Studies of Anomalous Cosmic Rays using the Geomagnetic Field

R. A. Mewaldt[1], J. R. Cummings[1], R. A. Leske[1],
R. S. Selesnick[1], E. C. Stone[1], and T. T. von Rosenvinge[2]

[1]California Institute of Technology, Pasadena, CA 91125 USA
[2]Goddard Space Flight Center Code 661, Greenbelt, MD 20771 USA

Abstract

We use instrumentation on SAMPEX and the Earth's field as a magnetic rigidity filter in a new "double spectrometer" approach to measure the composition and energy spectra of anomalous cosmic rays. We obtain a "pure" sample of anomalous cosmic ray C, N, O, and Ne, with no significant evidence for other species. The energy spectrum of anomalous oxygen extends to ~100 MeV/nuc, which has implications for models of the acceleration of these nuclei.

1 Introduction

Anomalous cosmic rays (ACRs) are a singly-charged component of interplanetary particles that include the elements H, He, C, N, O, Ne, and Ar. 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 ~5 to 50 MeV/nuc [1]. It is commonly assumed that the bulk of ACR acceleration takes place at the solar wind termination shock [2]. A key prediction of this model, now established experimentally, is that ACRs should be singly-ionized. In particular, Klecker et al. [3] find that <10% of ACRs have a charge $Q \geq 2$.

Being singly-charged, ACRs have a much greater magnetic rigidity than galactic cosmic rays (GCRs) or solar energetic particles (SEPs) with the same energy/nuc. As a result, they can be observed to much lower invariant latitude ($\Lambda = \cos^{-1}(1/L^{1/2})$, with L the McIlwain L parameter). Using the geomagnetic field as a magnetic rigidity filter, we obtain a "pure" sample of ACRs and measure their composition and energy spectra over a broad energy range.

2 Observations

The observations were made with the Mass Spectrometer Telescope (MAST) on the polar-orbiting (82° inclination) SAMPEX satellite from 92:183 to 95:007. Figure 1 shows measured kinetic energy vs. invariant latitude for quiet-time oxygen events. Three distinct particle populations are evident. At high latitudes ($\Lambda > 65°$), there is a mixture of GCR and ACR oxygen. At mid-latitudes ($\Lambda \approx 50°$ to 60°), fully-stripped GCRs are not allowed but singly-charged ACR oxygen has access because of its greater magnetic rigidity. Finally, at low latitudes ($\Lambda \leq 50°$) there is a concentration of trapped ACRs [4, 5].

Also shown in Figure 1 are boundaries used to isolate a pure sample of ACRs. We use the empirical geomagnetic cutoff vs. latitude relation determined by Leske et al. [6], lowered by an additional 20% to guard against contamination during geomagnetic storms that temporarily lower the cutoff. Trapped ACRs are characterized by an "adiabaticity" parameter (ε), such that

$\varepsilon Q < 0.8$, with $\varepsilon = 0.000052\cos^{-4}(\Lambda)(A/Q)[E^2+2M_pE]^{1/2}$ [5]. We require $\varepsilon Q > 1$, equivalent to a latitude restriction ~4° below the vertical cutoff. In addition, we require $\Lambda>45°$ in an effort to ensure that all ACRs with >15 MeV/nuc have access to SAMPEX, which is generally zenith oriented for $\Lambda>45°$, but has a more varied orientation at lower latitudes. The measured rigidity of each particle (based on measured nuclear charge, mass, and energy) is compared to this filter. The resulting quiet-time composition (Figure 2) shows evidence for ACR C, N, O, and Ne, but no significant evidence for other species. There is good consistency with Voyager ACR data (Table 1).

