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EVIDENCE FOR ANOMALOUS COSMIC RAY S, SI, AND FE IN THE OUTER HELIOSPHERE AND FOR A NON-ACR SOURCE OF S AT 1 AU

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ABSTRACT

We have examined the energy spectra of cosmic rays in the outer heliosphere using data from the Voyager 1 and 2 spacecraft for the period 1993 day 53 to 1997 day 53 in a search for possible new anomalous cosmic ray (ACR) species. We find enhancements above the expected galactic cosmic ray spectra below ~15 MeV/nuc for Si, S, and Fe, but not Mg. The S/Ar ratio observed at 1 AU by WIND and Geotail is 3 times larger than the ACR ratio observed in the outer heliosphere, suggesting that the S enhancement at 1 AU is dominated by a non-ACR inner heliosphere source, as is C.

INTRODUCTION

Anomalous cosmic rays (ACRs) are thought to originate primarily as interstellar neutrals (Fisk et al. 1974). In the heliosphere the neutrals are ionized to become pickup ions and are subsequently accelerated to cosmic ray energies at the solar wind termination shock (Pesses et al. 1981). Until recently seven elements comprised the ACR component: H, He, C, N, O, Ne, and Ar (Garcia-Munoz et al. 1973, McDonald et al. 1974, Hovestadt et al. 1973, Cummings & Stone 1988, Cummings & Stone 1990, Christian et al. 1988, Christian et al. 1995, McDonald et al. 1995). Recent observations of S at 1 AU have also been reported as evidence for ACR S (Reames et al. 1997, Takashima et al. 1997). In this paper we examine data from the Cosmic Ray Subsystem (Stone et al. 1977) on the Voyager spacecraft in an effort to confirm the recent report of ACR S at 1 AU and to look for yet other possible ACR species.

CARBON AND SULFUR

Enhancements in S at 1 AU have been reported in data from cosmic ray instruments on the Geotail and WIND spacecraft (Reames et al. 1997, Takashima et al. 1997). In Figure 1 we show part of the data from Figure 4 of Reames et al. (1997) along with energy spectra of the same species observed at Voyagers 1 and 2 (V1 and V2). The solid lines in Figures 1b and 1c depict expected spectra of C

Table 1: Voyager Expected and Observed S for 1993/53-1997/53 From WIND S/Ar Ratio

S/C	Emin MeV/nuc	Emax MeV/nuc	Coll. Power m^2 s sr	# Ar Obs	# S Expected	# S Obs
V1	5.3	5.9	2638	3	0.6	0
	5.9	7.1	5726	13	2.7	0
	7.1	9.6	8827	18	3.8	2
	9.6	12.5	11954	10	2.1	3
V2	5.3	12.5	7423	28	5.9	0
V1+V2	5.3	12.5		72	15.1	5

