THE ISOTOPIC COMPOSITION OF ANOMALOUS COSMIC RAYS FROM SAMPEX

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Abstract. Measurements of the anomalous cosmic ray (ACR) isotopic composition have been made in three regions of the magnetosphere accessible from the polar Earth orbit of *SAMPEX*, including the interplanetary medium at high latitudes and geomagnetically trapped ACRs. At those latitudes where ACRs can penetrate the Earth's magnetic field while fully stripped galactic cosmic rays (GCRs) of similar energies are excluded, a pure ACR sample is observed to have the following composition: ^{15}N/N < 0.023, ^{18}O/^{16}O < 0.0034, and ^{22}Ne/^{20}Ne $= 0.077(+0.085, -0.023)$. We compare our values with those found by previous investigators and with those measured in other samples of solar and galactic material. In particular, a comparison of ^{22}Ne/^{20}Ne measurements from various sources implies that GCRs are not simply an accelerated sample of the local interstellar medium.

Key words: abundances, isotopes, anomalous cosmic rays, *SAMPEX*, neon, interstellar medium, heliosphere, trapped heavy ions

1. Introduction

Anomalous cosmic rays (ACRs) originate from neutral interstellar atoms 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 $\sim$ 1 to $>$ 50 MeV/nuc (Fisk et al., 1974). They are mainly singly–charged, and include H, He, C, N, O, Ne, and Ar (see review by Klecker 1995). When impinging on the upper atmosphere, ACRs may become stripped of additional electrons and trapped in the Earth's magnetosphere by the mechanism of Blake and Friesen (1977), forming a radiation belt composed of interstellar material (Cummings et al., 1993). Since its launch in 1992, the Mass Spectrometer Telescope (MAST; Cook et al., 1993) on the *Solar, Anomalous, and Magnetospheric Particle Explorer* (*SAMPEX*) has been measuring the composition and energy spectra of ACRs in interplanetary space and in the magnetosphere, providing a new source of information on interstellar matter.

This paper discusses ACR isotope measurements, which are important for studying the evolution of the local interstellar medium (ISM) since the formation of the solar system and are relevant to galactic cosmic ray (GCR) isotope measurements (Mewaldt et al., 1984). We present measurements of N, O, and Ne isotopes (updated and expanded from Leske et al., 1995a and Mewaldt et al., 1996a) from three ACR samples in the near–Earth environment, and compare these with each other and with the composition of other solar system and galactic material.

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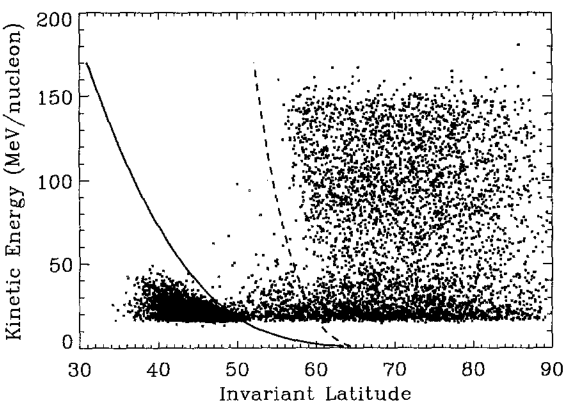

Figure 1. Kinetic energy vs invariant latitude for quiet time O events observed by MAST between July 1992 and November 1995, showing cuts used to select a pure ACR sample at mid–latitudes (see text). Trapped ACRs make up the dense concentration at low latitudes, while GCRs are restricted to the higher latitudes. (The drop in density between ~ 45 and 70 MeV/nuc is due in part to the loss of an intermediate–range detector in July 1994).

