

COSMIC-RAY H AND He ISOTOPES IN THE OUTER HELIOSPHERE IN 1994

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ABSTRACT

With the approach of the solar minimum period of cycle 22, the *Voyager 1* cosmic-ray data have shown continuous development of a higher flux of low-energy hydrogen. At an average heliocentric distance of 56 AU, the low-energy (<100 MeV) flux is higher than that measured during the 1987 solar minimum at much smaller heliocentric distances, whereas the high-energy (>100 MeV) flux has not quite recovered to that of the 1987 solar minimum. The low-energy $^2\text{H}/^1\text{H}$ ratio is significantly smaller than the previous measurements and the model predictions, while the $^2\text{H}/^3\text{He}$ ratio is consistent with the calculations. This can be explained by an excess of low-energy ^1H , which is attributed to the anomalous ^1H component.

Subject headings: cosmic rays — ISM: abundances

1. INTRODUCTION

Hydrogen, the most abundant neutral particle in the interstellar medium, can be easily ionized by photoionization or charge exchange with the solar wind, and according to the generally accepted model for anomalous cosmic rays (Fisk 1986), it should have an anomalous component. However, the detection of anomalous hydrogen has proved difficult since both Galactic and anomalous H are singly ionized. Christian, Cummings, & Stone (1988) inferred the detection of anomalous hydrogen from the spectral shape of cosmic-ray ^1H observed on *Voyager 2* in 1987 over the energy range 30–300 MeV. However, Reinecke & Moraal (1992) demonstrated that solar modulation produces characteristic bulges in the spectra in the outer heliosphere and concluded that the *Voyager 2* H spectrum did not have any detectable excess over the prediction of a standard modulation model. Similarly, Seo et al. (1994) studied the H and He isotopes observed on *Voyager 2* in 1987 and showed that the measured ^1H and ^2H spectra were both consistent with the calculated spectra, using standard Galactic and heliospheric propagation models without invoking an anomalous hydrogen component. The *Pioneer 10* investigation of ^1H and ^2H , at larger heliospheric distances than *Voyager 2*, also reported that their observations do not provide conclusive evidence for the presence of anomalous hydrogen (Lopate & McKibben 1991). Now, however, as we approach the solar minimum period of cycle 22, data from the *Voyager 1* cosmic-ray detector system (CRS) experiment is providing compelling evidence for the presence of anomalous ^1H .

We report in this Letter new measurements of the cosmic-ray ^2H and ^3He from the *Voyager 1* spacecraft in 1994 at an average heliocentric distance of 56 AU. The cosmic-ray ^2H and ^3He are mainly secondary products from the p - p and p - ^4He interactions of primary cosmic rays with the interstellar medium: ^3H secondaries contribute to the ^3He production, since ^3H decays into ^3He with a 12.2 yr half-life, which is negligible compared to the cosmic-ray propagation time ($\sim 10^7$ yr). Other reactions such as ^4He - ^4He and p -($Z > 3$) also contribute to a lesser extent to the productions of ^2H and ^3He . Measurements of ^2H and ^3He isotopes along with their main parents ^1H and ^4He can provide important information on both the Galactic and heliospheric propagation of cosmic rays. In particular, these isotopes can be a good test for the

anomalous component. Increases in ^1H and ^4He due to changes in the effect of cosmic-ray modulation would also be accompanied by corresponding increases in the ^2H and ^3He . However, increases in ^1H and ^4He due to the anomalous component, which is from a local source, should not reflect the same increase in ^2H and ^3He .

