

## EVIDENCE FOR ANOMALOUS COSMIC-RAY HYDROGEN

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### ABSTRACT

We present evidence for the emergence of a measurable anomalous cosmic-ray hydrogen component in 1987 which may account for 20%–40% of the total hydrogen flux at 60 MeV. Comparing this flux with that of anomalous cosmic-ray helium, we estimate that the H I/He I ratio in the very local interstellar medium is  $\sim 4$ , consistent with determinations from solar ultraviolet backscatter measurements.

*Subject headings:* cosmic rays: abundances — cosmic rays: general — interstellar: abundances

### I. INTRODUCTION

Anomalous cosmic rays (ACR) are believed to be interstellar neutrals (Fisk, Kozlovsky, and Ramaty 1974) which are ionized near the Sun, convected outward by the solar wind, and accelerated at the termination shock (Pesses, Jokipii, and Eichler 1981; Jokipii 1986; Potgieter and Moraal 1988). He, N, O, and Ne have long been known to have an ACR component (Garcia-Munoz, Mason, and Simpson 1973; McDonald *et al.* 1974; Hovestadt *et al.* 1973), while the anomalous cosmic-ray components of argon and carbon are smaller and have only recently been reported (Cummings and Stone 1987).

It has been suggested that hydrogen, which is the most abundant neutral in the interstellar medium and which is easily ionized by photoionization or charge exchange with the solar wind, should also have an ACR component (see, e.g., Fisk 1986), although no observations have been reported. However, as pointed out by Fisk (1986), the likely peak energy and shape of an anomalous cosmic-ray hydrogen spectrum may be very similar to the modulated galactic cosmic-ray (GCR) hydrogen spectrum, thus making it difficult to distinguish between the two. In this *Letter* we examine the energy spectra of hydrogen observed near the time of maximum fluxes in 1985 to 1987 from instruments on the *Voyager 1* (V1) and *Voyager 2* (V2) spacecraft and find changes which represent the first evidence for the existence of anomalous cosmic-ray hydrogen.

### II. DATA ANALYSIS

All of the spectra in this analysis were obtained in the outer heliosphere ( $\geq 18$  AU) with the Cosmic Ray Subsystem (CRS) on the two *Voyager* spacecraft (Stone *et al.* 1977). Hydrogen energy spectra for the two time periods 1985/261–365 and 1987/209–313 are shown for *Voyager 1* and *Voyager 2* in Figure 1. The spectra have been divided by energy to accentuate the differences in spectral shape. The curves which have been drawn through the two 1985 spectra are also scaled up in flux to match the 1987 spectra at the highest energy and illustrate the change in spectral shape that has occurred between the two periods. The high-energy points ( $\geq 150$  MeV) of these spectra are from the analysis of particles which fully penetrate the CRS high-energy telescopes (HETs) and have been corrected for a background which is less than 10% of the observed flux. Since the discussion in this *Letter* depends only on the relative differences between similar spectra, omitting this correction would result in only small quantitative differences in

the results. The 10–72 MeV fluxes are from the analysis of protons that stop in the telescopes and require no correction.

### III. DISCUSSION

The major difference between the two time periods in the spectra of Figure 1 is the increase in flux resulting from a decrease in the solar modulation level between 1985 and 1987. Both V1 and V2 spectra show a change in shape, which is more pronounced in V2. As discussed below, we believe that this change is evidence of the appearance of an anomalous hydrogen component during the period of minimum solar modulation.

To obtain an upper estimate for a presumed anomalous hydrogen flux in the 1987 spectra of *Voyager 1* and *Voyager 2*, we subtract estimates of the GCR flux which were determined by normalizing the 1985 spectra to the 1987 spectra at the highest energy (363 MeV), as shown by the dashed lines in Figure 1. This approach might be expected to underestimate the anomalous cosmic-ray hydrogen flux by 10%–20%, because the 1985 spectra should include an anomalous component which is about 10% to 20% of that in 1987, as is the case for ACR helium as shown in Figure 2. A further underestimate might be expected because there is likely a small anomalous contribution to the 1987 flux at the normalizing energy of 363 MeV. However, this approach will overestimate the anomalous flux to the extent that some of the change in spectral shape between 1985 and 1987 is due to changes in the spectrum of the modulated GCR flux.

