Cosmic Abundances
ASP Conference Series, Vol. 99, 1996
Stephen S. Holt and George Sonneborn (eds.)

Anomalous Cosmic Rays: A Sample of Interstellar Matter

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Abstract. Anomalous cosmic rays are a sample of the neutral interstellar medium that has been accelerated to energies of $\sim$ 1 to 50 MeV/nuc. A comparison of ^{22}Ne/^{20}Ne measurements from various sources implies that galactic cosmic rays with energies $>$ 100 MeV/nuc are not simply an accelerated sample of the local interstellar medium.

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, Koslovsky & Ramaty 1974). They are mainly singly–charged, and include H, He, C, N, O, Ne, and Ar (see review by Klecker 1994). It has recently been shown that ACRs impinging on the upper atmosphere can be stripped of their remaining electrons and trapped in the Earth's magnetosphere (by the mechanism of Blake & Friesen 1977), where they form a radiation belt composed of interstellar material (see Figure 1). Since its launch in 1992, 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. These measurements provide a new source of information on interstellar matter.

Cummings & Stone (1995) have used ACR measurements to determine elemental abundances in the neutral interstellar medium (ISM); SAMPEX is extending this study to isotopic abundances (Leske et al. 1995). ACR Isotope measurements are important for studying the evolution of the local ISM since the formation of the solar system, and they are relevant to galactic cosmic ray (GCR) isotope measurements (Mewaldt, Spalding & Stone 1984).

This paper presents measurements of Ne isotopes from three ACR samples in the near–Earth environment, and compares these with the composition of other solar system and galactic material.

2. Anomalous Cosmic Ray Isotopic Composition

Figure 2 shows the composition of Ne isotopes from three regions of SAMPEX's polar orbit. Over the geomagnetic poles (latitudes $\Lambda > 60°$ in Figure 1), where there is a mixture of ACRs and GCRs, the ^{22}Ne/^{20}Ne ratio varies with energy. At energies $>$ 50 MeV/nuc, where GCRs dominate, the ratio is $\sim$ 0.6, compared

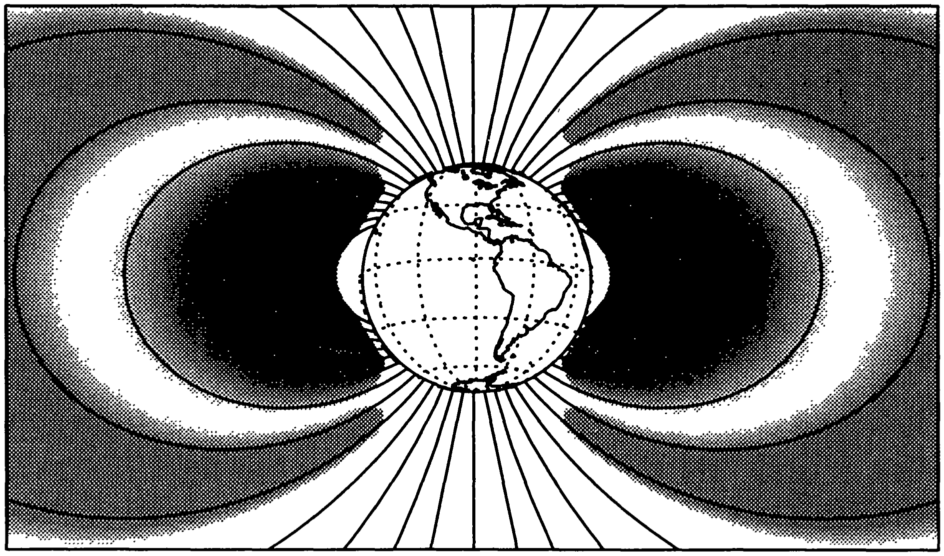

Figure 1. Illustration of the narrow radiation belt composed of interstellar material (*dark band*), embedded in the inner Van Allen belt. The new belt consists mainly of energetic O, N, and Ne with intensities > 100 times that of ACRs in interplanetary space, as well as smaller amounts of C and Ar (Selesnick et al. 1995).

to typical solar system material where ^{22}Ne/^{20}Ne$\sim$ 0.1. Even after correction for "secondary" ^{22}Ne produced by cosmic ray spallation, the resulting cosmic ray source ratio of ^{22}Ne/^{20}Ne $\simeq 0.45$ (e.g., Lukasiak et al. 1994) shows that the nucleosynthesis of cosmic ray and solar system material has differed.

