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ELEMENTAL COMPOSITION OF THE VERY LOCAL INTERSTELLAR MEDIUM AS DEDUCED FROM OBSERVATIONS OF ANOMALOUS COSMIC RAYS

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Abstract

We present a new determination of the relative abundances of the interstellar neutral atoms C I, N I, O I, and Ar I. These abundances are derived from Voyager observations of the energy spectra of the anomalous cosmic ray (ACR) component (He, C, N, O, Ne, and Ar), using a new analysis technique. We find that the abundances of N I, O I, and Ar I are in good agreement with solar system abundances, while the abundance of C I is ~1/100 of the solar system value, consistent with the expectation that C is mostly ionized in the local interstellar medium. As we have reported earlier, we find no evidence for charge-changing interactions associated with the heliopause region.

Introduction. The particles of the ACR component are thought to originate from interstellar neutrals which drift into the heliosphere, become singly ionized, and are then accelerated to the energies of observation (Fisk et al., 1974), possibly at the solar wind termination shock (Pesses et al., 1981; Jokipii, 1986). We have previously presented abundances of a group of interstellar neutral atoms based on observations of the ACR component for the period 1985/274-1986/254 (Cummings and Stone, 1987). In this paper we present new Voyager 2 observations of the energy spectra of ACR He, C, N, O, Ne, and Ar during the period 1987/105-313 when the flux of ACR O reached its maximum value (Cummings et al., 1990), which is approximately 10 times larger than that of the earlier period. In addition, we use a new technique for estimating the fractionation due to the acceleration and propagation processes, based on a normalization of the ACR abundances of He and Ne to the corresponding solar system abundances. This technique replaces the method based on the particle acceleration analysis of Dröge and Schlickeiser (1986) which resulted in relatively large uncertainties due to the lack of detailed knowledge of the injection process.

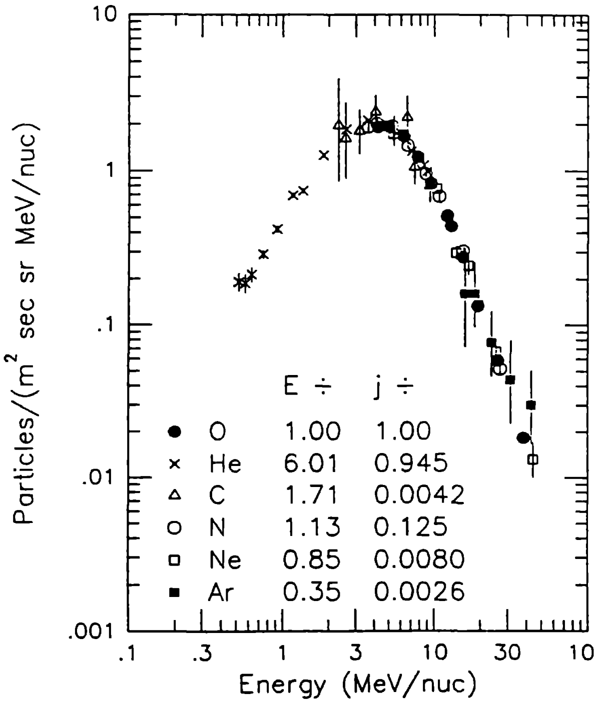

Figure 1. Voyager 2 energy spectra of ACR He, C, N, Ne, and Ar scaled to the ACR O spectrum with the best-fit factors in energy and flux as described in the text for the period 1987/105-313.

Observations. We have previously noted that the energy spectra of all the elements of the ACR component are similar, differing by factors in the energy and flux scales (Cummings et al., 1984; Cummings and Stone, 1987). In Figure 1 we show the ACR energy spectra of He, C, N, Ne, and Ar, all normalized to the ACR O spectrum by shifting the energy and flux scales for each species by the factors shown in the figure. The energy scaling factors are

TABLE 1. ACR-derived Interstellar Neutral Gas Abundances in the VLISM.

