Evidence for Anomalous Cosmic Ray Hydrogen During the 1976-1977 Solar Minimum

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Abstract

We report evidence for the presence of anomalous cosmic ray hydrogen at 1 AU, based on a re-examination of data from the 1976-1977 solar minimum. In particular, the IMP 7&8 (^{2}H + ^{3}He)/^{1}H ratio at ~25 MeV shows a marked decrease at the time of maximum anomalous He flux levels, indicating a contribution of "anomalous" protons. These measurements are consistent with the properties of anomalous hydrogen observed in the outer heliophere during 1987 and 1994.

1 Introduction

Anomalous cosmic rays (ACRs) are a singly-charged component of interplanetary particles originating from interstellar neutral particles that have been swept into the heliosphere, ionized by solar UV or charge exchange with the solar wind, convected into the outer heliosphere, and then accelerated to energies of ~5 to 50 MeV/nuc [1], presumably at the solar wind termination shock [2]. It is well establshed that cosmic ray spectra for the elements He, C, N, O, Ne, and Ar include ACR contributions that have their maximum intensity at ~3 to 30 MeV/nuc. It is also expected on theoretical grounds that ACR hydrogen should be accelerated [3,4].

In 1989 Christian, Cummings and Stone (CC&S, [5]) reported the first solid evidence for anomalous H based on Voyager data from the 1987 solar minimum. Their observations fit the spectral pattern and temporal history predicted on the basis of other ACR species. Confirming evidence was also reported from the 1976-78 solar minimum at 15 AU ([6], see also [7]), but subsequent searches have not always found ACR hydrogen [8], and there were also other suggested explanations for these observations ([7],[8],[9]; review in [10]). With the approach of the 1998 solar minimum, Voyager 1&2 and Pioneer-10 all observed unambigous evidence confirming the existence of ACR hydrogen in the outer solar system [11,12], with properties consistent with those originally reported by CC&S [5].

Prior to the CC&S study [5] there were two searches for ACR hydrogen at 1 AU. The first of these, carried out by Mewaldt and Stone [13] (see also [14]), was stimulated by the suggestion that ACR hydrogen would be accelerated along with other ACR species [3], and by the hypothesis that the so-called "superfluxes" of cosmic ray H [15] in the 1970's might be due to ACR hydrogen, which might have access to 1 AU at times of minimum solar modulation. This study used the (^{2}H+^{3}He)/^{1}H ratio to trace the galactic cosmic ray (GCR) H component. Although possible evidence was reported for ~25 MeV/nuc ACR hydrogen based on 1976-1977 measurements [13], these results were never published. Following this, Beatty [16] searched for anomalous H at ~56 MeV/nuc during this same time period using the ^{2}H/^{1}H ratio, but did not detect any additional source of ^{1}H.

In this paper we re-examine the IMP-8 data analyzed by Mewaldt and Stone [13] in light of more recent developments. Making use of general characteristics of ACRs that have been discovered and tested over the past decade, and the properties of ACR hydrogen observed by Voyager and Pioneer, we are able to make a clear identification of anomalous hydrogen at 1 AU during the 1976-1977 solar minimum.

2 Observations

The observations were made with the Caltech Electron/Isotope Spectrometers (EIS) on IMP-7 and IMP-8, designed to measure the energy spectra of low energy electrons (0.2 to ~5 MeV) and the isotopes of Z = 1 to 8 nuclei with ~5 to ~40 MeV/nuc [17]. In this study we measure the time dependence of the secondary to primary ratio (^{2}H+^{3}He)/^{1}H during solar quiet times from 1972 to 1979 in order to trace the GCR contribution to ^{1}H, and thereby isolate a possible ACR contribution.

Figure 1 shows time variations of several particle components over the years from 1972 to 1979. Note that the maximum intensity of 19 to 30 MeV/nuc ^{4}He (dominated by ACR He during these years) was reached during the period from mid-1976 to early 1978. At this same time the flux of 19 to 30 MeV protons also reached its maximum level, remaining for more than a year. Note, however, that the counting rate of >75 MeV protons [18], and that of ^{2}H+^{3}He, remained rather unchanged from late 1972 to early 1978; in particular, they did not exhibit any significant response at the time that ACR He reached its maximum level. The (^{2}H+^{3}He)/^{1}H ratio (bottom panel, Figure 1) shows a distinct ~30% dip begining in mid-1976, suggesting that there is an extra component of non-GCR origin contributing to the H flux over this ~21 month period. This component contributes to the low energy proton fluxes, but apparently does not contribute significantly to the >75 MeV/nuc fluxes.