Below 50 MeV/nuc, where ACRs dominate, the ^{22}Ne/^{20}Ne ratio suddenly drops to ~ 0.2. Similar variations in isotopic composition are observed for He, N and O (Mewaldt, Spalding & Stone 1984, Leske et al. 1995), although in these cases cosmic ray spallation makes a greater contribution to the rare isotopes ^{3}He, ^{15}N and ^{18}O. While it is possible to subtract the GCR contributions of ^{20}Ne and ^{22}Ne to obtain a corrected ACR ratio, this analysis is not yet complete. Instruments to be flown on the Advanced Composition Explorer (ACE) in 1997 will extend isotope measurements to lower energy (e.g., 5 to 15 MeV/nuc), where the ACR flux is greater and GCR contamination is minimized, with a collecting power > 30 times that on SAMPEX.

At mid–latitudes (e.g., $50° < \Lambda < 60°$) fully–stripped GCRs are not allowed, but singly–charged ACRs have access because of their greater magnetic rigidity. Here the Earth's field filters out a "pure" sample of ACRs, uncontaminated by GCRs or solar particles. In this region ^{22}Ne/^{20}Ne $\simeq 0.1$, with a sizable statistical uncertainty.

Finally, at lower latitudes ($\Lambda \sim 45°$) trapped ACRs can be measured. While there are mass–dependent processes (e.g., trapping efficiency and lifetime) to be considered, the ^{22}Ne/^{20}Ne ratio is again ~ 0.1.

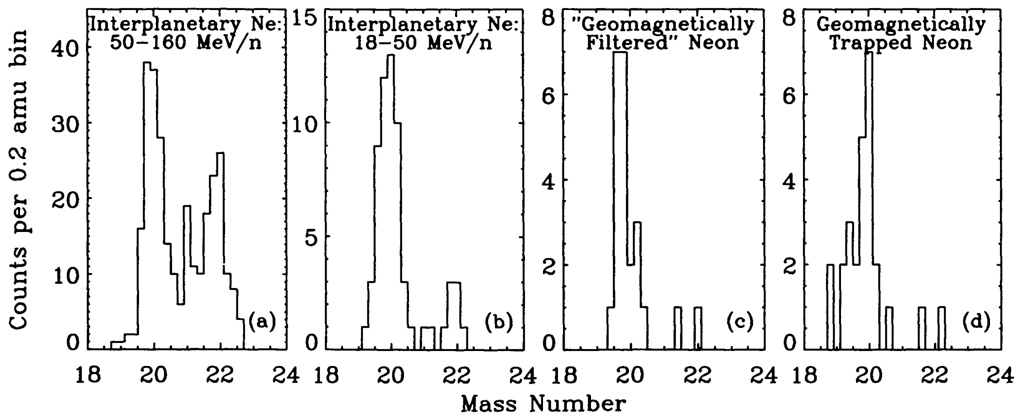

Figure 2. Ne isotope distributions from the MAST instrument on SAMPEX, including: a) 50 to 160 MeV/nuc GCRs from latitudes $\Lambda > 60°$; b) 18 to 50 MeV/nuc cosmic rays (mainly ACRs) from $\Lambda > 60°$; c) "filtered" ACRs from $50° < \Lambda < 60°$; and d) ACRs trapped in the magnetosphere ($\Lambda \sim 45°$).

