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OBSERVATIONS OF ANOMALOUS COSMIC-RAY HYDROGEN FROM THE *VOYAGER* SPACECRAFT

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ABSTRACT

As *Voyager 1* and *2* approach the solar wind termination shock, the hydrogen energy spectrum exhibits a rapidly increasing flux of anomalous cosmic-ray hydrogen, consistent with that observed for other anomalous cosmic-ray species. These results are consistent with the evidence for anomalous cosmic-ray hydrogen reported from *Voyager* observations during the period of minimum solar modulation in 1987.

Subject headings: cosmic rays — interplanetary medium — ISM: abundances

1. INTRODUCTION

It is thought that anomalous cosmic rays (ACRs) originate as interstellar neutral atoms that drift into the heliosphere due to the relative motion of the solar system and the very local interstellar medium (Fisk, Kozlovsky, & Ramaty 1974). In the inner heliosphere, some are singly ionized, either through charge exchange with the solar wind or by photoionization, and are convected outward with the solar wind to the termination shock, where they are accelerated (Pesses, Jokipii, & Eichler 1981). Anomalous cosmic-ray helium, carbon, nitrogen, oxygen, neon, and argon have all been observed (Garcia-Munoz, Mason, & Simpson 1973; Hovestadt et al. 1973; McDonald et al. 1974; Cummings & Stone 1987). Although interstellar pick-up hydrogen ions are observed (Gloeckler et al. 1993) and ACR H is expected (see, e.g., Fisk 1986), the ACR H will have much lower rigidities than other ACR species with the same velocity. As a result, ACR H with less than 100 MeV is more strongly modulated than other ACR species, making it more difficult to identify in the presence of Galactic cosmic-ray (GCR) protons.

During the previous solar minimum (1986–1987), changes were observed in the shape of the proton spectra in the outer heliosphere that were indicative of the emergence of an anomalous cosmic-ray hydrogen component (Christian, Cummings, & Stone 1988). Supporting evidence was also seen in the 1977 proton spectrum (Mewaldt 1990). In addition, the deuterium-to-proton ratio at *Pioneer 10* in 1987 exhibits a factor of ~2 reduction for a short period at solar minimum (Lopate & McKibben 1991), which would be expected if the deuterium-poor ACR hydrogen were present. Although these observations were consistent with the presence of ACR hydrogen, other explanations, such as temporal and spatial variations in the level of solar modulation, could not be ruled out (Lopate & McKibben 1991; Seo et al. 1994; Reinecke & Moraal 1992). However, the observations of Seo et al. (1994) were integrated over all of 1987, reducing the sensitivity to ACR hydrogen because the flux increased by a factor of 4 during the year, maintained a maximum flux for only 100–150 days, and then declined equally rapidly (Christian, Cummings, & Stone 1990; Lopate & McKibben 1991).

With each successive period of minimum solar modulation, the *Voyager* and *Pioneer* spacecraft move closer to the termination shock and the source of anomalous cosmic rays. *Voyager 1*, at about 57 AU radial distance and 247° heliospheric longitude, λ, 32° latitude, β, during 1994, has observed anomalous cosmic-ray fluxes which are higher than those observed at *Voyager 2* ($\sim$43 AU, $\lambda = 248°$, $\beta = -11°$ in 1994) or either *Voyager* during the 1987 solar minimum. Both *Voyager 1* and *2* are moving roughly upstream when compared to the inflowing interstellar neutrals, which are coming from $\lambda = 225°$, $\beta = -8°$ (Bertin et al. 1993).

2. OBSERVATIONS

Figure 1 shows the spectral evolution of the proton spectra at *Voyager 1* and *2* during 1993 and 1994. Because the analysis uses events from several different telescopes and trigger conditions, and there is a question of the normalization of the fluxes between these different event types, a 10% systematic error has been added in quadrature with the statistical fluctuations for points with energies less than 150 MeV nucleon^{-1}. The greater than 150 MeV nucleon^{-1} points are from events which fully penetrate the CRS HET (cosmic-ray system High Energy Telescope) detectors and have had 15% systematic errors added because of differences in absolute flux obtained by two different analyses (F. B. McDonald, private communication). This makes negligible quantitative difference in the subsequent discussion.