2. DATA ANALYSIS AND RESULTS

The data for this study were collected by the *Voyager* CRS, which contains three different types of telescopes that have been described previously (Stone et al. 1977). We have analyzed data from the High Energy Telescope (HET) using the dE/dx versus E technique. Our ^2H and ^3He are well separated from ^1H and ^4He with an excellent mass resolution, $\sigma_A < 0.1$ (Seo et al. 1994). The measured differential energy spectra of the H and He isotopes during the solar quiet time from January 1 to September 24 in 1994 on *Voyager 1* are shown in Figures 1a and 1b, respectively, along with the ^1H and ^4He spectra from the standard flux measurement, which provides fluxes for the primary elements (McDonald et al. 1992). The 1987 *Voyager 2* data and the calculated curves for those data (Seo et al. 1994) are also shown for comparison. The calculated curves were based on solar modulation, using a spherically symmetric model, of the interstellar spectra obtained from the leaky-box model. The 1987 data and the calculated curves are multiplied by a factor 0.76 in order to normalize them to the 1994 *Voyager 1* high-energy hydrogen data. The low-energy ^1H spectrum is much higher than both the 1987 low-energy data and the calculations. The low-energy ^4He shows the same effect due to the anomalous ^4He contribution. On the other hand, their secondaries ^2H and ^3He agree rather well with the 1987 *Voyager 2* data and the calculations.

The ^2H and ^3He data have also been analyzed for the latter part of 1994, September 25 to November 20. For this short time period, the ^2H and ^3He statistics are too low to get the energy spectra, but the ratios over the whole energy range can be obtained. The $^2\text{H}/^1\text{H}$ and $^2\text{H}/^3\text{He}$ ratios have been obtained for the two time periods in 1994 from the *Voyager 1* data and also for 1986, 1987, and 1988 from the *Voyager 2* data. Both ratios are compared with the previous measurements and the Galactic/heliospheric propagation calculations in Figures 2a and 2b. Since the measurements were made at different solar

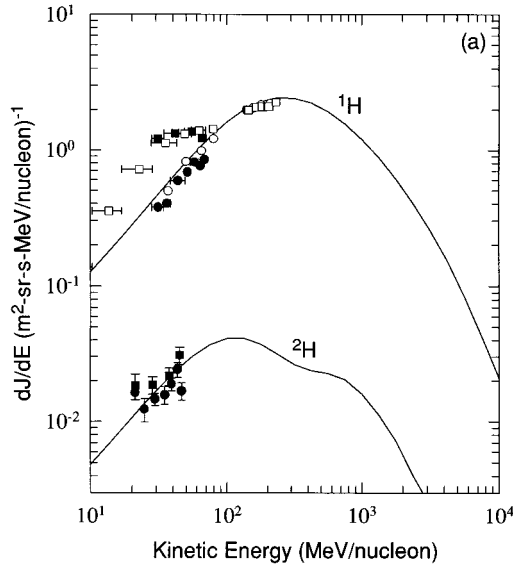


FIG. 1a

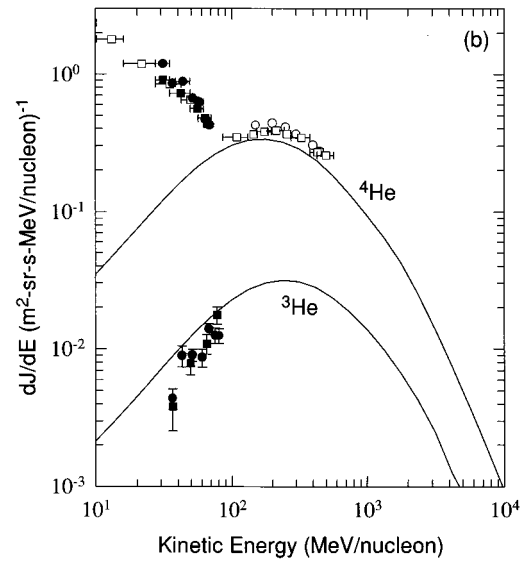


FIG. 1b

FIG. 1.—Differential energy spectra of (a) H and (b) He observed on *Voyager 1* from 1994 January 1 to September 24 at 56 AU (filled squares for this analysis; open squares for the standard flux measurements), along with the 1987 *Voyager 2* data (circles) and the calculated spectra (Seo et al. 1994), which are normalized to the high-energy *Voyager 1* ^1H flux.