Although modulation theory is not understood well enough to allow accurate calculations of spectra, we can use other observational evidence to estimate modulation induced changes in the spectra. For example, the peaks in the galactic cosmic-ray helium spectra in Figure 2 shifted downward by 21% between 1985 and 1987 on both *Voyager 1* and *Voyager 2*. An energy shift of 21% for the V1 hydrogen spectra also results from a least-squares fit of the 1985 spectrum to that of 1987, assuming there is negligible anomalous flux in the V1 spectra. If it is assumed that there was a similar energy shift in the V2 GCR hydrogen spectra, then an upper estimate of the V2 1987 GCR hydrogen spectrum can be made by shifting the V2 1985 spectrum downward 21% in energy and normalizing it in flux to the V2 1987 spectrum at the highest energy measured. Subtracting this shifted spectrum from the observed V2 1987 hydrogen spectrum results in a lower estimate of the ACR

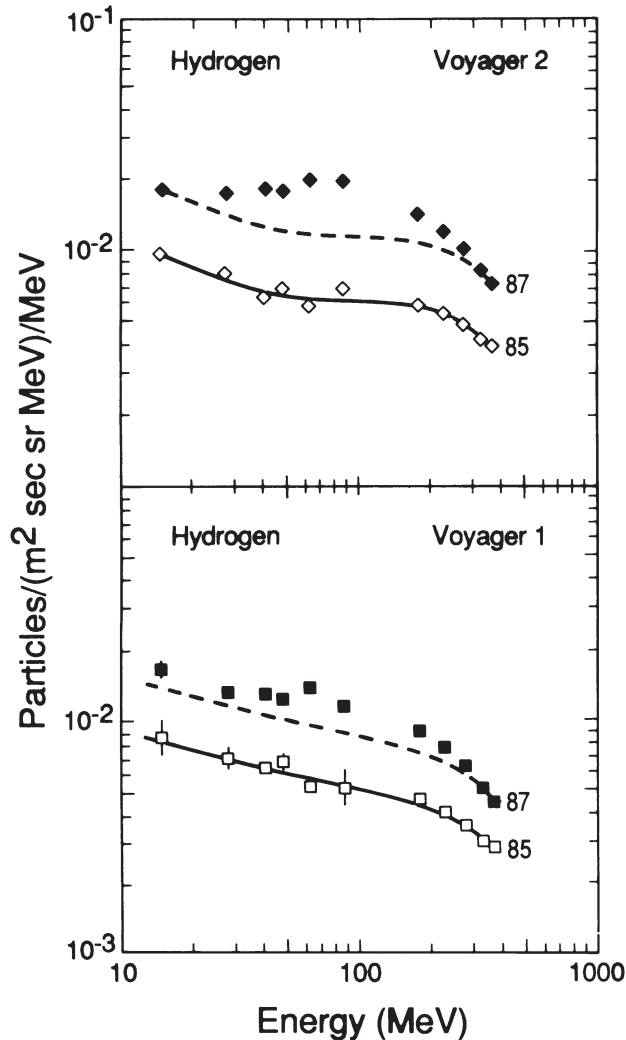


FIG. 1.—Observed hydrogen energy spectra for the time periods 1985/261–365 and 1987/209–313. The spectra have been divided by energy to emphasize changes. The dashed curves for both *Voyagers* are the same shape as the solid curves drawn through the respective 1985 spectra except shifted in flux to match the 1987 spectra at the highest energy point (363 MeV). The error bars include only statistical uncertainties.

hydrogen flux in *Voyager 2*. This approach is expected to underestimate the *V2* anomalous cosmic-ray hydrogen flux in 1987 because it assumes that there was no anomalous contribution to the 1985 spectra and that there was negligible anomalous flux in the *V1* 1987 spectrum.

Figure 3 shows both this lower estimate and the previously derived upper estimates for the anomalous hydrogen spectra, as well as the observed 1987 energy spectra. For *Voyager 2* we estimate that the ACR hydrogen component is  $\sim 20\%$ – $40\%$  of the total hydrogen flux at  $\sim 60$  MeV. The shape of the upper estimates of the *Voyager 1* and *Voyager 2* spectra are essentially the same, with the *Voyager 1* fluxes a factor of 2 lower as expected from the large negative latitudinal gradients observed for the other ACR components (Cummings, Stone, and Webber 1987).