3. Discussion

To place these measurements in context Figure 3 compares $^{22}Ne/^{20}Ne$ measurements from several sources. The isotopic composition of solar Ne has long been controversial. Cameron (1983) used the meteoritic component "Neon–A" (with $^{22}Ne/^{20}Ne = 0.122$) for his table of solar system abundances, while Anders & Grevesse (1989) chose the solar wind value of $^{22}Ne/^{20}Ne = 0.076$ (Geiss et al. 1972). The solar wind value is close to the lunar/meteoritic component "Neon–B", presumed to be implanted solar wind. Recent solar energetic particle (SEP) measurements from SAMPEX (Selesnick et al. 1993) give a $^{22}Ne/^{20}Ne$ ratio very close to the solar wind value. The GCR source ratio of ~ 0.45 greatly exceeds any of these solar system components. The SAMPEX and Voyager (Cummings, Stone & Webber 1993) values for the local ISM are both ~ 0.1, not sufficiently accurate to differentiate Neon–A and Neon–B, but clearly much less than the GCR source ratio. The values obtained from low energy ACRs over the poles (Figure 2b) and from trapped ACRs (Figure 2d) require additional analysis to estimate possible systematic corrections and uncertainties, but they also clearly favor a ratio of ~ 0.1 over a value as high as ~ 0.4.

These results provide the best evidence to date that cosmic rays are not simply a sample of local ISM that has been accelerated to high energies, as assumed in some models (e.g., Olive & Schramm 1982). Rather, the enhanced $^{22}Ne/^{20}Ne$ ratio in cosmic rays is evidence for contributions from sources especially rich in ^{22}Ne, such as Wolf–Rayet stars (Prantzos et al. 1986). This work demonstrates the potential of ACRs to provide unique information on the composition of the local ISM. In coming years we can expect improved statistical accuracy from SAMPEX as solar minimum approaches, and improved capability from ACE.

Acknowledgments. We appreciate contributions to this work by A. C. Cummings, R. S. Selesnick, E. C. Stone, and T. T. von Rosenvinge. This work was supported by NASA under contract NAS5-30704 and grant NAGW-1919.

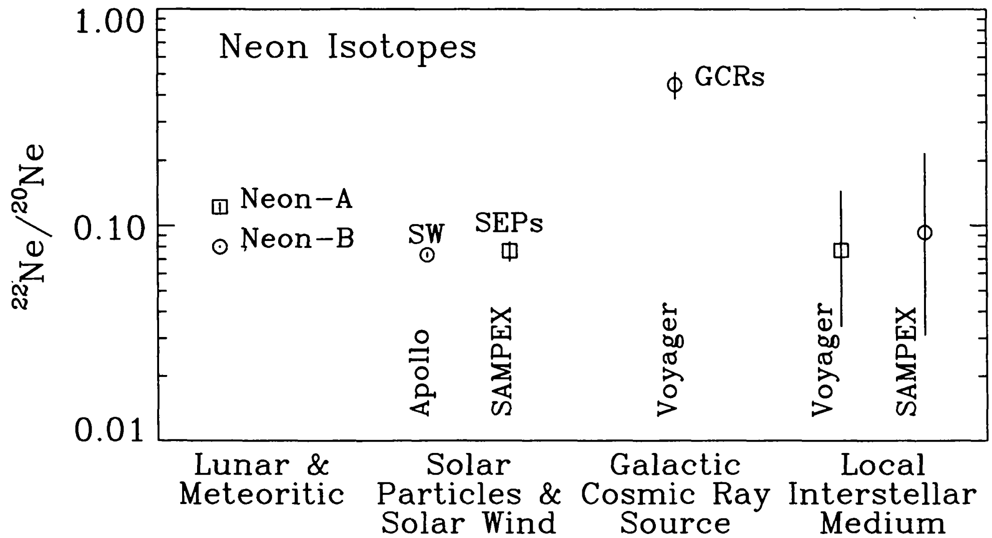

Figure 3. Comparison of $^{22}Ne/^{20}Ne$ ratios (references in text).

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