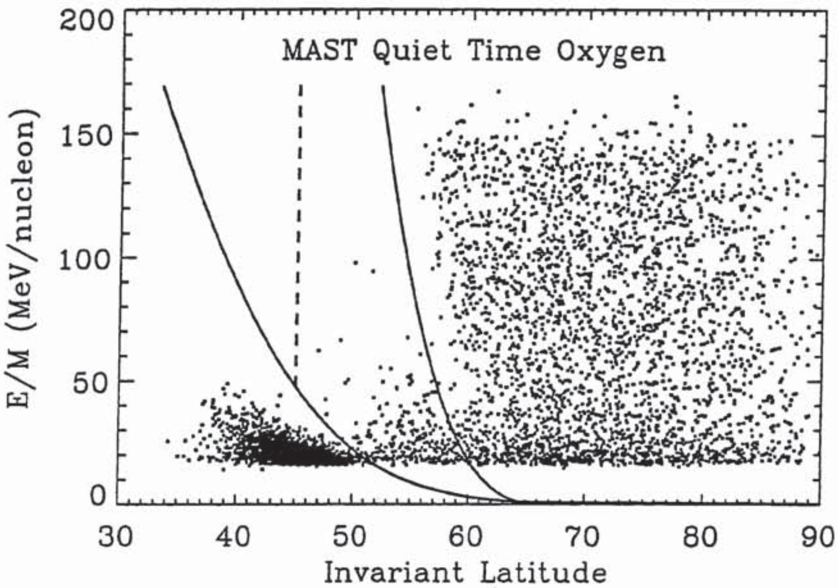

Figure 1: Measured energy/nuc vs. magnetic latitude for oxygen events. The study includes events between the solid lines, with the added requirement that Λ>45° (dashed line). Trapped ACRs are seen below 50°.

Figure 3 compares ACR energy spectra from the mid-latitude region with interplanetary spectra obtained at $\Lambda>65°$. It is interesting that the measured spectra appear to be consistent was power laws, but before attempting any quantitative comparison with theoretical models we warn the reader that we must still verify that ACRs of all rigidities have equal access to SAMPEX. In addition, note that interplanetary transport likely will have modified the accelerated spectra. These possibilities are presently under consideration.

3 Discussion

Figure 3 shows that the energy spectra of ACR N and Ne extend to >50 MeV/nuc, while that of ACR oxygen extends to ~100 MeV/nuc (where 2 O 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 to ~400 MeV/nuc for ACR He and 1.6 GeV for ACR hydrogen. Although this greatly exceeds the typical maximum energy of ~240 MeV estimated by Jokipii [7] for acceleration at the termination shock, it should be noted that these particles appear to be on the high energy tail of the ACR energy spectrum.

Table 1
Anomalous Cosmic Ray Abundances

Element	Mid-Latitude ACRs ≥17 MeV/nuc	Voyager-2 at 23 AU [5] 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	

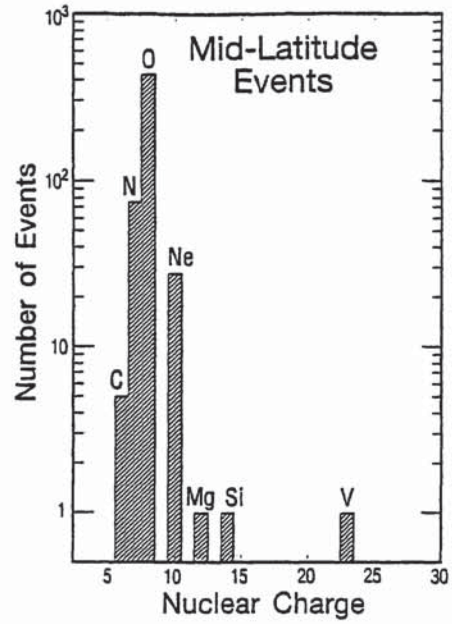

Figure 2 (at right): Raw number of events with energies greater than ~15 MeV/nuc at mid-latitudes. At this point no corrections have been applied for energy or latitude interval differences.