In order to further investigate the possibility that the spectral changes in Figure 1 might be due to a peculiar modulation effect rather than to anomalous cosmic-ray hydrogen, we have examined the spectral shapes of other galactic cosmic-ray

nuclei. Because modulation depends on the magnetic rigidity of the particle and hydrogen has only half the mass per charge of heavier nuclei, modulation related features will appear at higher energies in the hydrogen spectrum than in the others. Thus, the maximum GCR hydrogen flux in Figure 3 occurs at  $\sim 280$  MeV, while the maximum GCR helium flux occurs at  $\sim 210$  MeV per nucleon. As a result, if the excess hydrogen flux at 100 MeV was due to modulation, a similar excess would be expected at  $\sim 75$  MeV/nucleon for heavier galactic cosmic-ray nuclei. Carbon is the only sufficiently abundant heavier nucleus that is relatively free of contamination by the anomalous component at this energy (Cummings and Stone 1987).

Figure 4 shows the carbon flux-divided-by-energy spectra for both *Voyagers* in the time periods 1985/261–1986/105 and 1987/105–313. The time periods are double the length of those for hydrogen to reduce the statistical uncertainty. Averaging over these longer time periods for hydrogen would dilute the observed spectral shape change seen in hydrogen by only 10%–15%. As in Figure 1, the curves from the 1985/1986 spectra are also scaled up in energy to match the 1987 spectra at the highest energy. Except for an increase in the ACR com-

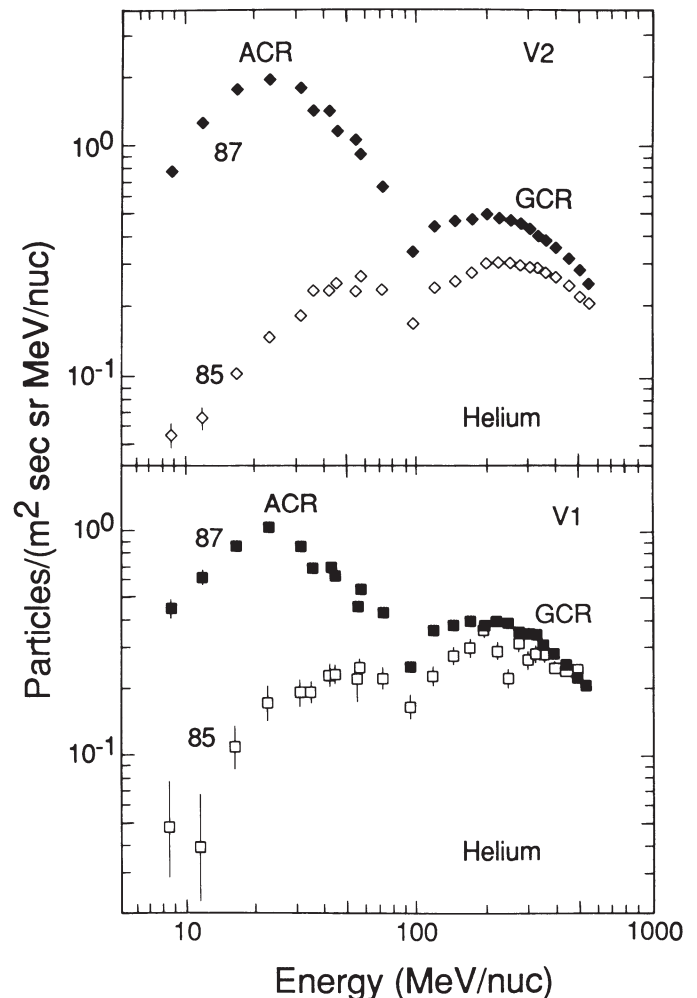


FIG. 2.—Observed helium energy spectra for the time periods 1985/261–365 and 1987/209–313. Below  $\sim 100$  MeV per nucleon, the spectra are predominantly due to anomalous cosmic rays (ACR), and above 100 MeV per nucleon the spectra are dominated by galactic cosmic rays (GCR). The error bars include only statistical uncertainties.

