Measurements of the Isotopic Composition of Anomalous Cosmic Ray N, O, and Ne from ACE

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Abstract

We have measured the elemental and isotopic composition of anomalous cosmic rays (ACRs) with energies > 8 MeV/nucleon during solar quiet periods between August 1997 and March 1998, using the Solar Isotope Spectrometer (SIS) on the Advanced Composition Explorer (ACE). The capabilities of the SIS instrument allow the examination of spectra of individual ACR isotopes. In addition to the well-known low-energy ACR enhancements in the intensity of elemental O and Ne, similar enhancements are found in ^{18}O and ^{22}Ne, with relative abundances of $^{18}O/^{16}O \sim 0.002$ and $^{22}Ne/^{20}Ne \sim 0.1$. The neon abundance ratio appears more similar to that found in the solar wind than in meteorites, and is far below that deduced for the galactic cosmic ray (GCR) source, indicating that GCRs are not simply an accelerated sample of the local interstellar medium.

1   Introduction:

Anomalous cosmic rays (ACRs) originate from neutral interstellar atoms that enter the heliosphere, become ionized by solar UV or charge exchange with the solar wind, convected into the outer heliosphere, and accelerated to energies of ~ 1 to > 50 MeV/nucleon (Fisk et al., 1974). During solar quiet periods, the Solar Isotope Spectrometer (SIS) on the Advanced Composition Explorer (ACE) measures the composition and energy spectra of ACRs in interplanetary space outside of the magnetosphere, providing a new source of information on this sample of interstellar matter. In particular, SIS is able to improve upon existing ACR isotope measurements (e.g., Leske et al., 1996), 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 SIS measurements of N, O, and Ne isotopes and compare these with earlier measurements and with the composition of other solar system and galactic material.

2   Data Analysis:

The SIS instrument uses the dE/dx versus residual energy technique in a pair of silicon solid-state detector telescopes to measure the nuclear charge, Z, mass, M, and total kinetic energy, E, of energetic particles which stop in the device (Stone et al., 1998). The ACR species of interest here are measured in energy intervals which range from 6.6–83.3 MeV/nucleon for N to 7.8–101.8 MeV/nucleon for Ne. Mass resolution varies from ~ 0.15 to > 0.3 amu, depending on E and Z.

Figure 1 shows the mass distributions of N, O, and Ne obtained during solar quiet times between August 1997 and the end of March 1998. Consistency was required among multiple determinations of Z and M in order to reject events that involved chance coincidences or experienced nuclear interactions in the instrument. Also, the measured trajectory of each particle was used to reject particles which could have exited through the sides of the instrument without stopping. Because of the likelihood of background from the neighboring peaks, we report only an upper limit on the lowest energy ^{18}O value, while a 20% systematic uncertainty has been added in quadrature to the statistical uncertainties on the ^{22}Ne values below 15 MeV/nucleon.

3   Results and Discussion:

As is seen in Figure 1, the isotopic abundances of these elements clearly vary with energy. At energies