In the time period 1993 days 53–157, both *Voyager 1* and *2* appear to have predominantly a modulated Galactic cosmic-ray spectrum and exhibit the flux-proportional-to-kinetic-energy slope at low energies (as shown by the dashed lines) that is expected from simple modulation theory (Rygg & Earl 1967). By the beginning of 1994, *Voyager 2* still appears to be mostly Galactic, but *Voyager 1* shows a large excess in the intermediate energies, where the flux has increased by a factor of about 3 at 30 MeV as compared to the 30%–40% increase seen at the highest and lowest energies. By late 1994, the *Voyager 1* spectrum has continued to evolve and appears to have a distinct hump below 100 MeV.

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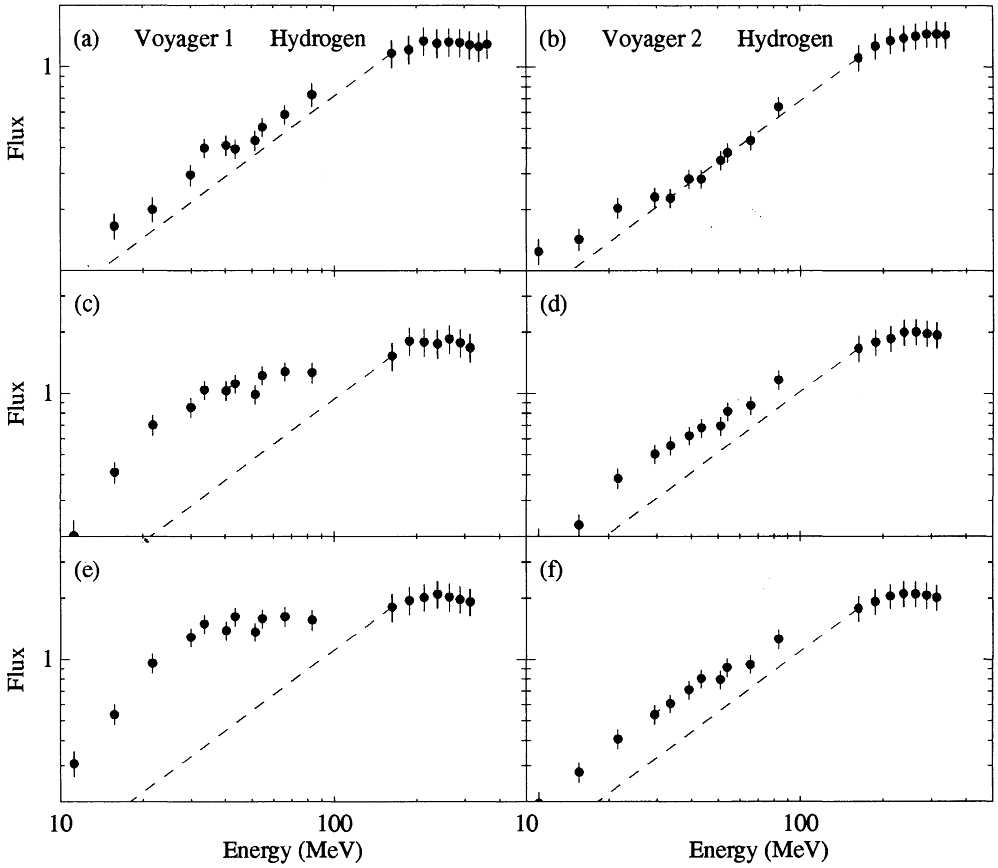

FIG. 1.—Observed proton energy spectra for *Voyager 1* (*left column*) and *Voyager 2* (*right column*) for the time periods (*a*)–(*b*) 1993 days 53–157, (*c*)–(*d*) days 1–105, and (*e*)–(*f*) 1994 days 157–261. Flux is measured in particles (m^2 sr s MeV)$^{-1}$. Dashed lines illustrate T^{+1} slopes for the six spectra normalized to the observed flux at 162.5 MeV. *Voyager 1* is at about 247° heliospheric longitude, λ, 32° latitude, β, and has moved radially from 52 to 57 AU during these three time periods. *Voyager 2* is at $\sim$284° λ, $-11°$ β, and has moved outward from 40 to 44 AU during 1993 and 1994. These positions can be compared to the inflowing interstellar neutrals which are coming from $\lambda = 255°$, $\beta = -8°$ (Bertin et al. 1993).