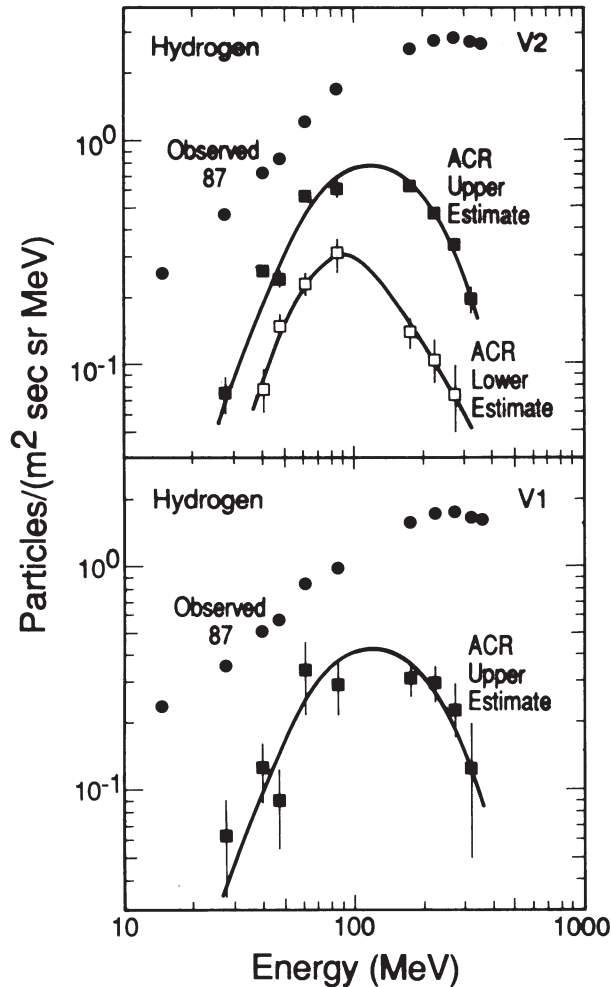


FIG. 3.—Estimates of anomalous hydrogen energy spectra during the time period 1987/209–313. The solid curves for the upper and lower estimates in *V2* are to guide the eye and are not fits to the data. The solid curve for *V1* is the curve for the upper estimate of *V2* shifted down by a factor of 2 in flux. Also included are the observed hydrogen energy spectra for both *Voyagers* during this time period. The error bars include only statistical uncertainties.

ponent at low energies (Cummings and Stone 1988), there is no apparent change in shape at  $\sim 75$  MeV per nucleon between 1985 and 1987. The comparison of Figures 1 and 4 thus suggests that the excess flux in *Voyager 2* hydrogen is not solely a result of the modulation of a purely galactic cosmic-ray spectrum.

Assuming that the excess flux is evidence for an anomalous component, we can then use the mean of the upper and lower estimates in Figure 3 as a measure of the anomalous cosmic-ray hydrogen flux at *Voyager 2*, with an uncertainty that includes both the lower and the upper estimate. When the peak anomalous hydrogen flux of *Voyager 2* is compared with the peak *V2* anomalous helium flux in Figure 2, we obtain an observed H/He flux ratio of  $0.20 \pm 0.08$ . As discussed in Cummings and Stone (1987), the relative abundances of neutral atoms in the very local interstellar medium (VLISM) can be estimated from the relative ACR peak fluxes. This requires that the observed ACR ratio be corrected for differences in the fraction of H I and He I ionized in the heliosphere and for differences in the acceleration and subsequent modulation of

the resulting ions arising from their differing mass per unit charge.

In order to correct for the relative ionization fractions, we have used the values for ionization rates determined from the solar ultraviolet backscatter experiment on *Prognoz 5* and *Prognoz 6*, which are  $3 \pm 1 \times 10^{-7} \text{ s}^{-1}$  (Bertaux *et al.* 1985) and  $1.25 \pm 0.23 \times 10^{-7} \text{ s}^{-1}$  (Dalaudier *et al.* 1984) for H and He, respectively. The *Prognoz 5* and *Prognoz 6* measurements were made mainly in 1977 when the solar activity, as indicated by the 10.7 cm solar flux (National Geophysical Data Center 1988), was similar to that during the 1987 time period of the *Voyager* measurements. When combined with a simple ionization model similar to that outlined by Axford (1972), these rates give ionization efficiencies of  $0.073 \pm 0.021$  for hydrogen and  $0.036 \pm 0.006$  for helium. Thus the correction factor for the relative ionization efficiencies,  $F_{\text{ion}}$ , is  $0.49 \pm 0.16$ .

