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A study of the composition and energy spectra of anomalous cosmic rays using the geomagnetic field

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Abstract. We use instrumentation on SAMPEX and the Earth's field as a magnetic rigidity filter in a "double spectrometer" approach to measure the composition and energy spectra of anomalous cosmic rays (ACRs) with $Z \geq 6$. A "pure" sample of anomalous cosmic ray C, N, O, and Ne is obtained, with no significant evidence for other species. The bulk of ACRs are now known to be singly-charged, and the geomagnetic filter allows their energy spectra to be measured to higher energies than before. The anomalous oxygen spectrum is found to extend to at least ~100 MeV/nuc, which has implications for models of the acceleration of these ions.

Introduction

Anomalous cosmic rays (ACRs) are a low-energy component of interplanetary particles that include the elements H, He, C, N, O, Ne, and Ar (see, e.g., reviews by Klecker 1995, and Simpson 1995). They are now known to originate from interstellar neutral particles that have been swept into the heliosphere, ionized by solar UV or charge exchange with the solar wind, convected into the outer heliosphere, and then accelerated to energies of ~10 MeV/nuc and more (Fisk, Ramaty, and Koslovsky 1974). It is commonly assumed that the bulk of ACR acceleration takes place at the solar wind termination shock (Pesses, Jokipii, and Eichler 1981). A key prediction of this model, now established experimentally, is that ACRs should be singly-ionized. In particular, Klecker et al. (1995) find that <10% of ~10 MeV/nuc ACR oxygen has an ionic charge $Q \geq 2$.

Being singly-charged, ACRs have a much greater magnetic rigidity (at a given energy/nuc) than either galactic cosmic rays (GCRs), which are essentially fully stripped, or solar energetic particles (SEPs), which have charge states characteristic of coronal temperatures of ~2 x 10^6 °K (Luhn et al. 1984; Leske et al. 1995a). As a result, ACRs can be observed to much lower invariant latitude with a polar orbiting spacecraft (Adams et al. 1991, Cummings et al. 1993, Klecker et al. 1995). The invariant latitude is $\Lambda = \cos^{-1}[(1/L)^{1/2}]$, where L is the McIlwain L parameter. In this paper we use the geomagnetic field as a magnetic rigidity filter to obtain a "pure" sample of ACRs, and then measure their composition and energy spectra over a broad energy range.

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Previously, Adams et al. (1991) used a similar approach to obtain orbit-averaged spectra of ACR oxygen using passive detectors flown on a series of Cosmos satellites. Our study differs from that of Adams et al. because the sub-second time resolution provided by SAMPEX allows the selection of data from specific latitude intervals. A preliminary version of this work appears in Mewaldt et al. (1995).

Observations

The observations were made with the Mass Spectrometer Telescope (MAST; see Cook et al. 1993) on the polar-orbiting (82° inclination) SAMPEX satellite (Baker et al. 1993) from 6 July 1993 to 7 January 1995. The measured kinetic energy vs. invariant latitude for quiet-time oxygen events is shown in Figure 1, limited to events observed during those periods when the daily-average flux of 8 to 15 MeV/nuc He was < 4 x 10^{-4} per cm^2sec·sr. This criterion eliminated ~10% of the available days.

Three distinct particle populations are evident in Figure 1. At high latitudes ($\Lambda > 65^\circ$), there is a mixture of GCR and ACR oxygen with the ACRs more abundant at the lowest energies (<30 MeV/nuc), and GCRs more abundant at higher energies. At mid-latitudes ($\Lambda \approx 50^\circ$ to 60°), fully-stripped GCRs are not allowed but singly-charged ACR oxygen nuclei have access because of their greater magnetic rigidity. Finally, at low latitudes ($\Lambda \leq 50^\circ$) there is a radiation belt composed of ions that originate from ACRs that have lost their electrons in the upper atmosphere and then been trapped in the geomagnetic field because of their resulting lower rigidity (Blake and Friesen 1977; Grigorov et al. 1991; Cummings et al. 1993).

Also shown in Figure 1 are the boundaries used to isolate a pure sample of ACRs. The upper boundary at $\Lambda \approx 52^\circ$ to 65° is designed to filter out GCRs and SEPs. It is based on the empirical geomagnetic cutoff vs. latitude relation determined by Leske et al. (1995a) from observations of solar energetic particle He and C, lowered by an additional 20% to guard against contamination by fully-stripped nuclei during geomagnetic storms that might temporarily lower the cutoff. This is equivalent to a latitude restriction ~4° below the vertical geomagnetic cutoff. The boundary location is calculated for the measured nuclear charge, mass, and kinetic energy of each particle, and only particles observed below this boundary are accepted.