2. Anomalous Cosmic Ray Isotopic Composition

At least three distinct populations of ACR nuclei are accessible in the polar Earth orbit of *SAMPEX*, each occupying a different region of the orbit, as illustrated in the plot of kinetic energy vs invariant latitude for quiet time O shown in Figure 1. At high latitudes, the energetic particle population of interplanetary space at 1 AU is sampled; GCRs extend to ~ 150 MeV/nuc in the plot, with a pronounced enhancement visible at low energies due to ACRs. In the mid–latitude interval, GCRs with $\leq$ 150 MeV/nuc fall below the local geomagnetic cutoff rigidity and are excluded, while singly–charged (and even doubly– or higher–charged; Mewaldt et al., 1996a) ACRs have a higher rigidity than fully stripped GCRs at the same energy per nucleon and can penetrate to these latitudes. Located at still lower latitudes is a trapped ACR belt (Cummings et al., 1993) with the highest particle fluxes. The solid curve in Figure 1, which bounds the trapped population, corresponds to the product $\epsilon Q = 0.9$ (Selesnick et al., 1995), where the adiabaticity parameter ϵ is the ratio of the particle gyroradius to the local scale length of the magnetic field and Q is the ionic charge. The dashed curve is an empirically derived cutoff for fully stripped particles (Leske et al., 1995b), conservatively adjusted down 10% in rigidity to reduce potential GCR contamination from cutoff suppression during geomagnetically active periods. Events between the two curves represent a "pure" sample of ACR O; similar cuts were made for N and Ne to select geomagnetically filtered ACRs. (See Mewaldt et al., 1996b for the elemental composition of ACRs measured in this way.)

Figure 2 shows the mass distributions of N, O, and Ne from all three regions, taken from MAST data during solar quiet times between July 1992 and November 1995. The data here have been further restricted to times when the instrument trigger rate was $< 15000\ \mathrm{s}^{-1}$, which helps to minimize resolution–degrading effects of

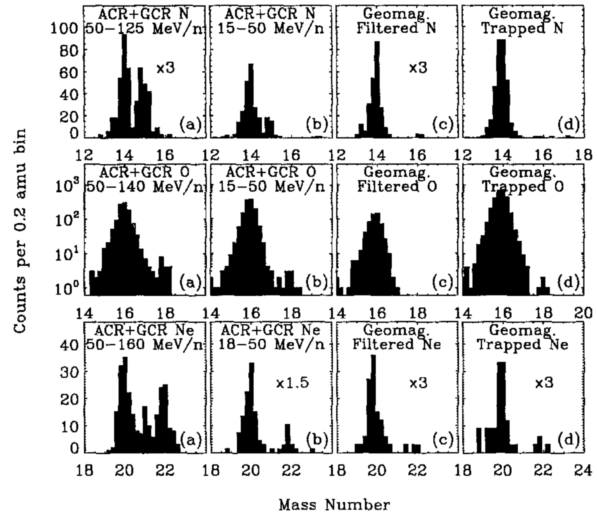

Figure 2. N, O (note logarithmic scales), and Ne isotope distributions from the MAST instrument on SAMPEX, including: a) > 50 MeV/nuc GCRs from latitudes Λ > 65°; b) < 50 MeV/nuc cosmic rays (mainly ACRs) from Λ > 65°; c) geomagnetically filtered, "pure" ACRs from ~ 50° < Λ < 60° (see Figure 1); and d) ACRs trapped in the magnetosphere (Λ ~ 45°).

trapped proton and alpha particle pileup in the position sensing detectors (as well as periods of sporadically noisy detectors).

Over the geomagnetic poles (latitudes Λ > 60°), the isotopic ratios of these elements vary with energy. At energies > 50 MeV/nuc, where GCRs dominate, most of the observed ^{15}N and ^{18}O is produced by cosmic ray spallation during transport through the galaxy and is not directly indicative of either the GCR source or the local ISM abundances (see e.g., Gibner et al., 1992). However, most of the observed ^{22}Ne originates in the cosmic ray source. Below 50 MeV/nuc, where ACRs dominate, the ^{15}N/N, ^{18}O/^{16}O, and ^{22}Ne/^{20}Ne ratios suddenly drop by factors of more than ~ 2 to 5 from those observed at higher energies, as illustrated in more detail in the right–hand panels of Figure 3 (following Mewaldt et al., 1984). Curves shown in the figure are preliminary estimates of the expected energy dependence of the isotopic ratios. They represent a weighted average of the observed GCR isotopic ratio and the assumed ACR ratio indicated on each curve (taken to be either solar or GCR source values), using energy–dependent weighting factors obtained from power–law fits to the ACR and GCR spectra. Our measurements provide the first clear evidence of the expected energy dependence of the ^{18}O/^{16}O ratio, and a much improved measure of the ^{15}N/N energy dependence.

