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ELEMENTAL COMPOSITION OF THE ANOMALOUS COSMIC-RAY COMPONENT

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Abstract

We report the first definitive observations of anomalous cosmic-ray (ACR) argon and carbon. Using a model for the ionization and acceleration of interstellar neutral atoms, we find ACR-derived abundances for N I, Ne I, and Ar I in the very local interstellar medium (VLISM) that are in excellent agreement with a compilation of solar system abundances, showing no evidence that significant charge-exchange processes are associated with the heliopause region. The abundance of C I is nearly 2 orders of magnitude lower than that of the solar system, indicating that most of the C in the VLISM is ionized. We find that neither of two spectroscopically determined local interstellar components have neutral compositions identical to that of the ACR-derived VLISM.

1. 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 [1], possibly at the solar wind termination shock [2,3]. In this paper we present new observations of the energy spectra of the elements comprising the anomalous component, derived from measurements from the Cosmic Ray System (CRS) [4] on the Voyager 1 and 2 (V1 and V2) spacecraft for the period 1985/274 - 1986/254.

2. Observations. The observed energy spectra (unweighted average of V1 and V2 data) for C and Ar are shown in Fig. 1a. The ACR spectra, shown in Fig. 1b, are obtained by subtracting a low-energy interplanetary and a high-energy GCR component from the observed spectra.

In Fig. 2 we show the ACR energy spectra of He, N, O, and Ne, all normalized to the ACR O spectrum by shifting the energy and flux scales for each species by the factors shown in the figure. In an earlier paper [5] we discussed how this scaling results from the fact that the cosmic-ray modulation process produces characteristic spectral features at an energy for each species for which the particles have the same diffusion coefficient. The energy scaling factors are shown in Fig. 3.

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 abundances, the flux factors (e.g., in Fig. 2) which normalize the spectra to that of

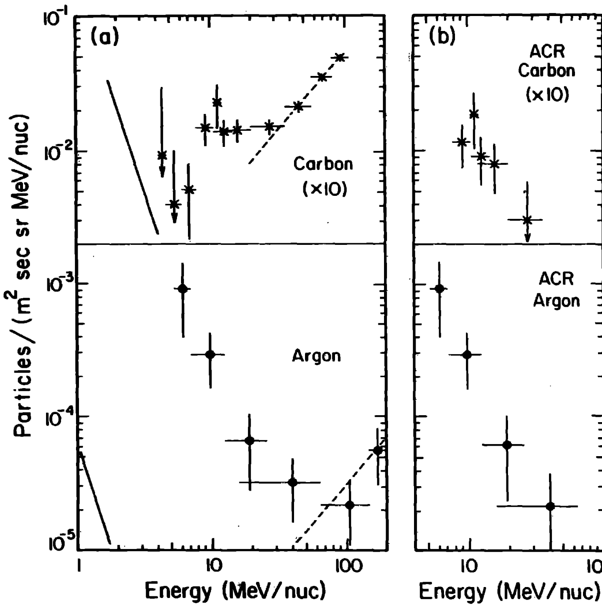

Fig. 1. (a) Observed V1+V2 average spectra of carbon (multiplied by 10) and argon for the period 1985/274 - 1986/254. The solid and dashed lines represent estimates of the low-energy interplanetary and high-energy galactic cosmic-ray spectra, respectively. (b) The spectra of ACR C and Ar after correcting for the interplanetary and galactic cosmic-ray contributions

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ACR O. In the case of Ar this flux normalization was done using an energy scaling factor extrapolated from the He - Ne data (see Fig. 3).

In the case of He the flux factor is a factor of ~2 smaller than we obtained for a period near solar minimum in 1977-78. We analyzed ten 52-day periods during which the flux of ACR He and O increased by more than a factor of 10 and found a factor of ~2 change in the He/O ratio, whereas Ne/O and N/O were essentially constant. Although we believe that this is due to the large rigidity difference between singly-ionized He and O, as compared to the rather similar rigidities of N, Ne, and O, the cause of this variation is unknown. Accordingly, we have adopted 2±0.7 for the value of the He/O abundance, which covers the range of variation we have observed.

Table 1 also shows values for H. We made no direct measurement of H in this experiment; however, measurements of the proton and helium spectra have been reported by McDonald et al. [6] for a recent time period using data from Pioneer 10. The protons have long been thought to be galactic cosmic rays and not part of the ACR component, although it has been suggested that interstellar neutral H should be ionized and accelerated similar to the other ACR species (see, e.g., [7]). As an upper limit we assume that all protons at ~200 MeV (the expected location of the peak energy according to Fig. 3) are in fact ACR H. Referring to Fig. 3 of [6], we find H/He=6 for the ACR abundance ratio (where we have assumed 16% of the He is due to GCR He). Since we observe He/O<2.7 (Table 1), we obtain an upper limit for the observed ACR abundance of H/O<16.2.