To filter out trapped anomalous cosmic rays we use the observation that they are characterized by an "adiabaticity" parameter (ε), such that $\varepsilon Q_s < 0.8$ (Selesnick et al. 1995). Here $\varepsilon = 0.000052\cos^{-4}(\Lambda)(A/Q_S)[E^2+2M_pE]^{1/2}$, where A is the number of nucleons, Q_S is the ionic charge state just after stripping in the initial atmospheric encounter, E is kinetic

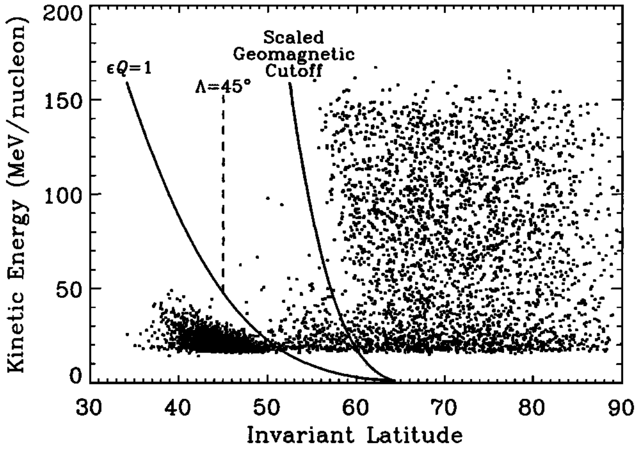

Figure 1. Measured energy/nucleon vs. invariant latitude for quiet-time oxygen events observed by the MAST instrument on SAMPEX from 6 July 1992 to 7 January 1995. The study includes events between the solid lines, with the added requirement that Λ>45° (dashed line). Trapped ACRs are seen below 50°.

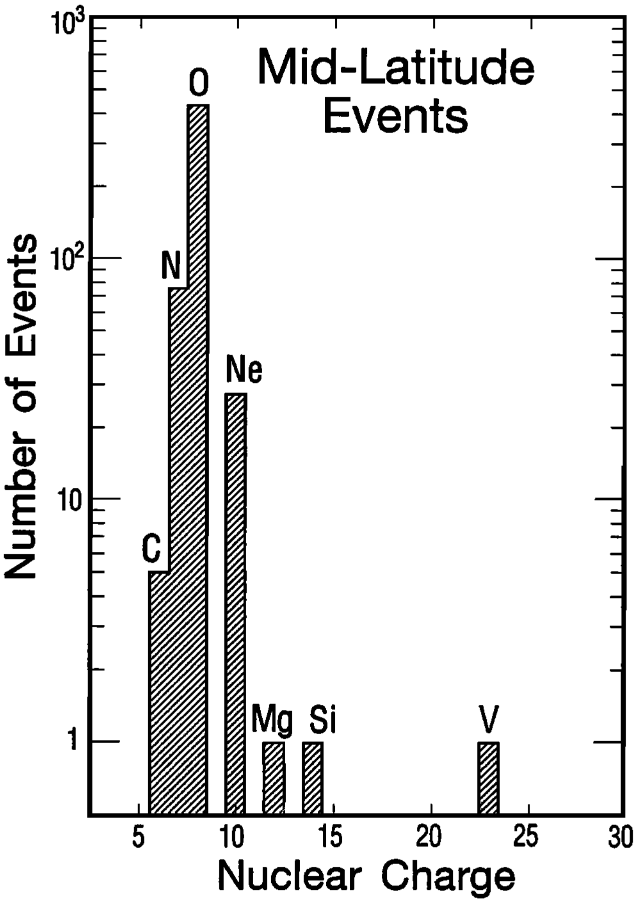

Figure 2. Composition of events with energies greater than ~15 MeV/nuc observed at mid-latitudes. No corrections have been applied for energy or latitude interval differences. The Mg and Si events both had an observed energy of ~30 MeV/nuc, while the single V event had ~200 MeV/nuc.

energy in MeV/nuc, and M_p is the proton rest mass in MeV. Note that εQ_S is a constant of motion as long as E and L [defined as $1/\cos^2(\Lambda)$] remain constant. Following Selesnick et al. (1995) we require $\varepsilon Q_S > 1$. In addition, we require Λ>45° to ensure that all ACRs with >15 MeV/nuc have good access to SAMPEX, which is generally zenith oriented for Λ>45°, but has a more varied orientation at lower latitudes. Using a Monte-Carlo approach, we have traced a large number of particle trajectories in the IGRF 1992 magnetic field and verified that the actual SAMPEX pointing directions for Λ>45° result in an acceptance of at least 90% for all singly-charged ACRs with Z≥6 and E≥15 MeV/nuc.