modulation levels and at different energy ranges, the ratios are plotted against the ^1H flux (the higher the flux, the lower the modulation level). The three different curves represent modulation calculations for three different interstellar ratios. To get the modulated ratios, the local interstellar spectra obtained from the Galactic propagation calculation were subjected to solar modulation based on a numerical solution for a spherically symmetric model (Fisk, Forman, & Axford 1973) includ-

ing diffusion, convection, and adiabatic deceleration. A solar wind speed $v = 400 \text{ km s}^{-1}$ and a heliospheric boundary distance $r_b = 130 \text{ AU}$ were assumed for these calculations. The interstellar ratios were obtained from the leaky-box model with two different types of the mean pathlength: (1) (*long dashed curves*) $\lambda_e = 8(5.5/R)^\delta \text{ g cm}^{-2}$, where $\delta = 0.6$ for rigidities $R \geq 5.5 \text{ GV}$ and $\delta = 0$ for $R < 5.5 \text{ GV}$; (2) (*dotted curves*) $\lambda_e = 35.1\beta R^{-0.6} \text{ g cm}^{-2}$, for $R \geq 3.3 \text{ GV}$, and $\lambda_e = 17.2\beta \text{ g}$

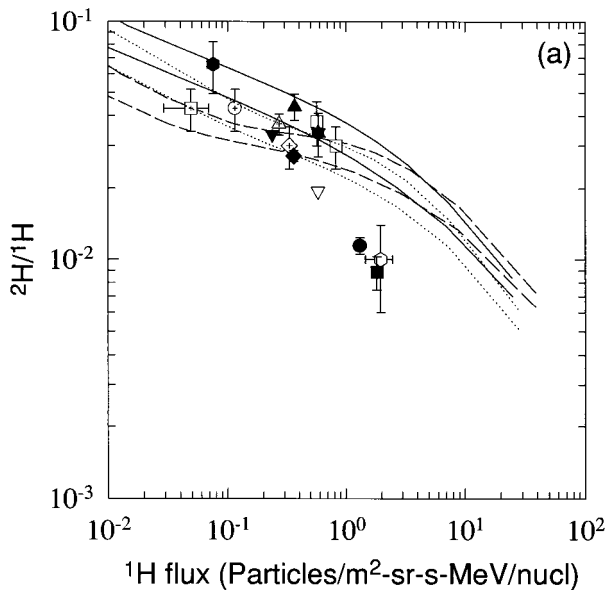


FIG. 2a

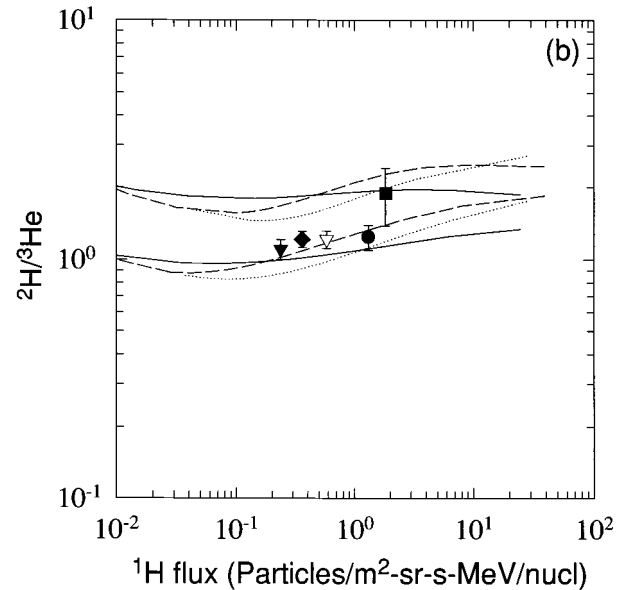


FIG. 2b

FIG. 2.—Measured cosmic-ray ratios (a) $19\text{--}48 \text{ MeV nucleon}^{-1} \text{ } ^2\text{H}$ to $28\text{--}70 \text{ MeV nucleon}^{-1} \text{ } ^1\text{H}$ and (b) $19\text{--}48 \text{ MeV nucleon}^{-1} \text{ } ^2\text{H}$ to $32\text{--}82 \text{ MeV nucleon}^{-1} \text{ } ^3\text{He}$ are compared with the calculated ratios and previous measurements: filled squares (1994 September 25–November 20; *Voyager 1* data), filled circles (1994 January 1–September 24; *Voyager 1* data), downward-pointing open triangles (1987 *Voyager 2* data), downward-pointing filled triangles (1986 *Voyager 2* data), filled diamonds (1988 *Voyager 2* data), this work; filled star, Seo et al. (1994); open hexagon, Lopate & McKibben (1991); open squares, Beatty (1986); upward-pointing filled triangle, Garcia-Munoz et al. (1975); crossed diamond (*ISEE 3* 1978 data); crossed triangle (*ISEE 3* 1979 data); crossed circle (*ISEE 3* 1980 data); crossed square (*ISEE 3* 1981 data); Kroeger (1986); filled hexagon, Hsieh & Simpson (1969). Calculated ratios are shown with curves identified in the text.

cm^{-2} , for $R < 3.3$ GV. The third interstellar ratio (*solid curves*) is based on a reacceleration model (Seo & Ptuskin 1994), which uses a Kolmogorov spectrum type $\lambda_c = 14R^{-0.33} \text{ g cm}^2$ and the reacceleration parameter $\alpha = 0.001$.