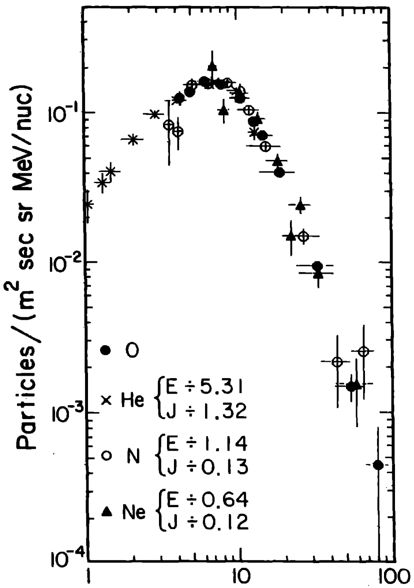

Fig. 2. Energy spectra of He, N, and Ne scaled to the O spectrum with the best fit factors in energy and flux as described in the text

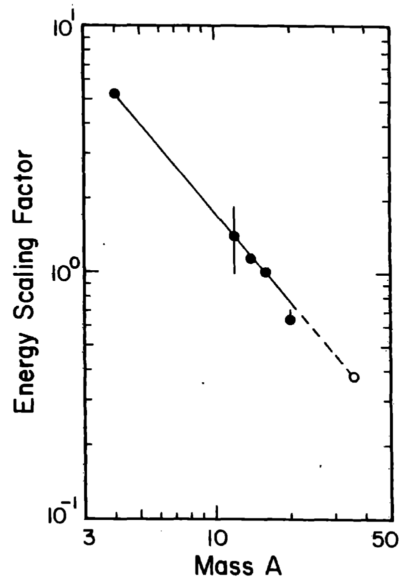

Fig. 3. Energy scaling factor vs. mass A. The solid line is a least-squares fit to the He, C, N, O, and Ne data. The dashed line is an extrapolation to Ar

3. Discussion. The observed relative abundances are related to the relative abundances in the source population of the ACR component, assumed to be interstellar neutral gas. The gas first becomes ionized, principally by the solar ultraviolet radiation from the Sun and by charge-exchange reactions with the solar wind. We have derived ionization rates for each of the elements following the method outlined in the review article by Axford [8]. Table 1 shows the calculated values at 1 AU.

We have calculated the acceleration efficiency of the ions by applying the flare particle analysis of Dröge and Schlickeiser [9] assuming losses dominated by diffusion. We find that the accelerated differential energy spectra of non-relativistic singly-charged ions with mass number A and energies/nuc, E, much greater than that corresponding to the injection velocity, β_0, can be represented by :

$$j(E) = S\, A^{\gamma(a+3)/(2(\gamma+1))}\, E^{(a+1)/4}\, (A\beta_0)^2 \exp(-G\, A^{\gamma}\, E^{(\gamma+1)/2}) \qquad (1)$$

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

Elem.	Obs. Flux Ratio	Ionization Rates at 1 AU[a] Photo	Charge Exch.	Fraction Ionized	Accel. Factor[c]	ACR-derived VLISM Abundances[c]	
H I	<16.2	0.67±0.07	4.48±0.45	0.219±0.015	5.3-1351	<80	<20000
He I	2.0±0.7	0.38±0.04	0.014±0.014	0.024±0.002	2.3-36.8	37±14	600±220
C I	$0.0075^{+0.0037}_{-0.0018}$	6.68±0.67	$(4.20^{+4.2}_{-2.1})^{b}$	$0.366^{+0.110}_{-0.050}$	1.19-2.11	$0.0047^{+0.0024}_{-0.0013}$	$0.0083^{+0.0043}_{-0.0023}$
N I	0.130±0.006	2.15±0.22	1.27±0.13	0.160±0.010	1.08-1.42	0.170±0.016	0.222±0.021
O I	1.0	2.06±0.21	2.29±0.23	0.193±0.010	1.0	1.0	1.0
Ne I	$0.12^{+0.011}_{-0.018}$	1.17±0.11	$0.083^{+0.360}_{-0.008}$	$0.069^{+0.013}_{-0.006}$	0.87-0.56	$0.295^{+0.039}_{-0.053}$	$0.189^{+0.025}_{-0.034}$
Ar I	0.019±0.006	3.24±0.32	2.80±0.28	0.246±0.013	0.61-0.12	0.0090±0.0029	0.0018±0.0006

[a] Units are $10^{-7}s^{-1}$. [b] Cross-section not found in literature; very uncertain estimate.
[c] Numbers to left assume injection at constant rigidity; numbers to right, constant velocity.

where S is proportional to the source abundance, a is related to the ratio of first- to second-order Fermi acceleration, G is a constant, and γ is the index of the diffusion coefficient κ (in $\kappa \propto \beta R^{\gamma}$, where R is rigidity). For two different particle types the spectra scale in energy to first order if we make the term in the exponential the same for each species. This leads to an energy scaling factor which is identical to that derived for the modulation process [5],

$$f_E \propto A^{-2\gamma/(\gamma+1)}. \qquad (2)$$

Using Equation 2 to scale spectra to that of O we find that the relative source abundances, S, are given by the ratio of the fluxes (the flux factors of Fig. 2) multiplied by an "acceleration factor" of $(A/16)^{-(3\gamma+2)/(\gamma+1)}$, assuming all species are injected at the same velocity, and $(A/16)^{-\gamma/(\gamma+1)}$, assuming all species are injected at the same rigidity. We find from Fig. 3 and Equation 2 that for this period $\gamma = 1.5$. The resulting acceleration factors are shown in Table 1.

