Elemental Composition of the Anomalous Cosmic Ray Component

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Abstract

We present a new determination of the abundances (normalized to He I and Ne I) of neutral atoms H I, C I, N I, O I, and Ar I in the very local interstellar medium. These abundances are derived from 1994 Voyager 1 observations of the energy spectra of the anomalous cosmic ray (ACR) component. 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 H I is ~1/10 and that of C I is ~1/80 of the solar system values, respectively. The low H I abundance suggests that H may be partially assimilated into the solar wind or is disfavored in the acceration process. The low C I abundance is consistent with the expectation that C is mostly ionized in the local interstellar medium. We find no evidence for significant charge-changing interactions associated with the heliosheath region or with significant depletion of atoms into grains in the very local interstellar medium.

1. Introduction

Anomalous cosmic rays are thought to originate from interstellar neutrals that drift into the heliosphere, become singly ionized, and are then accelerated to the energies of observation [1] at the solar wind termination shock [2]. We have previously presented abundances of a group of interstellar neutral atoms based on observations of the ACR component for the periods 1985/274-1986/254 [3] and 1987/105-313 [4]. In this paper we present new Voyager 1 (V1) observations of the energy spectra of ACR H, He, N, O, and Ne during the period 1994/157-365. This is the first time that ACR H has been conclusively shown to be present [5,6], although evidence was found for ACR H in the 1987 data [7]. From these spectra (and

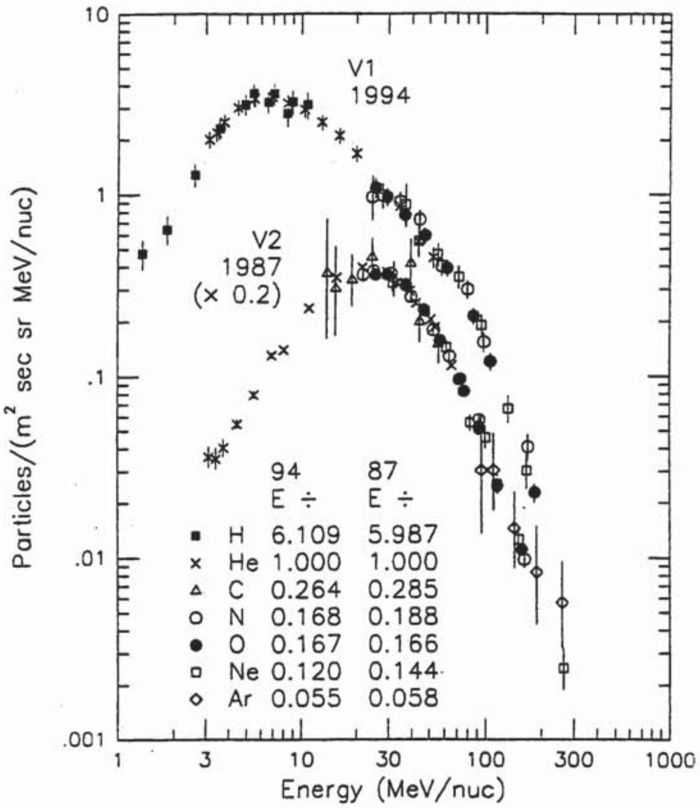

Figure 1. V1 and V2 "generic" ACR He spectra for the periods 1994/157-365 and 1987/105-313, respectively, using the scaling procedure described in the text.

TABLE 1. 1994 ACR-derived Interstellar Neutral Gas Abundances in the VLISM.

Elem.	Obs. Flux Ratio	Ioniz. Rates at 1 AU[a] Photo[b]	Ioniz. Rates at 1 AU[a] Charge Ex.	Fraction Ionized	Accel. Factor	ACR-derived Abundances
H I	0.396±0.021	0.64	4.14±0.83	0.106±0.016	0.068±0.018	1040±370
He I	1	0.57	0.018±0.004	0.019±0.003	1	1000
C I	0.0032±0.0010	6.17	0.41±0.08	0.149±0.024	8.45±1.80	0.048±0.021
N I	0.11±0.02	2.58	2.26±1.13	0.114±0.025	11.4±2.8	1.6±0.6
O I	$0.76^{+0.12}_{-0.18}$	2.60	2.04±0.51	0.110±0.015	14.8±4.0	8.8±3.6
Ne I	0.085±0.006	1.92	$0.14^{+0.14}_{-0.00}$	0.055±0.009	22.8±7.1	1.3±0.3
Ar I	0.013±0.010	3.61	3.73±0.37	0.164±0.016	71.4±30.3	0.022±0.018