A comparison of the isotopic ratios for the geomagnetically filtered ACRs in the mid–latitudes with those of the interplanetary fluxes at high latitudes reveals that GCRs make a significant contribution to interplanetary ^{15}N, ^{18}O, and ^{22}Ne even at the lowest energy interval in Figures 2 and 3. It is possible to subtract the GCR contributions to obtain a corrected ACR ratio, but this analysis is not yet complete. Instruments to be flown on the *Advanced Composition Explorer* (*ACE*) in 1997 will extend isotope measurements to lower energies (e.g., 5 to 15 MeV/nuc), where the ACR flux is greater and GCR contamination is minimized, with a collecting

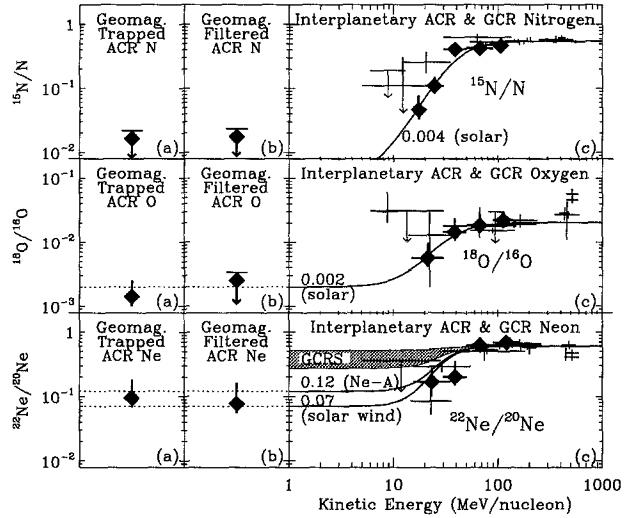

Figure 3. Observed isotopic composition of N, O, and Ne from MAST (*diamonds*), for a) trapped ACRs, b) geomagnetically filtered ACRs, and c) interplanetary particles (plotted vs energy) compared to previous measurements (*pluses*) and expected values (curves and shaded region; see text). Previous data are from the compilation by Mewaldt et al. (1984), and from Krombel and Wiedenbeck (1988), Garcia-Munoz et al. (1993), Connell and Simpson (1993a,b), DuVernois et al. (1993), Gibner et al. (1992), Lukasiak et al. (1994), Webber et al. (1996), and Cummings et al. (1991).

power > 30 times that on *SAMPEX*. However, *ACE* will not be able to make use of geomagnetic filtering as the satellite will be stationed outside the magnetosphere. Only upper limits are possible on the filtered ^{15}N and ^{18}O abundances at present due to limited statistics. The geomagnetically filtered ^{22}Ne/^{20}Ne ratio is $\simeq 0.1$, with a sizable statistical uncertainty.

To obtain ACR isotopic abundances from the geomagnetically trapped population, corrections must be applied for mass-dependent processes such as trapping efficiency and lifetime. These corrections have not yet been applied, but it appears that their effects are of opposing sign and small compared to the statistical uncertainties of our present measurements. Note that the observed ^{22}Ne/^{20}Ne ratio is again ~ 0.1, and the ^{18}O/^{16}O ratio appears to be consistent with the solar value of 0.002. The relatively intense flux of ACRs in this region offers the potential for excellent ACR isotope measurements, once the details of the trapping process are better understood.