For comparison, Figure 2 shows the corresponding evolution of the helium spectra, where the anomalous and Galactic components are clearly resolved. Between the beginning of 1993 and the end of 1994, the Galactic helium component has increased by about 30%, but the anomalous component has risen more than a factor of 5 at the lower energies. The carbon spectra for the same time periods are shown in Figure 3, and although there are poorer statistics for these points, there is no evidence of the spectral evolution seen in the hydrogen spectra.

3. DISCUSSION

In order to derive the amount of ACR hydrogen, the observed 1994 days 157–261 proton spectra will be deconvolved into Galactic and anomalous hydrogen. For a Galactic spectrum, the shape of the *Voyager 2* 1993 days 53–157 time period will be used, because the contribution of an anomalous component should be small. Because the shape of the anomalous spectrum is evolving much more quickly than the Galactic spectrum, the shape of the ACR helium for each *Voyager* will be used. The shape of the ACR helium is derived from the observed spectrum shown in Figure 2 by subtracting a flux-proportional-to-kinetic-energy spectrum at low energies (<100 MeV nucleon^{-1}) normalized to the high-energy (>100 MeV nucleon^{-1}) Galactic component. A least-squares fit between a sum of these ACR and GCR spectral shapes and the observed H spectra is then performed for *Voyager 1* and *2* simultaneously. The ACR energy shift is set to be the same for *Voyager 1* and *2*, but all other energy shifts and flux shifts are free parameters. This is similar to the method used to derive the ACR hydrogen in Christian et al. (1990).

Figure 4 shows the deconvolution for both *Voyagers* during the 1994 days 157–261 time period. The separation of the ACR and GCR components is made easier than it was in 1987 because the energy of the peak flux of ACR hydrogen is about 40 MeV for this time period, considerably lower than the $\sim$134 MeV peak energy seen in 1987 (Christian et al. 1990), as expected with the decreased level of solar modulation. The lower energy of the hydrogen peak flux is consistent with the other ACR components. For example, the helium flux in 1994 peaks at about 7 MeV nucleon^{-1} as compared with about 21 MeV nucleon^{-1} in 1987. Most of the other anomalous species currently have peak energies below the threshold of the CRS instrument, so it is not possible to demonstrate the power-law dependence of peak energy on ion mass as was observed during the last solar cycle (Cummings & Stone 1990; Christian et al. 1990). The ACR H/He ratios obtained from these fits are 0.37 ± 0.03 and 0.37 ± 0.04 for *Voyager 1* and *2*, respectively, which are consistent with the value of 0.37 ± 0.10 obtained in 1987 (Christian 1989). McDonald, Lukasiak, & Webber (1995), in an accompanying paper, also observe ACR hydrogen in *Pioneer 10* data.