[a] Units are $10^{-7}s^{-1}$. [b] Uncertainties are ±20%.

from the spectra of C and Ar) we derive abundances normalized to He I and Ne I of five interstellar neutral atoms in the very local interstellar medium (VLISM).

2. Observations

In Figure 1 we show the ACR energy spectra of H, N, O, and Ne for the period 1994/157-365 at V1 (57.0 AU and 32.6° N), all normalized to the ACR He spectrum by shifting the energy and flux scales for each species by the factors shown in the figure and in Table 1 (see [4] and [8] for discussion of the shift procedure). Also shown are the ACR energy spectra at V2 (23.4 AU and 2.3° N) of C, N, O, Ne, and Ar normalized to ACR He for the period 1987/105-313.

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 1994 ACR abundances the flux factors which normalize the spectra to that of ACR He. In the case of Ne and Ar this flux normalization was done using the energy scaling factor extrapolated from the fit to the H through O data.

3. Discussion

The Sun is thought to be moving through an interstellar cloud of medium temperature and density which it entered approximately 2000 - 8000 years ago [9]. The ions in the VLISM will be deflected around the heliosphere, but the neutral atoms flow in and, after ionization in the interplanetary medium (IPM), become the parent particles of the ACR component. However, it has been suggested that significant charge-changing reactions of neutrals and hot protons occur in the heliosheath region that would deplete H I, C I, N I, and O I [10]. In this work, we investigate this and other fractionation effects, such as depletion into grains and partial ionization of atoms in the VLISM by using Equation 1 to relate our observed ACR abundances to the abundances of the neutral atoms in the VLISM:

$$X = Y \cdot \frac{f_{I,X}}{f_{I,He}} \cdot \frac{f_{P,X}}{f_{P,He}} \qquad (1)$$

where X is the ACR observed abundance of element X relative to He, Y is the ACR-derived neutral gas abundance in the VLISM, $f_{I,X}$ is the fraction of element X ionized in the IPM, and $f_{P,X}$ is the acceleration/propagation correction factor for element X to account for differences in the injection/acceleration process at the termination shock and for differences in propagation in the IPM. We will compare our ACR-derived abundances (Y) with solar system abundances and attribute any differences to fractionation processes we have ignored in the analysis.

For the charge-exchange rates in the IPM we have used a solar wind flux of 2.54 × 10^8 protons cm^{-2} s^{-1} and a solar wind velocity of 541 km/s (corresponding to an interaction energy of 1.5 keV), representing average values from V2 for the period 1994/157-365 [11]. References to the cross-sections for all but C and H can be found in [4]. For C we used [12] and for H we used [13].

For calculating the photoionization rates we have used the same procedures and cross-sections as in [4]. We have added the H photoionization cross-section from [14]. The 2800 MHz solar radio flux value (F10.7) used in normalizing the rates was 81.5.

In order to correct the abundances for the differences in the ionization rates in the IPM, we have used the same procedure and model parameters as in [4]. The charge-exchange and photoionization rates at 1 AU and the resulting ionization fractions are shown in Table 1.

To address the fractionation inherent in the acceleration and propagation processes we adopt the following approach (same as in [4]). We assume that the abundance correction factor is a power-law in atomic mass, and to derive it we assume that the two atoms (He and Ne) with the highest first-ionization potentials (FIPs) are completely neutral in the VLISM and have the solar system abundance given by [15]. The resulting power-law correction factor is given by $f_{P,X} = 0.068 \cdot A^{1.94}$ where A is atomic mass number. The values for each element are shown in Table 1.