> 50 MeV/nucleon, 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 representative of either the GCR source or the local ISM abundances, while most of the observed ^{22}Ne originates in the cosmic ray source. Below ~ 30
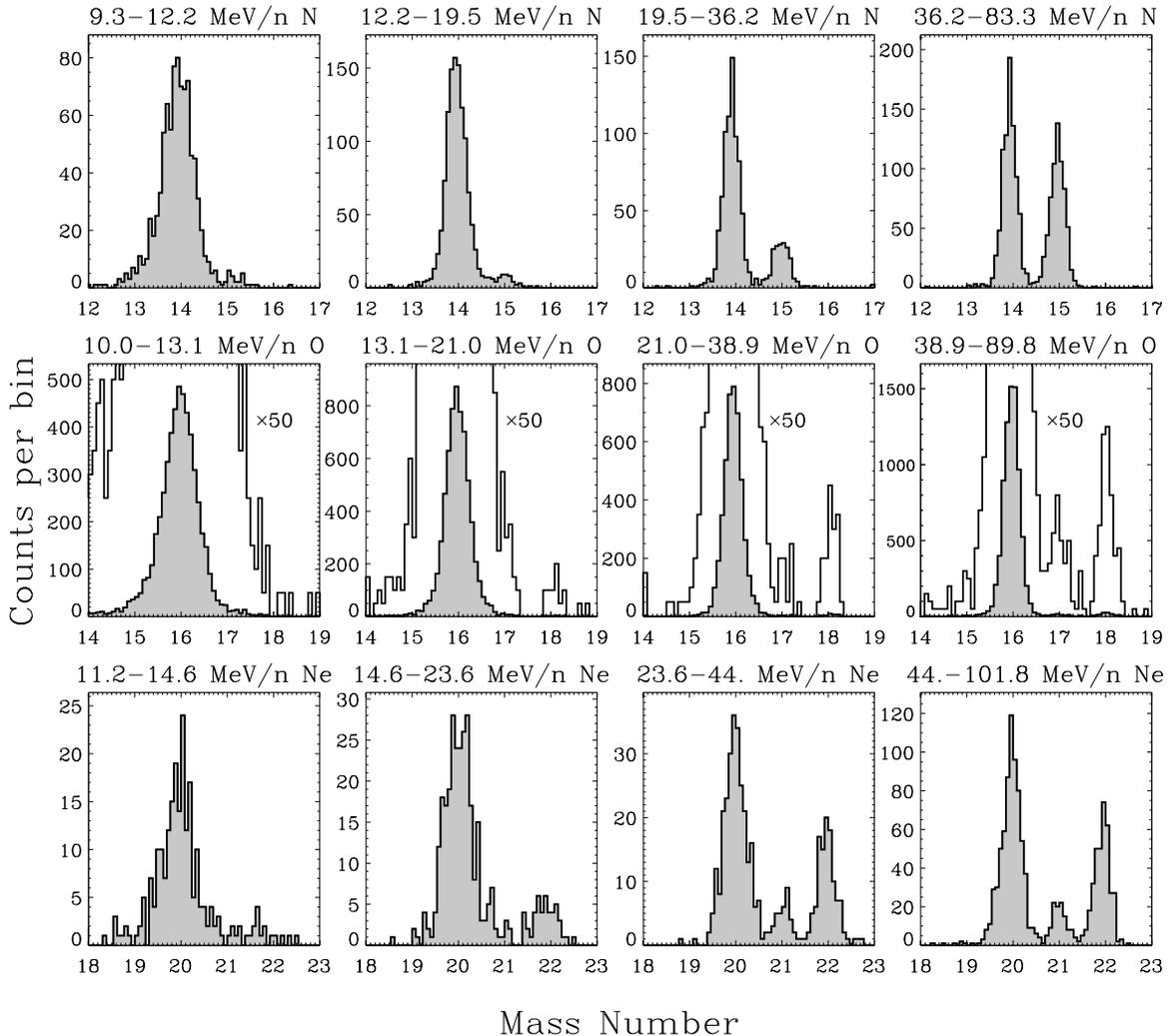
Figure 1: N, O, and Ne isotope distributions during ~ 165 solar quiet days, at the indicated energies, corresponding to SIS range 1, 2-3, 4-5, and 6-7 particles (left to right). A factor of 50 expansion of the oxygen histograms is also shown to better illustrate the ^{17}O and ^{18}O peaks.

