 2$ is presently of unknown origin. While there may be other sources of trapped heavy nuclei that contribute, it appears that ACR nuclei are the dominant component of high-energy ions with $Z > 2$ in the inner magnetosphere at the time of these observations, with an intensity at $L = 2$ that is $\sim 10^2$ times that in interplanetary space at this time. If the intensity of trapped ACRs does indeed wax and wane over the solar cycle, as suggested by the COSMOS data, it is likely to increase by at least another factor of ~5 as solar minimum approaches. The analysis of additional SAMPEX data should better define the distribution, composition, energy spectra, and temporal behavior of this heavy-ion radiation belt, providing additional clues to its complex history. In particular, we hope to eventually use this trapped sample of interstellar matter to study the isotopic composition of the local interstellar medium (Mewaldt, Spalding, and Stone 1984; Cummings, Webber, and Stone 1991).

Acknowledgments: This work was supported by NASA under contract NAS5-30704 and grant NAGW-1919. We appreciate conversations with J. H. Adams, Jr., J. B. Blake, and A. J. Tylka.

References

Adams, J. H., Jr., private communication, 1993.

Adams, J. H. Jr. et al., The charge state of the anomalous component of cosmic rays, *Ap. J. Ltrs. 375*, L45, 1991.

Baker, D. N. et al., An overview of the Solar, Anomalous, and Magnetospheric Particle Explorer (SAMPEX) mission, *IEEE Trans. on Geoscience and Remote Sensing*, in press, 1993.

Biswas, S., and N. Durgaprasad, Skylab measurements of low energy cosmic rays, *Space Science Reviews 25*, 285, 1980.

Blake, J. B., Geomagnetically trapped heavy ions from anomalous cosmic rays, *Proc. 21st Internat. Cosmic Ray Conf.* (Adelaide) 7, 30, 1990.

Blake, J. B., private communication, 1993.

Blake, J. B. et al., Injection of electrons and protons with energies of tens of MeV into $L < 3$ on 24 March 1991, *Geophys. Res. Lett. 19*, 821, 1992.

Blake, J. B., and L. M. Friesen, A technique to determine the charge state of the anomalous low energy cosmic rays, *Proc. 15th Internat. Cosmic Ray Conf.* (Plovdiv) 2, 341, 1977.

Bobrovskaya, V. V. et al., A new method for the investigation of the anomalous component of cosmic rays, to be published in the *Proc. of the Transregional Cosmic Ray Conference* Samarkand, Uzbekistan, 1993.

Cook, W. R. et al., MAST: A Mass Spectrometer Telescope for studies of the isotopic composition of solar, anomalous, and galactic cosmic ray nuclei, *IEEE Trans. on Geoscience and Remote Sensing*, in press, 1993.

Cummings, A. C., and E. C. Stone, Elemental composition of the very local interstellar medium as deduced from observations of anomalous cosmic rays, *Proc. 21st Internat. Cosmic Ray Conf.* (Adelaide) *6*, 202, 1990.

Cummings, A. C., E. C. Stone, and W. R. Webber, The isotopic composition of anomalous cosmic ray neon, *Proc. 22nd Internat. Cosmic Ray Conf.* (Dublin) *3*, 362, 1991.

Cummings, J. R. et al., New evidence for anomalous cosmic rays trapped in the magnetosphere, *Proc. 23rd Internat. Cosmic Ray Conf.* (Calgary), *3*, 428, 1993.

Fisk, L. A., B. Kozlovsky, and R. Ramaty, An interpretation of the observed oxygen and nitrogen enhancements in low-energy cosmic rays, *Ap. J. (Ltrs.)*, *190*, L35, 1974.

Grigorov, N. L. et al., Evidence for anomalous cosmic ray oxygen ions in the inner magnetosphere, *Geo. Res. Ltrs. 18*, 1959, 1991.

McDonald, F. B. et al., The Cosmic Radiation in the Heliosphere at successive solar minima, *J. Geophys. Res.* 97, 1557 1992.

Mewaldt, R. A. et al., The return of the anomalous cosmic ray component to 1 AU in 1992, *Proc. 23rd Internat. Cosmic Ray Conf.* (Calgary), *3*, 404, 1993.

Mewaldt, R. A., J. D. Spalding, and E. C. Stone, The isotopic composition of the anomalous low energy cosmic rays, *Astrophys. J. 283*, 450, 1984.

Pesses, M. E., J. R. Jokipii, and D. Eichler, Cosmic ray drift, shock wave acceleration, and the anomalous component of cosmic rays, *Ap. J. Lett. 246*, L85, 1981.

Spjeldvik, W. N., and T. A. Fritz, Experimental determination of geomagnetically trapped energetic heavy ion fluxes, *Energetic Ion Composition in Earth's Magnetosphere*, R. G. Johnson, ed. (Terra Scientific, Tokyo) 1983.

Rossi, B. and S. Olbert, *Introduction to the Physics of Space*, McGraw-Hill, New York, 1970

Tylka, A., Spectra and geographical distribution of geomagnetically trapped anomalous cosmic rays, *Proc. 23rd Internat. Cosmic Ray Conf.* (Calgary), *3*, 436, 1993.

A. C. Cummings, J. R. Cummings, R. A. Mewaldt, R. S. Selesnick, and E. C. Stone, California Institute of Technology, 220-47, Pasadena, CA 91125

T. T. von Rosenvinge, NASA/Goddard Space Flight Center, Greenbelt, MD 20771

(Received: June 21, 1993;
accepted: July 14, 1993.)