EVIDENCE FOR ANOMALOUS COSMIC RAY HYDROGEN

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Abstract

The period of solar minimum activity in 1987 provided the first evidence for the existence of anomalous cosmic ray (ACR) hydrogen (Christian *et al.* 1988). More recent data from the *Voyager 1 (V1)* and *Voyager 2 (V2)* spacecraft and subsequent improved analysis of earlier data serve to confirm the presence of ACR hydrogen. This paper will cover some of these new developments in the analysis.

1. Introduction. The ACR component is thought to be composed of interstellar neutrals (Fisk *et al.* 1974) which are ionized in the heliosphere, convected to the termination shock by the solar wind, and then accelerated (Pesses *et al.* 1981, Jokipii 1986, Potgieter and Moraal 1988). Because neutral hydrogen is abundant in the interstellar medium and is easily ionized in the heliosphere, it has been expected that an ACR component of hydrogen exists (see, e.g., Fisk 1986), although the acceleration may not be as efficient as it is for heavier elements (Cummings and Stone 1987a). The ACR hydrogen spectrum is also expected to be difficult to distinguish from the modulated galactic cosmic ray (GCR) hydrogen spectrum because the ACR and GCR hydrogen undergo very similar modulation. Heavier elements have very different modulation effects for the singly-charged (Cummings *et al.* 1984) ACR particles as compared to the fully stripped galactic cosmic rays.

However, the ACR component is affected by the changing level of solar modulation to a greater extent than the galactic cosmic ray component (Webber and Cummings 1983). Because of this, ACR hydrogen is most likely to be observable during the low level of solar modulation seen by *V1* and *V2* during the 1987 solar minimum.

2. Discussion. Figure 1 shows the observed hydrogen energy spectra for *Voyager 2* during the time periods 1985/261-365 and 1987/209-313. These fluxes differ slightly ($< 10\%$) from the earlier published fluxes (Christian *et al.* 1988) due to improved background subtraction and data selection. There is an increase in flux resulting from the decrease in modulation level between 1985 and 1987, and there is a change in the shape of the spectrum. There is a similar, although less pronounced effect observed in the *V1* hydrogen energy spectra. Some of this spectral shape change is certainly due to the changing modulation, but we believe that this change is also evidence for the appearance of an ACR hydrogen component.

Simple, spherically symmetric modulation theory (Fisk 1971) predicts that as the modulation level decreases, the flux will increase and the peak of the energy spectrum will shift downwards in energy. But to first order, the shape of the energy spectra will remain the same for small changes in the modulation level. If we assume that the spectral shape change observed is due to an ACR hydrogen component which is present in the 1987 spectrum but negligible in the 1985 spectrum, then the 1985 spectrum gives, to first order, the shape of the underlying galactic cosmic ray spectrum in the observed 1987 spectrum. The ACR component of the 1985 spectrum is expected to be small because the fluxes of other ACR components observed (He, O, C, N, Ne, and Ar) are smaller by a factor of 10 in 1985 than in 1987, whereas the galactic components were less than a factor of two smaller (Christian 1989, Cummings and Stone 1987b).

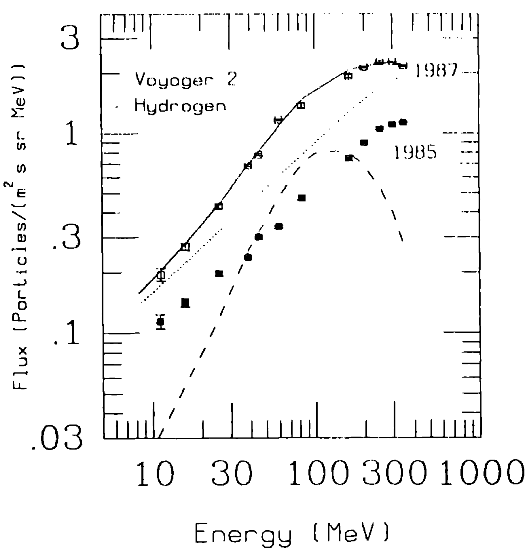

Fig. 1. *Voyager 2* observed hydrogen energy spectra for periods 1985/261-365 and 1987/209-313. 1987 spectrum is deconvolved into GCR (dotted line) and ACR (dashed line) components. Solid line shows derived observed spectrum.

The expected shape of the ACR hydrogen spectrum is obtained from the other ACR components because of the similarity in the ACR spectral shapes (Cummings and Stone 1990). The combination of the assumed ACR and GCR spectra which replicates the observed 1987 hydrogen energy spectrum can then be determined, and this is also shown in Figure 1. The dotted line shows the presumed GCR spectrum, the dashed line is our estimate of the ACR hydrogen contribution, and the solid line is the sum, which can be compared to the observed spectrum. This ACR flux is higher than the published upper estimate (Christian *et al.* 1988) because of the improved normalization procedure used (Christian 1989).

In the decomposition of the observed spectrum into ACR and GCR components, there was no constraint on the peak energy of either component. However, the energy of the derived ACR peak flux can be compared to an expected value. This is because the ACR spectra of the heavier components scale in energy as a power law in mass (Cummings and Stone 1990). Figure 2 shows the peak energy vs. mass for the H, He, N, O, and Ne ACR components during the 1987 solar minimum. The dashed line is a least-squares best-fit power law for the helium through neon points. It is clear that the energy obtained for the hydrogen component agrees very well with the extrapolation from the heavier elements.