Due to the variety of the energy bins used for the ratio measurements, two curves are presented for each model. For $^2\text{H}/^1\text{H}$, the lower curves represent the 31.6 MeV nucleon $^{-1}$ ^2H to 46.7 MeV nucleon $^{-1}$ ^1H ratio, and the upper curves represent the 42.2 MeV nucleon $^{-1}$ ^2H to 42.2 MeV nucleon $^{-1}$ ^1H ratio. For $^2\text{H}/^3\text{He}$, the lower curves represent the 31.6 MeV nucleon $^{-1}$ ^2H to 56.2 MeV nucleon $^{-1}$ ^3He ratio, and the upper curves represent the 42.2 MeV nucleon $^{-1}$ ^2H to 42.2 MeV nucleon $^{-1}$ ^3He ratio. The latter part of the 1994 *Voyager 1* $^2\text{H}/^1\text{H}$ ratio (*filled square*) exhibits the lowest value ever measured, and it deviates significantly from the calculated ratios. The 1987 *Pioneer 10* data (*open hexagon*) had a quite low ratio, but with much larger uncertainty: in this analysis, the 1987 *Pioneer 10* data alone could not give conclusive evidence for the presence of anomalous hydrogen (Lopate & McKibben 1991). The $^2\text{H}/^3\text{He}$ ratio should not change appreciably over the solar cycle, and the measured values are consistent with the calculations. They show that the low $^2\text{H}/^1\text{H}$ ratio is not due to a low ^2H flux, but rather to the high ^1H flux.

3. CONCLUSIONS

We have measured the spectra of H and He isotopes as well as their ratios in 1994 using the CRS detector on

Voyager 1. The observed low-energy (<100 MeV) H flux is higher than that observed during the 1987 solar minimum, whereas the high-energy (>100 MeV) H flux is still below that of the 1987 solar minimum. The measured spectra are compared with the spectra of H and He isotopes measured in 1987 from *Voyager 2*, as well as the calculated spectra to fit that data with the interstellar and heliospheric propagation models. The current *Voyager 1* data clearly show an excess in the low-energy ^1H spectrum that cannot be explained with the standard cosmic-ray propagation models. The *Voyager 1* $^2\text{H}/^1\text{H}$ ratio from the latter part of 1994 is definitely lower than the calculated ratios, while the $^2\text{H}/^3\text{He}$ ratio is consistent with the calculations. This excess of low-energy ^1H is understood to be due to the anomalous ^1H component, like the excess flux of low energy ^4He is due to anomalous ^4He .

Our conclusion is essentially the same as two other independent observations of anomalous hydrogen, namely, Christian, Cummings, & Stone (1995) and McDonald, Lukasiak, & Webber (1995). The former used the evolution of the low-energy H and He spectra in 1993 and 1994, while the latter used the carbon spectrum, which is almost entirely galactic, to identify anomalous hydrogen.

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