The ACR H source spectrum for a strong termination shock

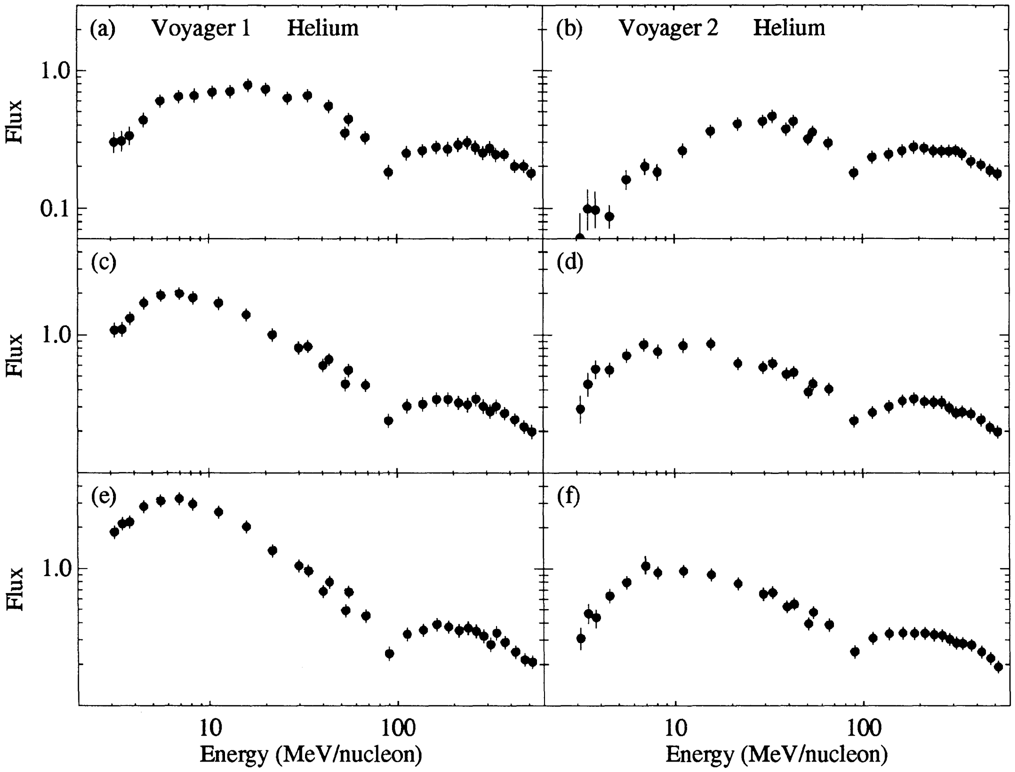

FIG. 2.—Observed helium energy spectra for *Voyager 1* (*left column*) and *Voyager 2* (*right column*) for the same time periods as in Fig. 1. Flux is in units of particles $(\mathrm{m}^2 \text{ sr s MeV nucleon}^{-1})^{-1}$.