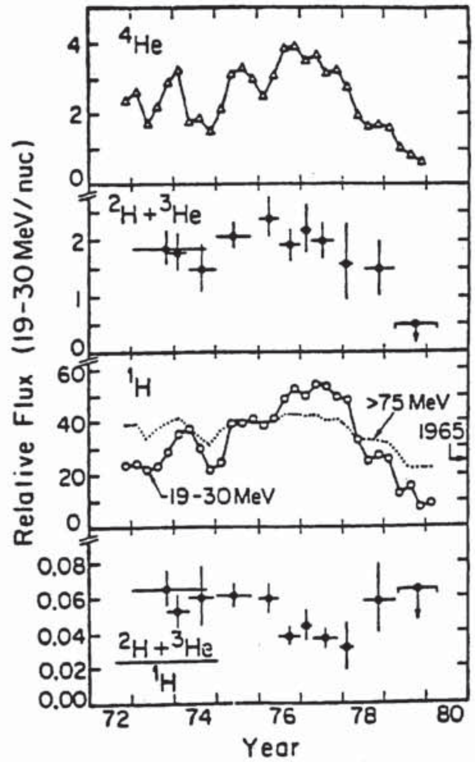

Figure 1: IMP-7&8 measurements of the relative flux of: 19-30 MeV/nuc ^{4}He, ^{2}H + ^{3}He, and ^{1}H (with >75 MeV protons. At bottom is the (^{2}H+^{3}He)/^{1}H ratio.

Figure 3 shows the energy spectra for the quartet of H and He isotopes for 1/75 to 10/75, and for 6/76 to 3/78, when the ACR fluxes reached their maximum. Note that from 1975 to mid-1976 the level of the ^{1}H and ^{4}He fluxes both increased by ~50%, while both ^{2}H and ^{3}He remained essentially unchanged. The pattern that emerges is that during this ~21 month period the temporal variations of low energy ^{1}H behaved like those of anomalous ^{4}He, rather than like the other GCR components (^{2}H, ^{3}He, and >75 MeV protons), suggesting that anomalous ^{1}H made a significant contribution to the low energy proton flux during this period.

The possibility has been considered that this might be a solar modulation effect, brought about because ^{1}H is more sensitive to solar modulation than either ^{2}H or ^{3}He, because of its larger charge to mass ratio. However, attempts to model this behavior with standard spherically symmetric solar modulation routines were unsuccesful in producing the dip in the (^{2}H+^{3}He)/^{1}H ratio without violating the approximately level counting rate of >75 MeV protons (Figure 1).

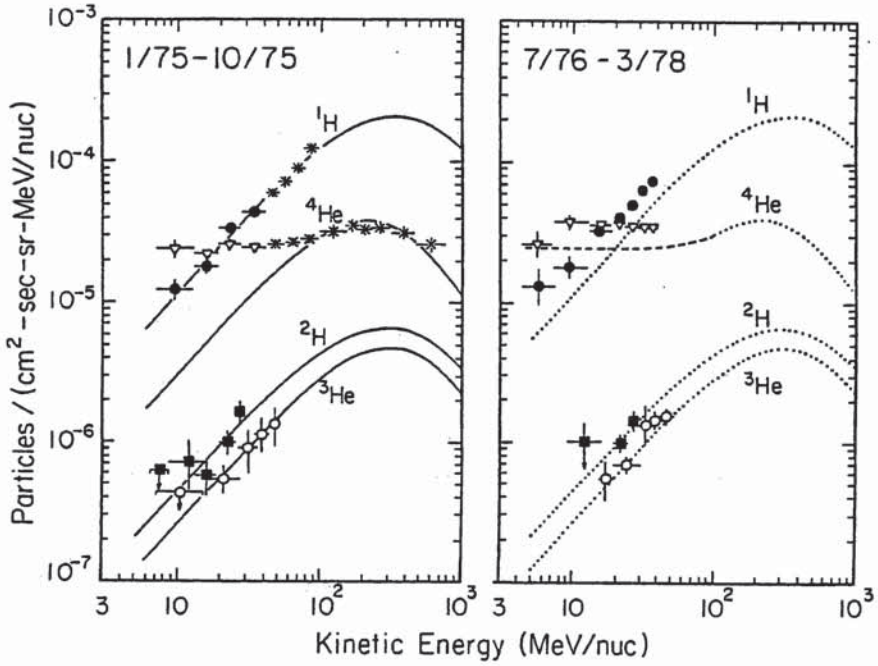

Figure 2: Energy spectra of H and He isotopes for 1975 (left) and for the 7/76 to 3/78 period when ACR He is at its maximum. The 1975 spectra are reproduced on the right as dotted lines (dashed for ACR He). Data <40 MeV/nuc are from the Caltech experiment; those at higher energy are from the Chicago IMP-8 experiment [23].