MeV/nucleon, ACRs are the dominant contributor to the quiet time fluxes. Since, unlike GCRs, the ACRs have passed through a negligible amount of material, no secondary spallation products should be present. As expected, the ^{15}N/N, ^{18}O/^{16}O, and ^{22}Ne/^{20}Ne ratios suddenly drop by an order of magnitude or more from the values observed at higher energies, as illustrated in more detail in Figure 2 (following Mewaldt et al., 1984). Curves shown in the figure are estimates of the expected energy dependence of the isotopic ratios. They represent a weighted average of the isotopic ratio measured in GCRs at 1 AU and the assumed ACR ratio indicated on each curve (taken to be either solar or GCR source values). Energy–dependent weighting factors used in this average were obtained from exponential fits to the ACR spectra and power–law fits to the GCR spectra. These curves were calculated using ACE data, and may not be appropriate for other measurements at a different phase of the solar cycle, when the ACR/GCR ratio may be different. By reaching lower energies than is possible with SAMPEX (Leske et al., 1997), our measurements provide the lowest values yet detected for the ACR ^{18}O/^{16}O and ^{22}Ne/^{20}Ne ratios at 1 AU. Previously, a smaller upper limit on the ^{15}N/N ratio
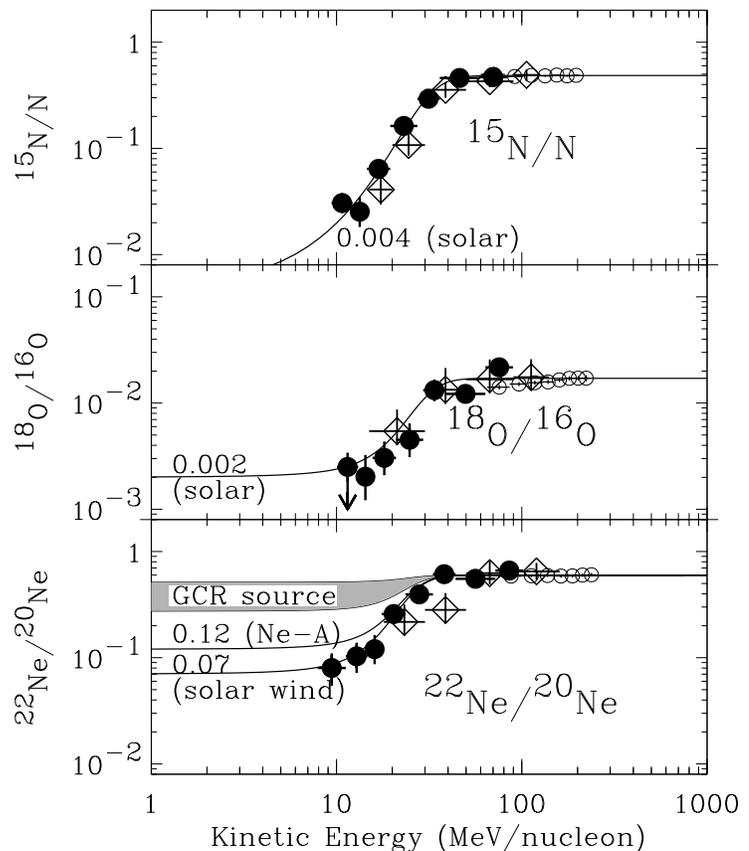
was obtained with SAMPEX using the geomagnetic filter approach (Leske et al., 1997), while a ^{22}Ne/^{20}Ne value similar to what we report (but with larger uncertainties) has also been measured in the outer heliosphere (Cummings et al., 1991).

Spectra of individual ACR isotopes are illustrated in Figure 3. Although ^{14}N shows the typical ACR enhancement at low energies, ^{15}N has no significant enhancement; its spectrum is consistent with that expected for GCRs after solar modulation. Taking the slope of the ^{15}N spectrum to be characteristic of that of GCRs in this charge and energy interval, and subtracting this spectrum (after scaling to pass through the high energy ^{14}N points) results in the ACR ^{14}N spectrum shown by the filled squares. If the ^{15}N/^{14}N ratio in ACRs is the same as that in the solar system (0.0037; Anders & Grevesse, 1989), the ACR ^{15}N spectrum would be as shown by the scaled ^{14}N curve at the bottom of the figure. Note that the ACR ^{15}N/^{14}N ratio could be consistent with the solar value, yet ^{15}N would not be detectable.

The analogous figure for O isotopes in the middle panel of Figure 3 shows a rather different picture, with a low energy increase in the ^{18}O flux clearly evident. Note that the observed intensity of ACR ^{18}O after subtracting the GCR background (filled diamonds) is in good agreement with the ACR ^{16}O curve scaled by the solar system ^{18}O/^{16}O ratio of 0.002

Figure 2: Observed isotopic composition of N, O, and Ne from SIS (*filled circles*) plotted vs. energy, compared to SAMPEX measurements (*diamonds*; Leske et al. [1997]) and expected values (*curves* and *shaded region*; see text). *Open circles* are from the Cosmic Ray Isotope Spectrometer (CRIS) on ACE (N. E. Yanasak, private communication).

(Anders & Grevesse, 1989). Thus, the ACR ^{18}O/^{16}O value appears to be roughly consistent with solar system abundances.

For Ne (right panel of Figure 3), no enhancement of ^{21}Ne is evident, and if the ^{21}Ne/^{20}Ne ratio in ACRs is similar to that in the solar system (0.0024; Anders & Grevesse, 1989), none is expected. As is the case for ^{18}O, however, ^{22}Ne also shows a significant low energy ACR enhancement. The level of this enhancement is well below that which would be seen if the ^{22}Ne/^{20}Ne ACR ratio were that found for the GCR source. Various recent calculations of the GCR source ^{22}Ne/^{20}Ne ratio range from 0.322 (Connell & Simpson, 1993) 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 2, with the average value indicated by curve (*a*) in Figure 3. The observed ACR ^{22}Ne intensity also appears low compared to what it would be if the ^{22}Ne/^{20}Ne ACR ratio were similar to that of the meteoritic component Neon–A, with ^{22}Ne/^{20}Ne = 0.122 (Cameron, 1982), as shown by curve (*b*). It agrees well, however, with curve (*c*), which makes the assumption that the ^{22}Ne/^{20}Ne ACR ratio is the same value as that found in the solar wind, 0.073 (Geiss et al., 1972).