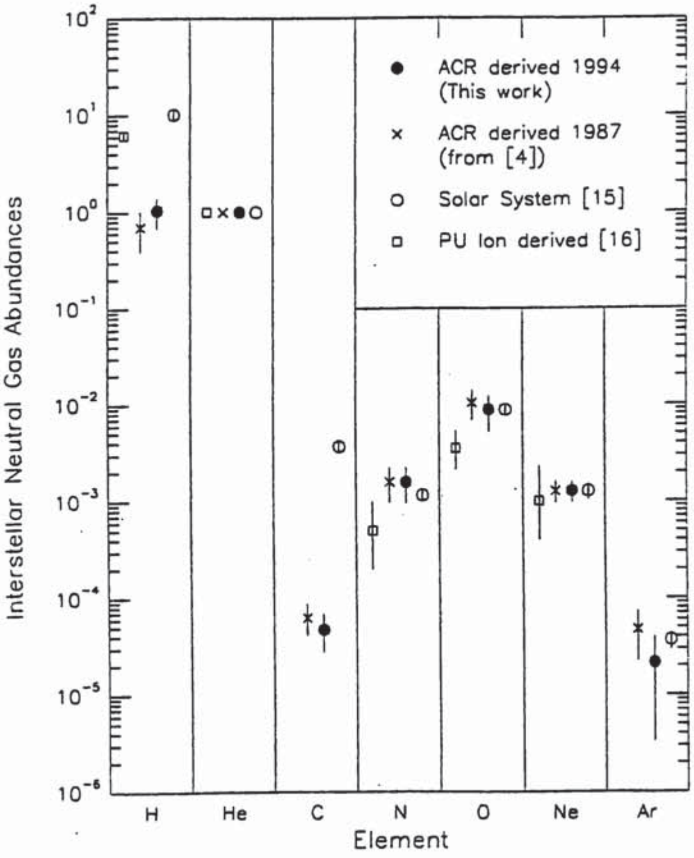

Figure 2. Abundances of neutral gases in the VLISM normalized to He I and Ne I.

In Figure 3 we display the ACR-derived interstellar neutral gas abundances for 1994 and 1987 along with the solar system abundances [15] and the abundances derived from the pick-up ion measurements on Ulysses [16]. The 1987 results have been reanalyzed to include H, to use the charge-exchange cross-section for C [12], and to use the average solar wind flux and velocity from V2 (3.73 × 10^8 protons cm^{-2} s^{-1} and 384 km/s, respectively), and to express the abundances relative to He. The results are changed only slightly from [4] and they are in excellent agreement with the 1994 results. Given that the spectra and modulation levels differ markedly, this agreement attests to the robustness of the approach.

The ACR-derived abundances for N I, O I, and Ar I are in good agreement with the solar system values. It might have been expected that N and O would show enhanced ionization in the VLISM over that of He and Ne or that a significant fraction would be in grains or that a significant fraction of these atoms would be lost in the heliosheath [10]. From our results it appears that the combination of these effects must be less than a factor of 2. We note that recent far UV observations of the VLISM also suggest low depletion and similar ionization fractions for O I and N I [17].

It is expected that most of the C is ionized in the VLISM because of its low first ionization potential and the C I abundance we derive is consistent with this expectation, being a factor of ~80 below that of the solar system C abundance. The C I abundance for the 1987 data has been used, together with other measurements in the interstellar medium, to estimate that H is significantly ionized (60 - 80%) in the VLISM [9].

If H is highly ionized, it could explain the low H I abundance we deduce from the ACR observations. However, H and O have similar FIPs and might be expected to have a similar degree of ionization in the VLISM. We do not see evidence of enhanced ionization of O in the VLISM. In addition, the pick-up ion abundances indicate that nearly the expected rate of H ionizations is occurring at ~5 AU [16]. We conclude that H is either significantly assimilated into the solar wind on its way to the termination shock or that the injection/acceleration process at the shock does not favor H (see, e.g., [18]).

Acknowledgements. We thank E. Christian for providing the ACR hydrogen spectrum and M. Allen for a compilation of photoionization cross-sections. We thank M. Gruntman for finding the charge-exchange cross-section for C and bringing it to our attention. We also thank J. Richardson and J. Belcher for providing the V2 plasma data in advance of publication. This work was supported in part by NASA under contract NAS-7-918 and grant NGR-05-002-160.

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