Differences in the acceleration and modulation of the ions is more difficult to estimate accurately because of incomplete

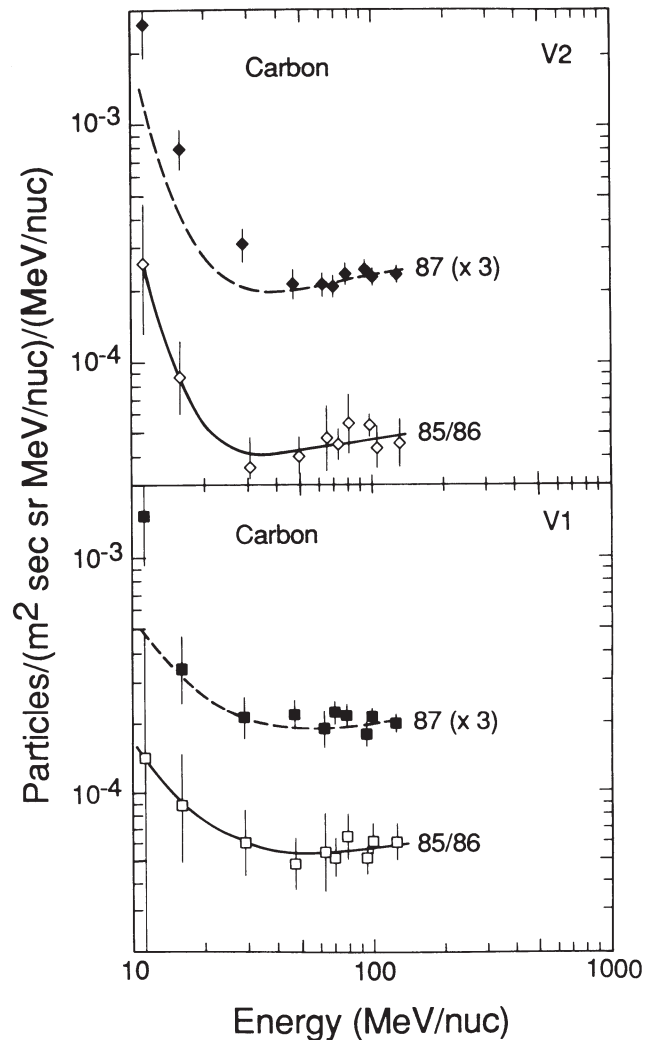


FIG. 4.—Observed carbon energy spectra for the time periods 1985/261–1986/105 and 1987/105–313, with the 1987 spectra for both *Voyagers* multiplied by 3. The spectra have been divided by energy per nucleon to emphasize changes. The dashed curves for both *Voyagers* are the same shape as the solid curves drawn through the respective 1985/1986 spectra except shifted in flux to match the 1987 spectra at the highest energy point (125 MeV per nucleon). The error bars include only statistical uncertainties.

theoretical understanding. Cummings and Stone (1987) examine acceleration correction factors for one acceleration model, finding that if equal abundances of hydrogen and helium ions are injected at the same velocity (e.g., the solar wind velocity), the peak fluxes of accelerated and modulated helium would be  $\sim 37$  times that of hydrogen. Although the uncertainty in this value is difficult to assess, it is nevertheless illustrative to use this as the acceleration correction factor,  $F_{\text{acc}}$ . This results in a H I/He I abundance of  $4 \pm 2$  in the VLISM, as given by  $F_{\text{ion}} \times F_{\text{acc}} \times (\text{H/He})_{\text{ACR}}$ , where the indicated uncertainty excludes the unknown uncertainty in  $F_{\text{acc}}$  and any variation in  $F_{\text{ion}}$  due to changes in solar activity. This H I/He I ratio is comparable to the ratios of  $6.5 \pm 3.1$  (Chassefière *et al.* 1986) and  $7 \pm 3$  (Ajello *et al.* 1987) derived

from solar ultraviolet backscatter results. Although there are modeling uncertainties in this estimate of H I/He I, the agreement with previous values suggests that with further theoretical work it may be possible to derive accurate relative abundances of neutrals in the VLISM from observations of the composition of the anomalous cosmic-ray component.