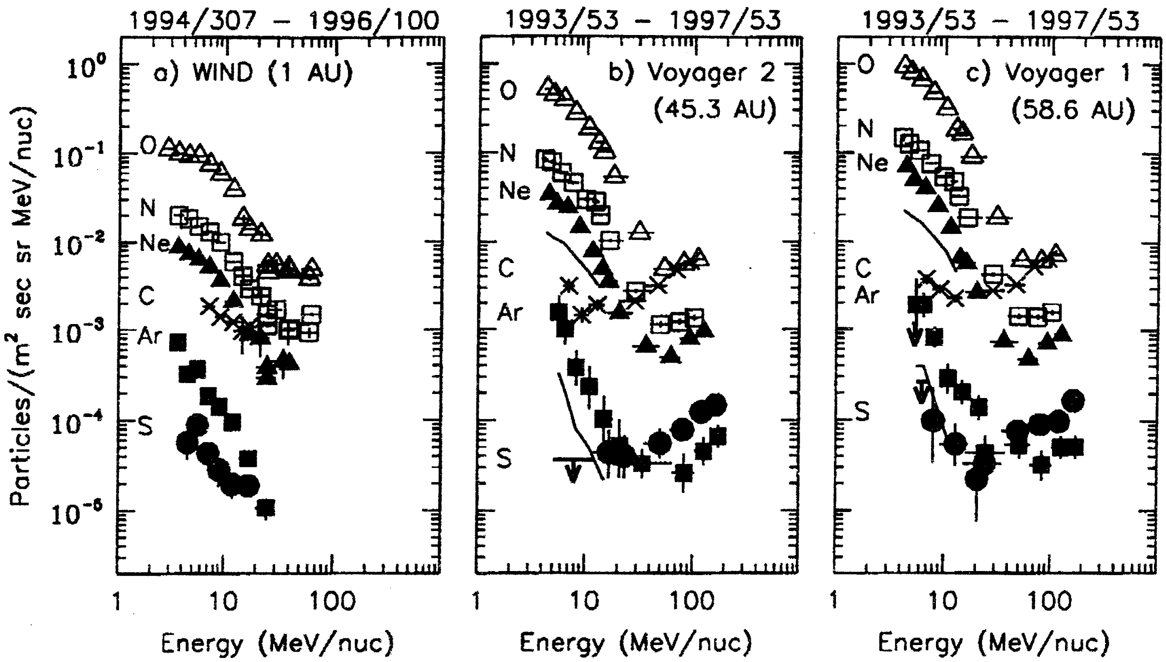

Fig. 1: a) Energy spectra of O, N, Ne, C, Ar, and S at 1 AU for the period 1994/307 - 1996/100 from Figure 4 of Reames et al., 1997. b) Energy spectra of the same elements as in a) at V2 for the period 1993/53 - 1997/53. c) Same as b) except for V1.

and S at V1 and V2 if the same ratios of C/O and S/Ar as observed at 1 AU (Figure 1a) apply in the outer heliosphere. The observed intensity increases at low energies at V2 are clearly smaller than the corresponding increases at 1 AU. The lowest two energy bins of S for V1 had no events and the upper limits are shown.

In order to quantify the Voyager and WIND comparison for S we show in Table 1 the expected and observed S ions in several energy ranges of the V1 and V2 cosmic ray instruments. The expected values are arrived at by scaling the observed Ar by the factor 0.21, the ratio of S/Ar in the WIND data in Figure 1a in the energy range 4.5 - 12.0 MeV/nuc. Combining the V1 and V2 data we observe 5 S ions whereas we expected 15.1 from the WIND observations. Thus the S observed at 1 AU by the WIND instruments is about a factor of 3 higher than that observed at the Voyagers.

The evidence that the 1 AU S enhancement is dominated by a source other than ACRs accelerated at the termination shock can be seen by comparing the intensities of low-energy C, N, O, Ne, S, and Ar from Figure 1 as a function of helioradius (Figure 2). Although the time period of the 1 AU observations is not precisely the same as that of the Voyager measurements, the data in Figure 2 represent a reasonable approximation to the radial gradient. Note that the dashed lines in Figure 2 are the solid line scaled by the V1 flux ratios to O. The ACR-dominated

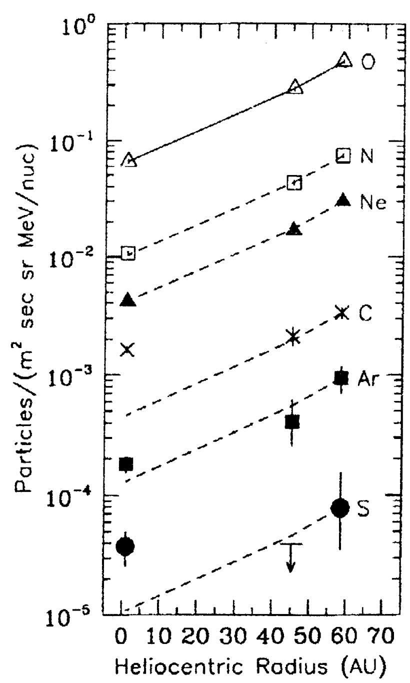

Fig. 2: Fluxes at 8 MeV/nuc at WIND, V2, and V1.

species (N, O, Ne, and Ar) exhibit essentially identical gradients between 1 and 58 AU. In the outer heliosphere, C and S are consistent with the same ACR-dominated gradient but the fluxes are enhanced at 1 AU, indicating a non-ACR source for C and S in the inner heliosphere.