The quiet-time composition of Z≥6 ions measured at mid-latitude, shown in Figure 2, shows evidence for ACR C, N, O, and Ne, but no significant evidence for other species. The resulting composition, including corrections for the differing energy interval covered by each species, is shown in Table 1. Note that there is good consistency with the ACR composition observed by Voyager in 1987 at 23 AU. Voyager also observes ACR Ar at low energies (Cummings and Stone 1988), but the number of ACR Ar events that would be expected to be observed by MAST during this time interval is less than one.

ACR energy spectra from the mid-latitude region are compared with interplanetary spectra obtained at Λ>65° in Figure 3. It is interesting that the mid-latitude spectra appear to be consistent with a power law shape, with a spectral index of approximately -3.5 to -4. While it is possible that interplanetary transport to 1 AU may have modified the slope of the accelerated spectra, one would not expect this to be a significant effect because of the relatively large rigidities of these ions (~3 to 7 GV for 16 to 100 MeV/nuc singly charged oxygen).

The data in Figure 3 show that the energy spectra of ACR N and Ne extend to >50 MeV/nuc (the highest energy N and Ne had 57 and 68 MeV/nuc, respectively), while that of ACR oxygen extends to at least 100 MeV/nuc (where two O ions were observed, well below cutoff, on geomagnetically quiet days). This means that the ACR accelerator (presumably the termination shock) must be capable of accelerating particles to at least 1.6 GeV, corresponding in the model of Jokipii (1990) to 400 MeV/nuc for ACR He and 1.6 GeV for ACR hydrogen.

Discussion

The acceleration of singly-charged ACRs to energies >1 GeV must occur in a time less than the lifetime against electron stripping if ACRs are mainly singly ionized. Based on arguments in Adams and Leising (1991), Jokipii (1992) obtained a lifetime against stripping of ~5 years at ~100 AU for 10 MeV/nuc ACRs. He further estimated that diffusive

Table 1. Anomalous Cosmic Ray Abundances

Element	Mid-Latitude ACRs >17 MeV/nuc	Voyager-2 at 23 AU * 16-30 MeV/nuc
C	0.014 ± .009	0.020 ± .004
N	0.19 ± .03	0.194 ± .013
O	1	1
Ne	0.06 ± .02	0.048 ± .006
All Others	<0.01	

*Selesnick et al. (1995)

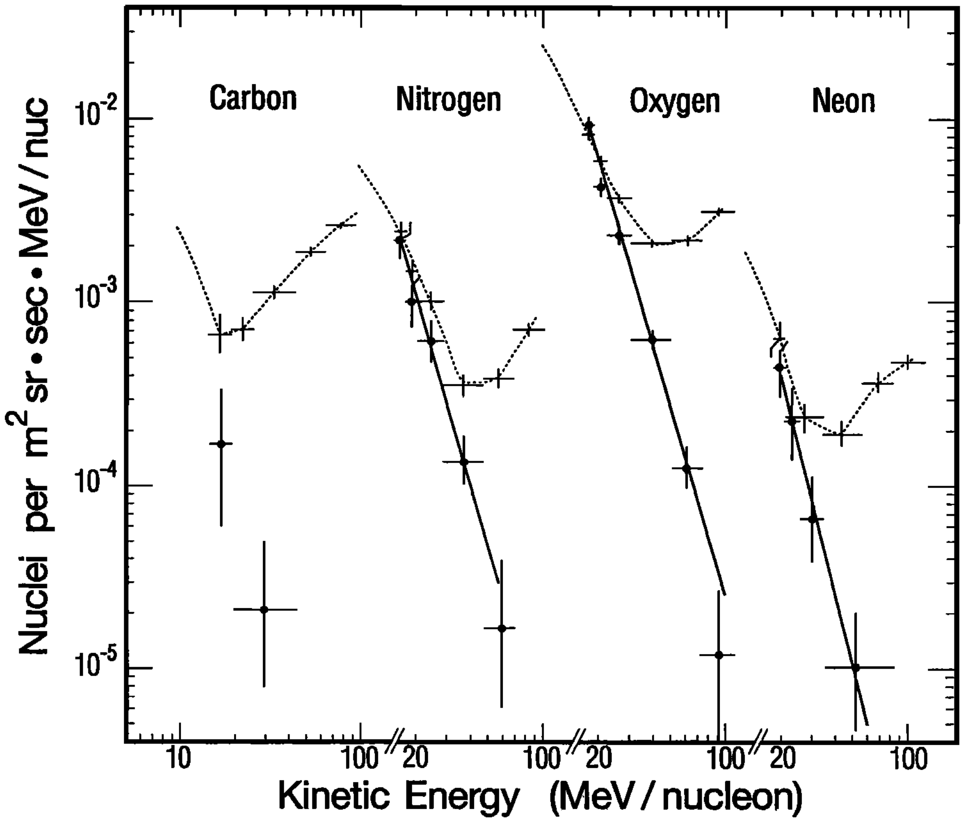

Figure 3. Energy spectra of ACRs measured at mid-latitudes, compared to interplanetary spectra obtained at Λ > 65° (dashed lines). Below ~15 MeV/nuc the dashed lines have been extended to illustrate the shape of the 1992-1993 spectra observed by Mewaldt et al. (1993). The solid lines are power law fits to the mid-latitude spectra, with spectral indices for N, O, and Ne of -3.56 ± 0.43, -3.45 ± 0.15, and -4.17 ± 0.85, respectively.