This is the first time that evidence indicating ACR enhancements in the spectra of ^{18}O and ^{22}Ne has been available. Although final numbers require a more careful evaluation of systematic effects and background,

especially at the lowest energies, it is clear that the isotopic composition of ACR O and Ne is similar to that of solar system material. As deduced from earlier measurements (Cummings et al., 1991; Leske et al., 1996) the Ne results indicate that GCRs are not simply an accelerated sample of the local ISM material (e.g., Olive & Schramm, 1982), but apparently include contributions from sources especially rich in ^{22}Ne, such as Wolf–Rayet stars (Prantzos et al., 1986).
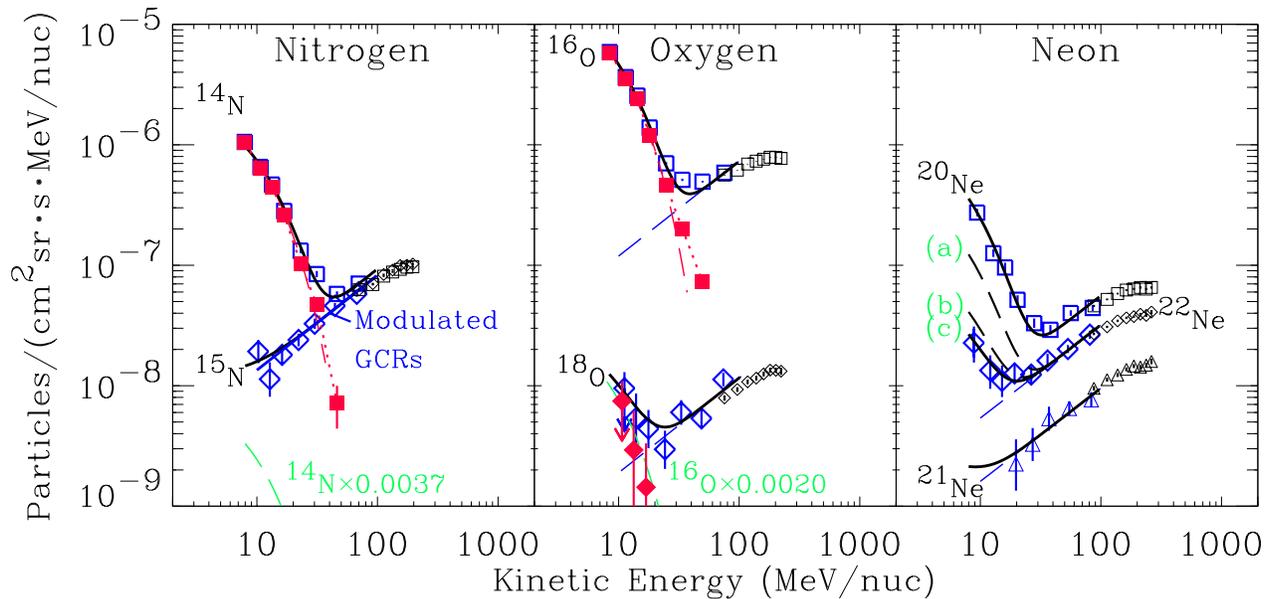
Figure 3: SIS quiet time isotopic energy spectra from 8/97-3/98 for N (*left*), O (*center*), and Ne (*right*). Open symbols are measured values, while filled symbols are obtained by subtracting the GCR background. The location of the ^{14}N and ^{16}O ACR spectra scaled by the solar system ^{15}N/^{14}N and ^{18}O/^{16}O values, respectively, are also shown. Lettered curves show the expected ACR ^{22}Ne spectrum if the ACR ^{22}Ne/^{20}Ne ratio is that found in the GCR source (*a*), meteoritic Neon-A (*b*), or the solar wind (*c*). Smaller symbols above ~ 80 MeV/nucleon are data from CRIS (N. E. Yanasak, private communication).

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