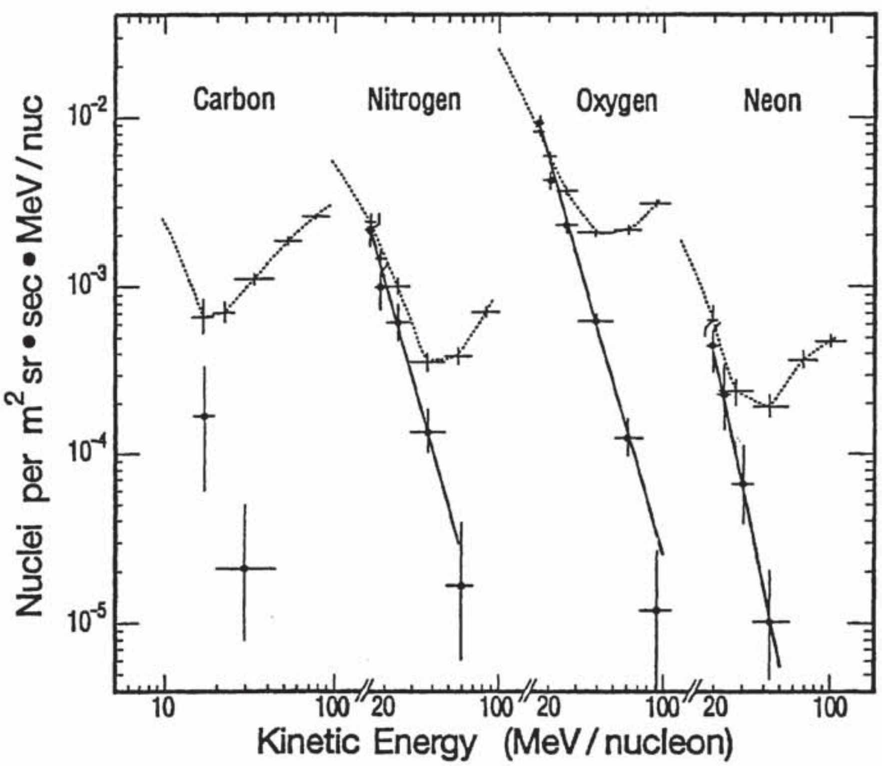

Figure 3: Energy spectra of ACRs measured at mid-latitudes (the solid lines are to guide the eye), compared to interplanetary spectra obtained at L>65 (dashed lines). Below ~15 MeV/nuc the dashed lines have been extended as in the 1992-1993 spectra from SAMPEX [8].

The acceleration of singly-charged ACRs to >1 GeV must occur in a time less than the lifetime against electron stripping. Based on arguments in Adams and Leising [9], Jokipii [10] obtained a lifetime against stripping of ~5 years at ~100 AU for 10 MeV/nuc ACRs. He further estimated that diffusive shock acceleration to 10 MeV/nuc at ~100 AU takes a minimum of 0.5 yr. for a perpendicular shock, and at least 4 years for a normal shock. Thus the acceleration and stripping times are comparable. Corresponding acceleration times for 100 MeV/nuc ACRs would be a factor of ~10 longer, and the integrated probability of stripping one or more electrons considerably greater because of the much greater pathlength traversed. This suggests that higher energy ACRs may not all be singly-charged, and that measurements of the charge states of higher energy ACRs in the manner of Klecker et al. [3] may provide insight into the acceleration times of ACRs in the heliosphere. Detailed trajectory tracing calculations of these high energy ACRs are planned.

SAMPEX [8] and Geotail [11] have observed a "bump" in the 1992-1993 C spectrum at ~10 to 15 MeV/nuc that was ~5 times more intense than expected for ACR carbon. Although the MAST data is limited to C with >14 MeV/nuc, Figures 2 and 3 (and Table 1) indicate an ACR carbon intensity similar to that at Voyager, indicating that the 1992-1993 feature in the C spectrum was apparently not due to singly-ionized carbon.

Biswas et al. [12] reported Spacelab-3 observations of heavy nuclei with $21 \leq Z \leq 26$ that were apparently partially stripped, since they were observed at latitudes inaccessible to fully stripped cosmic rays. They concluded that ~25% of heavy GCRs <100 MeV/nuc were partially ionized during their 1985 flight. We see no strong evidence for the presence of these particles in 1992-1994, when the vast majority of cosmic ray nuclei with $Z \geq 12$ appear to be fully stripped. Mewaldt [13] 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.

The observations presented here demonstrate that the geomagnetic filter approach can successfully obtain a pure sample of ACR nuclei. 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. [14].

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