3. Discussion

Although limited in statistical accuracy, the geomagnetically filtered ACR sample is far less subject to GCR contamination than the high latitude, low energy interplanetary sample, and less prone to selection processes than the trapped sample. In this region, we find preliminary values of the arriving ACR isotopic abundances (at the 84% confidence level) to be: ^{15}N/N < 0.023, ^{18}O/^{16}O < 0.0034, and ^{22}Ne/^{20}Ne $= 0.077^{+0.085}_{-0.023}$. After applying corrections for ACR acceleration and transport effects (Cummings et al., 1984, 1991) appropriate for measurements at 1 AU at this point in the solar cycle, these values become: ^{15}N/N < 0.023, ^{18}O/^{16}O < 0.0035,

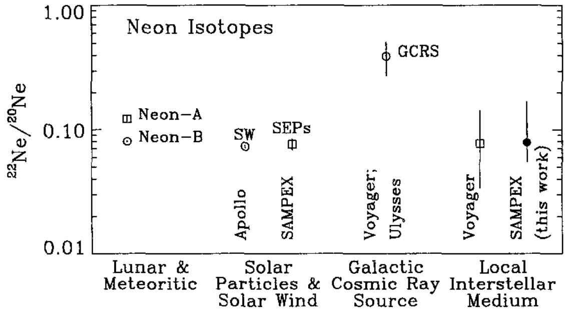

Figure 4. Comparison of ^{22}Ne/^{20}Ne ratios (references in text).

and ^{22}Ne/^{20}Ne $= 0.078^{+0.090}_{-0.024}$. While the ^{15}N and ^{18}O upper limits still exceed the solar system values for these species by factors of ~ 6 and 1.8 respectively, both are significant improvements over previous attempts to measure these ratios in ACRs (Figure 3). The ^{18}O/^{16}O upper limit is becoming comparable to values measured in other parts of the galaxy (Wilson and Rood, 1994).

To place the Ne measurements in context, Figure 4 compares ^{22}Ne/^{20}Ne measurements from several sources. There is some disagreement regarding the isotopic composition of solar Ne. In the Cameron (1982) table of solar system abundances, the meteoritic component "Neon–A" (with ^{22}Ne/^{20}Ne = 0.122) was used. Anders and Grevesse (1989), on the other hand, chose the solar wind value of ^{22}Ne/^{20}Ne = 0.076 (Geiss et al., 1972), which is close to the lunar/meteoritic component "Neon–B", thought to be implanted solar wind. Solar energetic particle (SEP) measurements from *SAMPEX* (Selesnick et al., 1993) find a ^{22}Ne/^{20}Ne ratio very close to the solar wind value. Determination of the GCR source (GCRS) ratio for ^{22}Ne/^{20}Ne depends on the details of transport through the galaxy, particularly the interaction cross sections for producing secondary ^{22}Ne from heavier species in spallation reactions with the gas of the interstellar medium. Various recent calculations of the GCRS ^{22}Ne/^{20}Ne ratio range from 0.322 (Connell and Simpson, 1993a) to 0.448 (Lukasiak et al., 1994). This range of values, along with the reported 1σ uncertainties, is represented by the shaded region in Figure 3 and the error range of the GCR data point in Figure 4. It is clear that the GCR source ratio greatly exceeds any of the solar system components. The *SAMPEX* and *Voyager* (Cummings et al., 1991) values for the local ISM are both ~ 0.1 and are not sufficiently accurate to differentiate Neon–A and Neon–B, but are clearly much less than the GCR source ratio. Although the values obtained from interplanetary ACRs (Figures 2b and 3c) and from trapped ACRs (Figures 2d and 3a) require further analysis to estimate possible systematic corrections and uncertainties, they also support a ratio of ~ 0.1 rather than a value as high as ~ 0.4.

These ^{22}Ne/^{20}Ne results indicate that GCRs are not simply a sample of local ISM that has been accelerated to high energies (e.g., Olive and Schramm, 1982), but rather suggest that GCRs include contributions from sources especially rich in ^{22}Ne, such as Wolf–Rayet stars (Prantzos et al., 1986). This work illustrates the potential of ACRs to provide unique information on the composition of the local ISM and to better understand the nature of GCRs. In the coming years we can expect improved statistical accuracy from *SAMPEX* as it continues to gather data under solar minimum conditions with increased ACR fluxes, and improved capability from *ACE*.

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