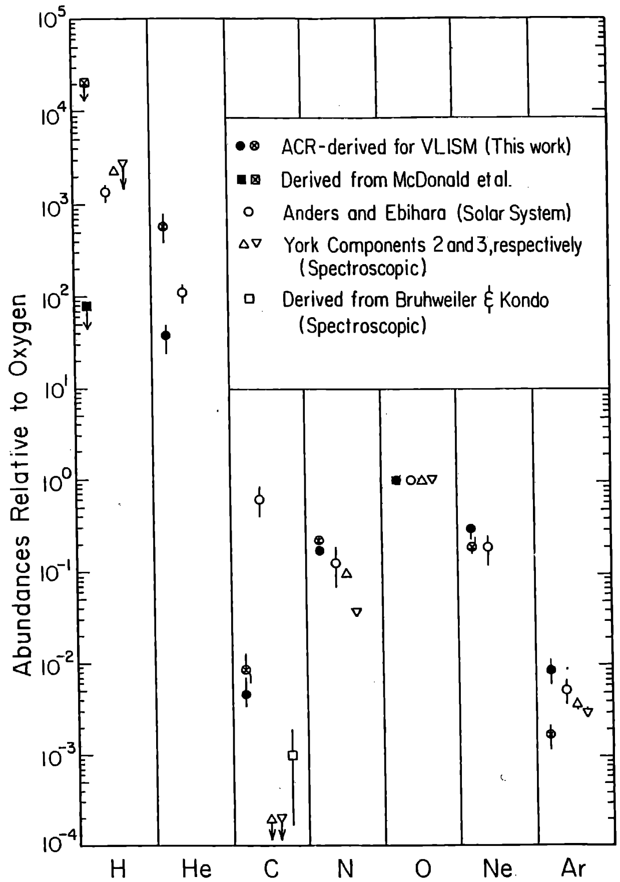

Fig. 4. Relative abundances (to O) of neutral gases in the local interstellar medium. The ● and ■ are derived assuming injection at fixed rigidity for all species; the ⊗ and ⊠ assume injection at fixed velocity

The resulting ACR-derived interstellar neutral gas abundances under both injection assumptions are shown in Table 1. Note that we have not included effects of charge exchange at the heliospheric interface [10].

In Fig. 4 we display the ACR-derived interstellar neutral gas abundances along with various estimates from other measurements. The characteristics of these abundances fall into three groups.

N, Ne, and Ar -- These gases all have first ionization potentials larger than that of H and might be expected to be predominantly neutral in the VLISM [1]. The abundances

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we derive for N and Ne are in excellent agreement with the solar system abundances compiled by Anders and Ebihara [11], indicating that there is no large depletion (compared to O) of these gases in the VLISM. The abundance of Ar is also in general agreement with the solar system compilation, although the derived abundance is somewhat dependent on the injection mechanism. We note that Klecker [12], by comparing observed spectra with model calculations, also found that the data for ACR N, O, and Ne were reasonably consistent with solar system abundances. Since the charge-exchange cross section for Ne differs markedly from that of O (see Table 1), we find no evidence that significant charge-exchange processes are occurring at the heliospheric interface, contrary to the suggestion of Fahr and Ripken [10]. We note that our ratio of N I/O I is significantly greater than that of both components 2 and 3 of York [13], which have recently been proposed as being representative of the LISM and VLISM, respectively [14].

C -- The C abundance is a factor of ~100 below that of Anders and Ebihara. It is expected that most of the C is ionized in the VLISM because of its low first ionization potential. A local spectroscopic measurement of C I was made by Bruhweiler and Kondo [15] who measured along a 7 parsec line of sight to α PsA. Combining their measurement of C I, H I, and H II with the H/O abundance of Anders and Ebihara [11], we derive C I/O I = $(1.02^{+0.89}_{-0.85}) \times 10^{-3}$. Our measurement is a factor of ~5-10 higher than this rather uncertain value derived from the spectroscopic observations. Our measurement is also greater, by a factor of ~25-50, than the upper limits from York [13] components 2 and 3. This difference, together with the N I/O I difference noted above, suggests that neither of the two York components can be identified with the VLISM.

He and H -- Although the above abundance estimates are relatively insensitive to injection assumptions, such is not the case for H and He. As a result, more accurate estimates of their abundances will require further consideration of the fractionation introduced by the injection and acceleration process.

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