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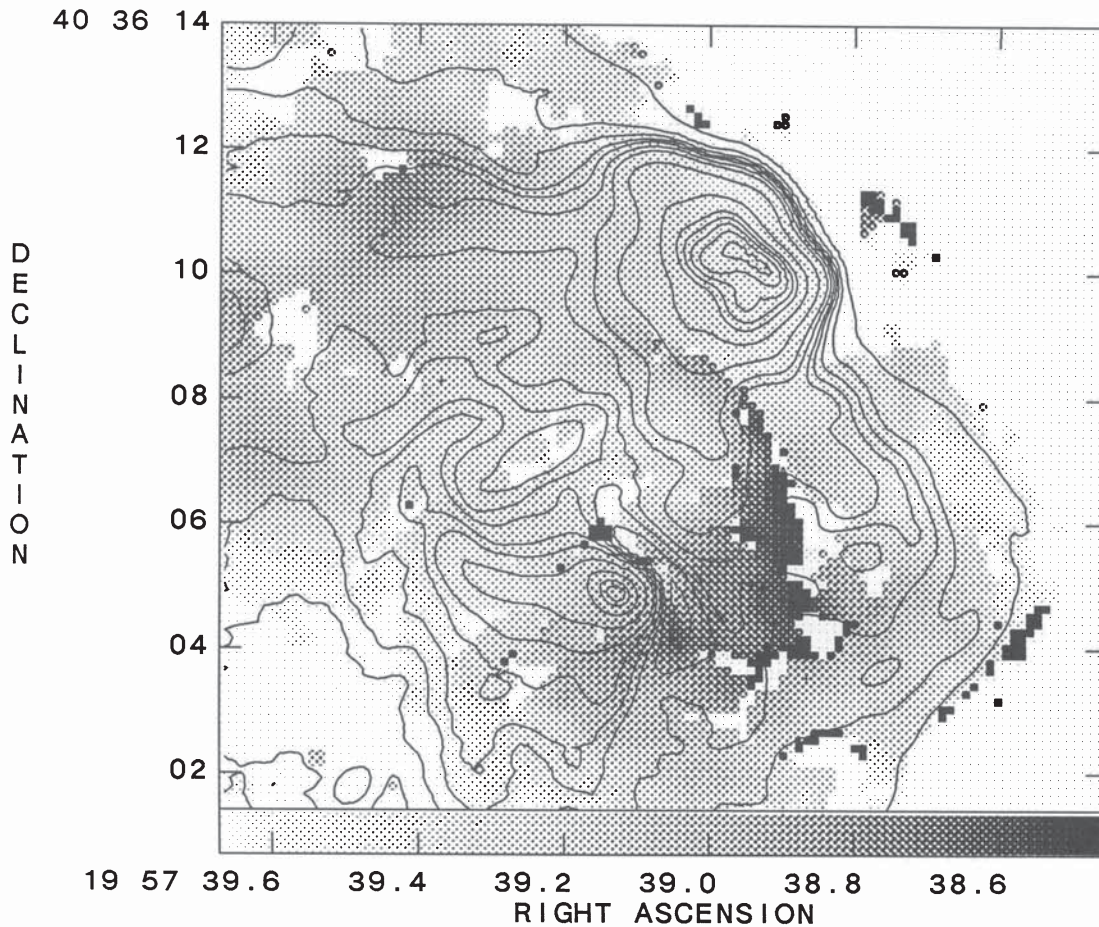


FIG. 1.—An image of the hot spots in the northwest lobe of Cygnus A. Contours are of total intensity at 4525 MHz, while the gray scale is the rotation measure (RM) distribution. The effective resolution (FWHM of the restoring beam) for the image is  $0''.4$ . The RM gray scale ranges from  $-200$  to  $1000 \text{ rad m}^{-2}$ . Hot spot B is the more compact hot spot to the south, while A is the larger hot spot to the north. Notice the arc of large  $\text{RM} \approx 3''$  west and north of hot spot B. This feature we interpret as the radio-quiet bow shock induced by the supersonic advance of the primary into the IGM.

CARILLI *et al.* (see 334, L22)