Elem.	Obs.	Ionization Rates at 1 AU^a		Fraction	Accel.	ACR-derived
	Flux Ratio	Photo	Charge Exch.	Ionized	Factor	Abundances
He I	0.945 ± 0.009	0.64 ± 0.13	0.021 ± 0.002	0.020 ± 0.004	15.92 ± 3.63	114 ± 35
C I	$0.0042^{+0.0011}_{-0.0005}$	6.88 ± 1.38	7.23 ± 7.23	$0.272^{+0.088}_{-0.116}$	2.14 ± 0.42	$0.0049^{+0.0026}_{-0.0020}$
N I	$0.125^{+0.0052}_{-0.0085}$	2.88 ± 0.58	1.98 ± 0.99	0.119 ± 0.24	1.61 ± 0.35	0.253 ± 0.079
O I	1.0	2.90 ± 0.58	3.49 ± 0.35	0.149 ± 0.013	1.26 ± 0.30	1.26 ± 0.30
Ne I	$0.080^{+0.0072}_{-0.0054}$	2.14 ± 0.43	0.43 ± 0.30	0.069 ± 0.13	0.84 ± 0.23	0.145 ± 0.050
Ar I	0.026 ± 0.006	4.02 ± 0.80	4.63 ± 0.46	0.190 ± 0.016	0.29 ± 0.11	0.0059 ± 0.0028

[a] Units are $10^{-7} s^{-1}$.

well-correlated with atomic mass number as shown in Figure 2.

The ACR energy spectra are derived from the observed spectra by subtracting low-energy interplanetary and high-energy galactic cosmic ray (GCR) components. These contributions are typically very small ($<5\%$) for most of the energy range shown, approaching 20% only at the highest energies.

Because of the energy shift of the spectra, the composition of the ACR component cannot be determined in common energy intervals. Instead, we present in Table 1 as the observed ACR abundances the flux factors (e.g., in Figure 1) which normalize the spectra to that of ACR O. In the case of Ar this flux normalization was done using an energy scaling factor extrapolated from the He-Ne data (see Figure 2).

Discussion. The observed relative abundances are related to the relative abundances in the source population of the ACR component, assumed to be neutral gas from the very local interstellar medium (VLISM). The gas first becomes ionized, principally by the solar ultraviolet radiation from the Sun and by charge-exchange reactions with the solar wind. For the charge-exchange rates we have used a solar wind flux of 4.25×10^8 protons cm^{-2} s^{-1} and a solar wind velocity of 459 km/sec (corresponding to an interaction energy of 1.1 keV) appropriate for quiet solar minimum conditions (Ajello et al., 1987). The charge-exchange cross sections for He, Ne, and Ar are from Tawara (1978) and for O are from Stebbings et al. (1964). We have estimated the uncertainties in the cross sections for these elements from the scatter of the data. For N we have used the cross section for the inverse reaction $N^+ + H \rightarrow N + H^+$ (Stebbings et al., 1960) and attached an uncertainty of ±50%. For C we found no cross section data in the literature in the proper energy range and have used a large value, appropriate for H, with an uncertainty of ±100%. The resulting ionization rates at 1 AU are shown in Table 1.

For calculating the photoionization rates we have used the solar EUV reference spectrum F74113 of Hinteregger (1977) modified by doubling the flux below 250 Å as suggested by Richards and Torr (1988). The photoionization cross sections for He, Ne, and Ar are from Marr and West (1976) and those for C, N, and O are from a compilation by Allen (1987). We have assumed the calculated ionization rates are proportional to the 2800 MHz solar flux value, F10.7. Thus we have scaled the calculated ionization rates for the reference solar EUV

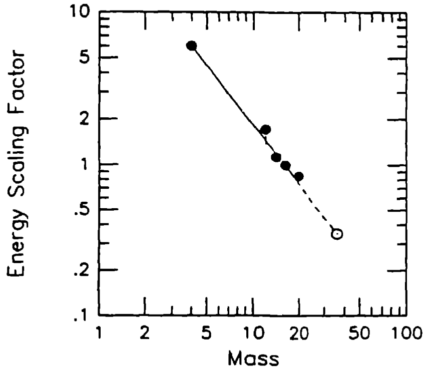

Figure 2. Energy scaling factor versus mass. The solid line is a least-squares fit to the He, C, N, O, and Ne data. The dashed line is an extrapolation to Ar.

spectrum (F10.7 = 73.9) to the average solar flux level for the period of observation (F10.7 = 90.9) by multiplying by the factor 1.23. The scaled He photoionization rate using this procedure is reasonably consistent with the directly determined photoionization rate of 1.08 × $10^{-7}\,s^{-1}$ for F10.7 = 132.1 (Ogawa and Judge, 1989), with the value 7.1 × $10^{-8}\,s^{-1}$ used in a recent solar UV backscatter study (1977 average F10.7 = 86.9) (Chassefière et al., 1988), and with the value 6.5 × $10^{-8}\,s^{-1}$ inferred from measurements of He^+ pick-up ions (F10.7 = 82.2 for 15 November 1985) (Möbius et al., 1988). The charge-exchange ionization rates, with an assumed uncertainty ±20%, are shown in Table 1.