The C enhancement observed at SAMPEX at 1 AU was attributed by Mewaldt et al. (1993) to a possible solar component, resulting in C/O ~0.1. Mewaldt et al. (1996) subsequently used geomagnetic cutoffs to determine that the ratio $C^+/O^+ = 0.014 \pm 0.009$, indicating that singly-charged ACR ions make a small contribution to the C enhancement at 1 AU. If the principal source of the 1 AU C enhancement is a multiply-charged solar component, then we might expect that S/C ~0.08 (Breneman & Stone 1985). However, the observed S/C ~0.03 is somewhat smaller. It should be noted that Geiss et al. (1995) have observed C pickup ions at 1 AU that they ascribe to the evaporation of carbon compounds from grains within ~3 AU of the Sun. However, these ions are singly charged and could not contribute to the multiply-charged fraction of energetic C ions. Thus, the inner heliosphere source of the C and S enhancements requires further investigation.

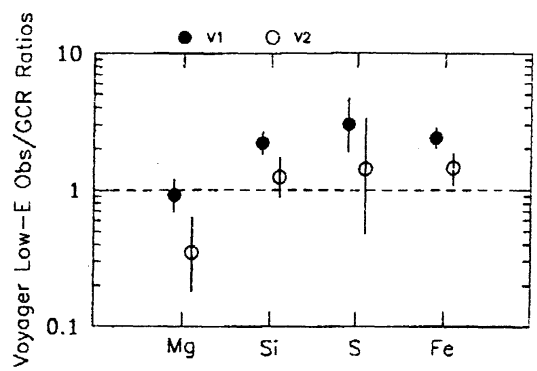

Fig. 3: Enhancement factors in low-energy cosmic rays for Mg, Si, S, and Fe at V1 and V2 for the period 1993/53 - 1997/53. The energy ranges in MeV/nuc for each ratio are as follows: Mg 6.2-14.9; Si 6.6-15.9; S 5.7-16.9; Fe 6.4-20.5.

ACR SI, S, AND Fe

In addition to S, we have examined the V1 and V2 spectra of Mg, Si, and Fe to see if there are possible enhancements. We first fit a power-law to the high-energy portions of the spectra of C, Mg, Si, S, and Fe, which are dominated by galactic cosmic rays (GCRs), for both V1 and V2. We found that the power-law indices were consistent with a value of 0.8 and then re-fit the GCR portions using a fixed power-law index of 0.8. We then calculated the expected number of GCR Mg, Si, S, and Fe ions in a lower energy range where ACR turn-ups might be observable. The ratios of the observed ions at the low energies to the expected GCR ions are shown in Figure 3.

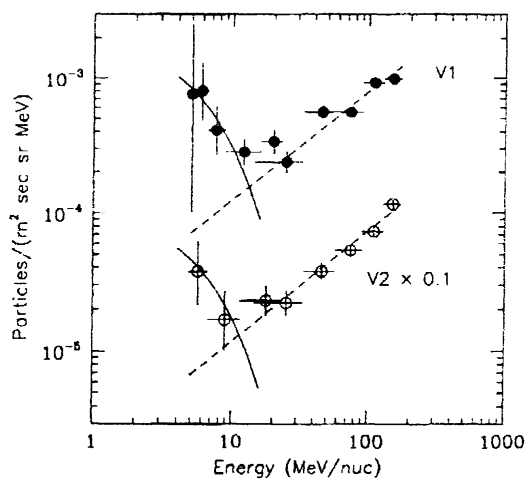

Fig. 4: Energy spectra of Si at V1 and V2 for the period 1993/53-1997/53. The dashed lines show the estimated GCR component. At low energies the observed intensity clearly exceeds the estimated GCR intensity for both V1 and V2. The solid lines are the V1 and V2 Ne spectra scaled by 0.015.

There is no enhancement observed for Mg at either V1 or V2. There are significant enhancements observed for Si, S, and Fe at V1 and these are uniformly larger than at V2. An example of the enhancement in Si is shown in Figure 4. The solid lines are scaled in flux from the observed V1 and V2 ACR Ne spectra, yielding an observed abundance ratio of Si/Ne = 0.015. Thus, both the spectral shape and the V1/V2 gradient are consistent with that of other ACR species. The observed abundance ratios are summarized in Table 2. Further analysis will be required in order to deduce source abundances of the new species.

Table 2: Observed abundances of ACR Si, S, and Fe to ACR Ne

Element	Energy MeV/nuc	Abundance
Ne	6 - 20	1
Si	6.6 - 15.9	~0.015
S	5.7 - 16.9	~0.004
Fe	6.4 - 20.5	~0.015

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