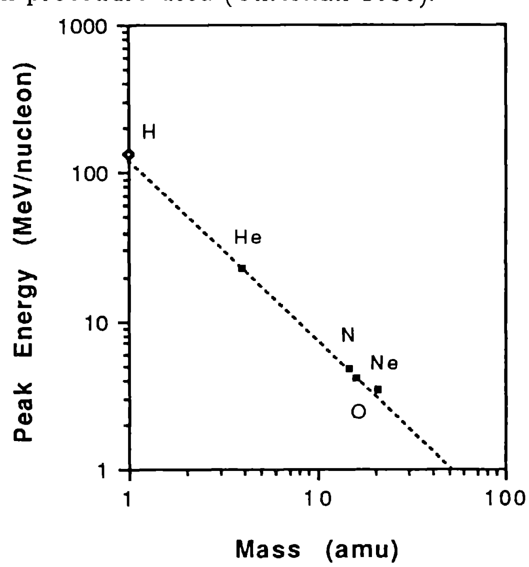

Fig. 2. Energy of spectral peak vs. mass for ACR components during the 1987 solar minimum. Dashed line is a least-squares power-law fit through all points except hydrogen.

Although the observed spectral shape change is consistent with the emergence of a measurable ACR hydrogen flux, other possible explanations must be explored. A typical explanation in the framework of modulation theory is that, as a consequence of the time-dependent nature of modulation, particles of lower rigidities react to the decrease in modulation faster than particles of higher rigidity. In order to investigate this question, the observed hydrogen fluxes in several energy bins are plotted as a function of time in Figure 3(a). Each point is a 26 day accumulation to average out effects due to the solar rotation period, and a point is plotted every thirteen days. The dashed lines trace out the high energy (275 MeV-375 MeV) points, but are shifted down to match the lower energy bins at the beginning of 1986. The excess flux can be clearly seen for the 49-72 MeV point, which is where the presumed ACR hydrogen component comprises the largest fraction of the observed flux.

Note, however, that the time profile of the low energy (18.7-33.0 MeV) flux tracks well with the highest energy. Thus the spectral shape change can be characterized by an excess flux observed in the intermediate energies, but not at lower or higher energies, contrary to usual energy-dependent hysteresis effects. These time profiles can be compared to the helium fluxes in Figure 3(b). Here the 18.7-33.0 MeV/nucleon fluxes, which are composed predominantly of anomalous cosmic rays, are seen to have a much larger response to the decrease in modulation before solar minimum and the increase in modulation after solar minimum than the higher energy (240-325 MeV/nucleon) galactic cosmic ray fluxes. Thus the hydrogen observations are again consistent with a galactic cosmic ray spectrum with a superimposed ACR hydrogen spectrum which is non-negligible only in the intermediate energies at the low modulation levels seen in the outer heliosphere at solar minimum.

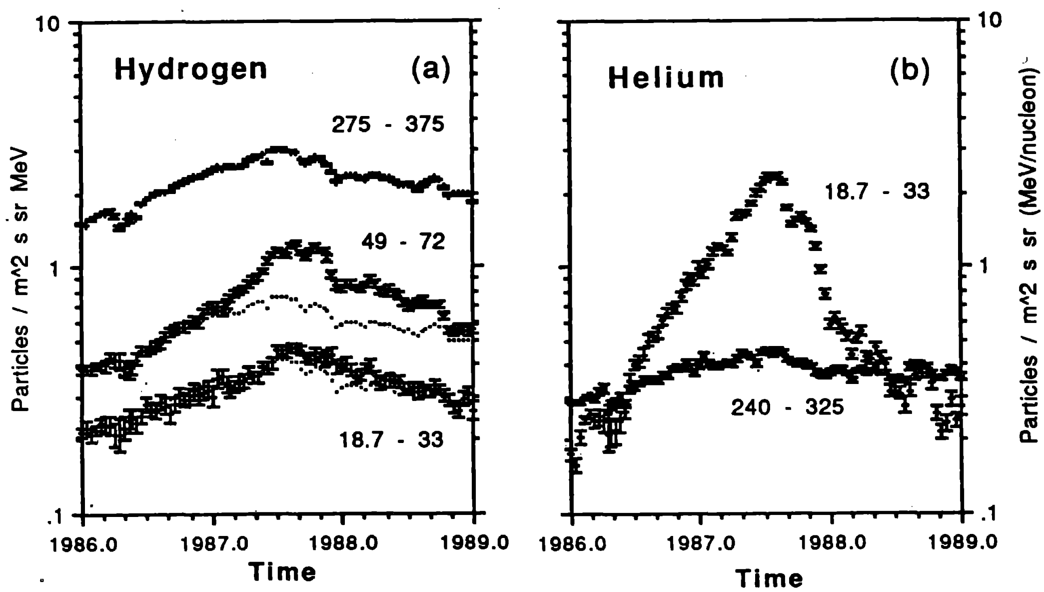

Fig. 3. (a) Hydrogen fluxes for three energy bins (18.7 - 30 MeV, 49 - 72 MeV, and 275 - 375 MeV) during the years 1986, 1987, and 1988. Points are for 26 day accumulations, every 13 days. The dashed lines show the 275 - 375 MeV fluxes shifted down to match the lower energy fluxes at the beginning of 1986.
Fig. 3.(b) Helium fluxes for the same time periods. The 18.7 - 30 MeV/nucleon fluxes are predominantly ACR, and the 240 - 325 MeV/nucleon fluxes are mostly GCR.

3. Conclusion. Although there have been small quantitative changes as the analysis evolved, qualitatively the picture has remained very stable. The change in spectral shape observed for hydrogen can be characterized as an excess of flux in the intermediate energies between about 30 MeV and 300 MeV. The excess has a peak at about the correct energy for ACR hydrogen. The temporal response and energy dependence of the excess are difficult to explain as a hysteresis in the modulation. However, the evidence is consistent with the emergence of an anomalous cosmic ray hydrogen component.

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