shock acceleration to 10 MeV/nuc at ~100 AU would require a minimum of ~0.5 years for a perpendicular shock (the expected geometry of the termination shock), and at least four years for a quasi-parallel shock (see also Klecker 1995). Corresponding acceleration times for 100 MeV/nuc ACRs would be a factor of ~10 longer, in which case the integrated probability of stripping one or more electrons would be considerably greater than at lower energies because of the much greater pathlength traversed. Thus, the acceleration and stripping times appear to be comparable, suggesting that higher energy ACRs may not all be singly-charged. If this is the case, measurements of the charge states of ACRs with higher energy than the ~10 MeV/nuc particles studied by Klecker et al. (1995) and Adams et al. (1991) may provide insight into the acceleration times of ACRs in the heliosphere.

The possibility that a significant fraction of higher energy ACRs may have a charge Q > 1 may also provide a partial explanation of how ACRs are accelerated to energies >1 GeV. According to Jokipii (1990), the energy gain ΔE by an ion with an electrical charge Qe at a quasi-perpendicular shock is approximately the electrostatic potential Δϕ gained in drifting along the shock face: $\Delta E \approx Qe\Delta\phi$. He finds $\Delta E \approx 240$ MeV for the termination shock, assuming Q=1, and predicts that there should be a steepening of the accelerated ACR spectra at energies >240 MeV (corresponding to ~15 MeV/nuc for ACR oxygen). While the expected location of this break is at the lower edge of the MAST energy interval, data from the HILT sensor on SAMPEX do show a flattening of the spectrum below 15 MeV/nuc (see Mewaldt et al. 1993).

According to the above relation for ΔE, singly-charged ACRs that happen to be stripped of additional electrons in the course of their acceleration will gain more energy than those that remain singly-charged. Thus the likely existence of ACRs with Q>1 may help explain the relatively large flux of ACRs with kinetic energies many times greater than 240 MeV Jokipii and Kota (1995) have also recently suggested that increased latitudinal diffusion can help explain how ACRs get accelerated to >1 GeV.

Both SAMPEX (Mewaldt et al. 1993) and Geotail (Hasebe et al., 1994) investigators have reported a "bump" in the 1992-1993 carbon spectrum at ~10 to 15 MeV/nuc that was ~5 times more intense than expected for ACR carbon, giving a C/O ratio of ~0.1. Although the MAST data are limited to carbon with >14 MeV/nuc, Figures 2 and 3 (and Table 1) indicate a C/O ratio at mid-latitudes similar to that observed at Voyager, indicating that the 1992-1993 feature in the carbon spectrum was apparently not due to singly-ionized carbon.

Biswas et al. (1990; see also Dutta et al. 1993) have reported Spacelab-3 observations of heavy nuclei with $21 \le Z \le 28$ that were apparently partially stripped, since they were observed at latitudes inaccessible to fully stripped cosmic rays. They concluded that ~20% of heavy GCRs with <100 MeV/nuc observed during their 1985 flight were partially ionized (Dutta et al. 1993). We see no strong evidence for the presence of these particles in 1992-1994, when the vast majority of cosmic ray nuclei with Z ≥12 appear to be fully stripped (see also Tylka et al. 1995). If we assume, for example, that 20% of the GCRs in the SAMPEX energy range are partially stripped nuclei with $Q/Z < 1/4$, we would expect to have observed >100 mid-latitude events with $Z \geq 12$, compared to the three candidates in Figure 2. Mewaldt (1995) has suggested that the apparent "partially stripped GCRs" might be solar particles re-accelerated at the termination shock, which should be more abundant during the Spacelab-3 period than in 1992-1994 (although this explanation would not explain the apparently large fraction of nuclei with $22 \leq Z \leq 24$ reported by Dutta et al.). In addition, Tylka et al. (1995) have suggested a cosmic ray albedo origin.

The observations presented here demonstrate that the geomagnetic filter approach can successfully obtain a pure sample of ACR ions. This approach will be particularly useful for measuring the isotopic composition of ACR nuclei as a means of studying the isotopic composition of the nearby interstellar medium (for preliminary results see Leske et al. 1995b). In addition, the fact that the ACR energy spectrum extends to ~1.6 GeV, when combined with theoretical considerations, suggests that the highest energy ACRs may not be singly-charged. A possible test of this hypothesis using SAMPEX data is now in progress.

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