In order to correct the abundances for the differences in the ionization rates, we have derived the fraction of each species which is ionized in the passage through the heliosphere using the method described by Christian (1989). In his model we have used an interstellar wind velocity of 20 km/sec and a distance to the heliopause of 100 AU. The values of the abundances derived below are relatively insensitive to these parameter values. The calculated ionization fractions are shown in Table 1.

To address the fractionation inherent in the acceleration and propagation processes we adopt the following approach. We assume that the abundance correction factor is a power-law in atomic mass, consistent with theories of acceleration and modulation (see Cummings and Stone, 1987). The appropriate power-law is derived by assuming that the two atoms (He and Ne) with the highest first-ionization potentials (FIPs = 24.5 and 21.5 eV, respectively) are completely neutral in the VLISM and have the solar system abundance given by Grevesse and Anders (1988). In Figure 3 we show the ratio of the solar system abundance of these two elements to the ionization-corrected ACR abundances. The solid line is the correction factor for acceleration and modulation effects that we apply to the other elements.

In Figure 4 we display the ACR-derived interstellar neutral gas abundances along with the solar system abundances (Grevesse and Anders, 1988). The ACR-derived abundances for N I, O I, and Ar I are in good agreement with the solar system values. Since these atoms have FIPs higher than that of H they might be expected to be predominantly neutral in the interstellar medium, consistent with our observations. Since the charge-exchange cross section for Ne differs markedly from that of O (see Table 1), we find no

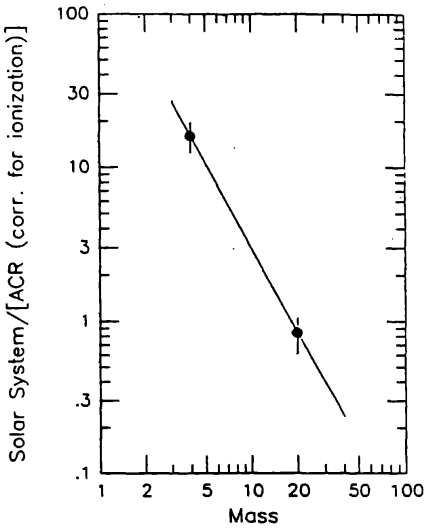

Figure 3. Ratio of solar system abundances (relative to O) to ACR abundances corrected for ionization fraction. The solid line is used to correct the ACR abundances for acceleration and propagation effects.

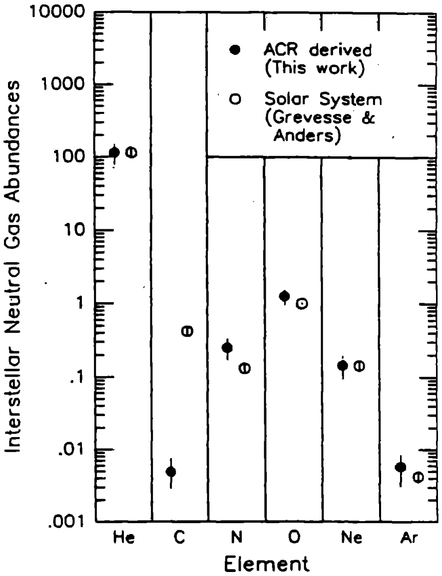

Figure 4. Relative abundances of neutral gases in the very local interstellar medium. The solar system abundances are normalized to O. The ACR-derived abundances are normalized to the solar system abundances at He and Ne as described in the text.

evidence that significant charge-exchange processes are occurring at the heliospheric interface, contrary to the suggestion of Fahr and Ripken (1984).

It is expected that most of the C is ionized in the VLISM because of its low first ionization potential. The C I abundance we derive is consistent with this expectation, being a factor of ~100 below that of the solar system C abundance. In future studies we plan to investigate the applicability of the method described here to the recently reported ACR hydrogen abundances (Christian et al., 1988; Christian et al., 1990).

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