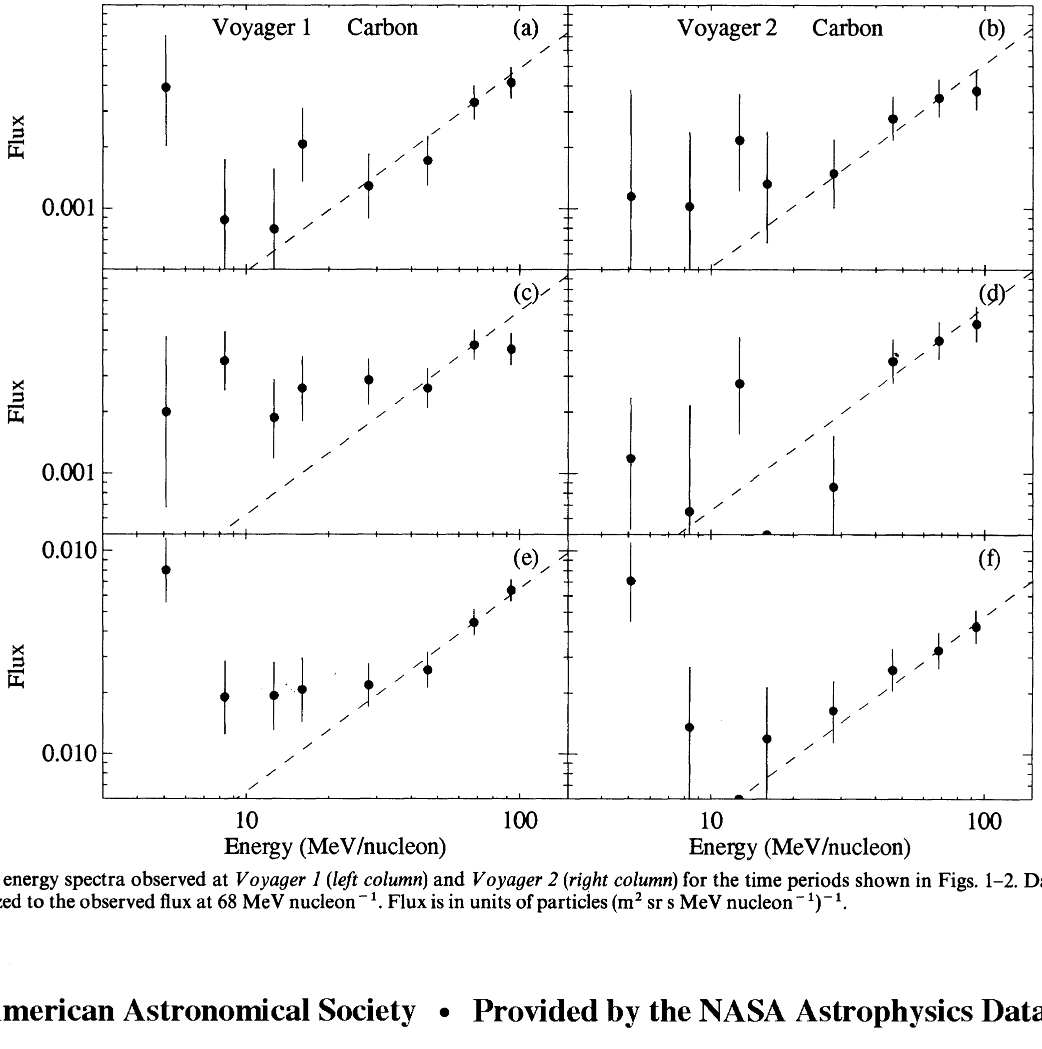

FIG. 3.—Carbon energy spectra observed at *Voyager 1* (*left column*) and *Voyager 2* (*right column*) for the time periods shown in Figs. 1–2. Dashed lines illustrate T^{+1} slopes normalized to the observed flux at 68 MeV nucleon^{-1}. Flux is in units of particles $(\mathrm{m}^2 \text{ sr s MeV nucleon}^{-1})^{-1}$.

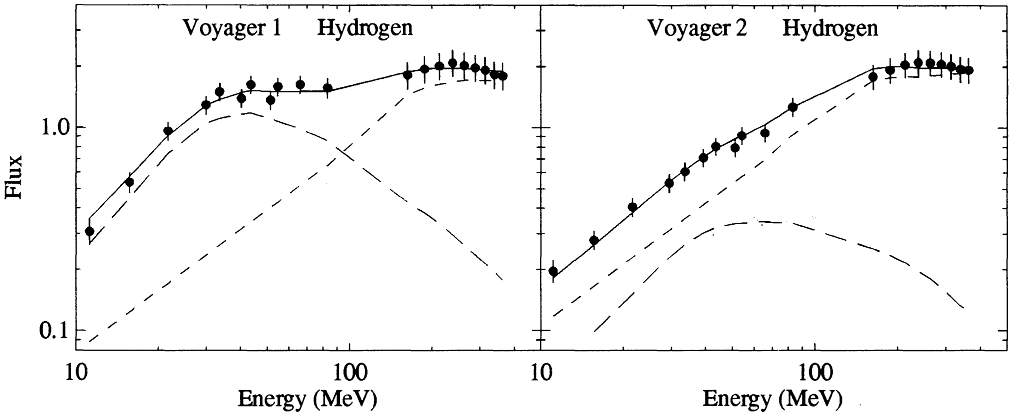

FIG. 4.—Decomposition of the observed proton energy spectra into anomalous cosmic-ray and galactic cosmic-ray components for 1994 days 157–261. Large-dashed lines show the best-fit anomalous spectra, small-dashed lines are the galactic spectra, and solid lines are the sum, which should be compared with the observed points. Flux is in units of particles (m^2 sr s MeV)$^{-1}$.

should be proportional to E^{-1}, with an exponential rolloff above ~300 MeV (see, e.g., Cummings, Stone, & Webber 1994). Upstream from the shock source, diffusive effects will suppress the lowest energies, resulting in a spectrum that peaks at an energy that increases with increasing distance from the shock. Thus, in 1987 when *Voyager 2* was ~44 AU from the shock, the peak energies for ACR H and He were ~130 MeV and ~21 MeV nucleon^{-1}, respectively. In 1994, Stone, Cummings, & Webber estimate that the shock was at less than 80 AU and moving inward, placing *Voyager 1* less than ~23 AU from the shock, with correspondingly lower peak energies for ACR H and He.

4. CONCLUSIONS

The lower peak energy and increased flux at *Voyager 1* has resulted in an H spectrum that shows a much more distinct signature of ACR H than was the case in 1987. However, combining the H/He ratio observed in 1994 with the clearly resolved ACR He spectrum in 1987 indicates that, in 1987, there should have been an ACR H flux comparable to that reported by Christian et al. (1988, 1990).

As *Voyager 1* continues moving outward at about 3.6 AU yr^{-1} and assuming that the shock continues moving inward, the peak in the ACR H should progressively decrease in energy until the spectrum approaches the E^{-1} dependence characteristic of the expected source spectrum and already exhibited by the ACR He spectrum above ~10 MeV nucleon^{-1} (see Fig. 2*e*).

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