Discussion

To interpret the excess low-energy proton flux in 1976-77 as ACR protons, it is necessary to consider what is known about the other ACR species at this time. In particular, Cummings, Stone and Webber (hereinafter CS&W, [19]) showed that during 1977-1978 ACR He, N, O, and Ne all had a generic spectral shape, and that the energy of the intensity maximum scaled as a power law in the charge to mass ratio (Q/A), where Q=1 for all ACR species. Thus, ACR oxygen peaked at ~4 MeV/nuc at this time, while ACR He peaked at ~15 MeV/nuc [19]. When this relation is extrapolated to H it predicts that the ACR proton peak should be at ~53 MeV. CC&S used a similar power law relation, fit to 1987 data, and later to 1994 data [5,11], to verify that the location of the 1987 and the 1994 ACR proton peaks in the outer heliosphere were at their predicted locations. Note that the 1976-77 proton peak is almost a factor of 3 lower in energy than than in 1987 at 23 AU.

It is possible to predict the intensity level for ACR H in 1977-78 if we normalize to the 1987 and 1994 observations. Christian et al. [5,11] found ^{1}H/^{4}He = 0.37±0.10 in 1987 and ^{1}H/^{4}He = 0.37±0.04 in 1994. From a combination of the intensity scaling relations for 1977-78 and 1987 [19,20] the predicted ^{1}H/^{4}He intensity ratio for 1977-78 should be ~0.6. Figure 3 illustrates the predicted location, shape, and intensity of the ACR H peak. Note that at this intensity level ACR protons do not exhibit a pronouced spectral feature - rather they lead to a general bulge in the low energy intensity, with their maximum effect at ~10 to 20 MeV/nuc. This may help explain why Beatty [16] did not detect anomalous H; while there is a limited decrease in his ^{2}H/^{1}H ratio at the predicted time, its magnitude is expected to be somewhat less at 56 MeV than at lower energies. Christian [22] has also reported possible evidence for anomalous hydrogen at ~1.6 AU from Voyager data in 1977-78. His results are consistent with our interpretation of the IMP-8 measurements.

We can also check whether the IMP-8 ACR flux is consistent with Pioneer-10 observations at this time. Mewaldt [6] identified a contribution of ACR hydrogen in the 1977 Pioneer-10 data at ~15 AU, with an intensity maximum of ~1 per m^2sr.sec.MeV. Combining this with the apparent flux level of ACR protons at 1 AU, we find a radial gradient of ~12%/AU between 1 and 15 AU, consistent with that for ACR He. This result agrees with the measured radial gradient of ~8%/AU for 30-70 MeV protons in 1976-77 [21], taking into account that GCR protons contribute ~50% of the flux at 15 AU and ~70% of the 1 AU flux. In early 1978, the 30-70 proton gradient suddenly dropped [21], just when the $(^2H+^3He)/^1H$ ratio increased.

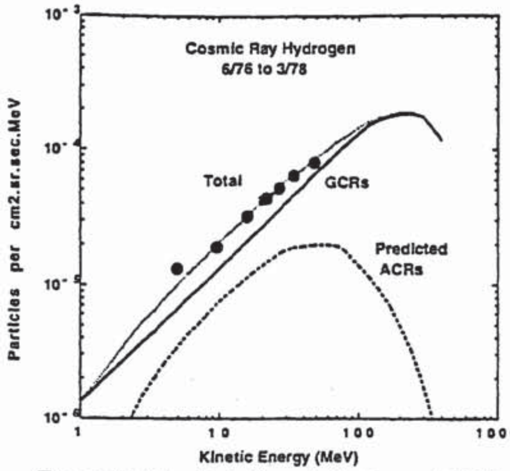

Figure 3: Predicted contribution of ACR hygrogen to the proton flux for 1976-77.

In conclusion, the IMP-8 observations of H and He isotopes during the extended solar minimum of the 1970s provide evidence for a component of low-energy H of non-GCR origin. While these data were not sufficient by themselves to "discover" ACR hydrogen, when placed in the context of ACR hydrogen measurements from the outer solar system they provide strong evidence that anomalous hydrogen was present at 1 AU in 1976-1977. While the flux of ACR hydrogen was apparently not sufficient to explain why the proton fluxes during the 1970s exceeded those in 1965, the presence of ACR hydrogen in the inner solar system does help explain a number of puzzling observations of the energy spectra, time variations, and radial gradients of low energy cosmic rays (see also [13]).

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