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INTERSTELLAR DEUTERIUM ABUNDANCE IN THE DIRECTION OF BETA CENTAURI

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ABSTRACT

Interstellar absorption lines due to the Lyman series transitions in hydrogen and deuterium have been observed in the spectrum of β Cen. From these, a ratio of deuterium to hydrogen, by number, of 1.4 ± 0.2 (m.e.) $\times 10^{-5}$ has been obtained. If one assumes that the present deuterium abundance is a relic of the big-bang element synthesis, a value of 1.5×10^{-31} g cm^{-3} for the present density of the Universe is derived.

Subject headings: abundances — cosmology — interstellar matter — spectra, ultraviolet

I. INTRODUCTION

A number of investigations have been undertaken to determine the interstellar deuterium abundance, but completely satisfying results have not yet been obtained. The deuterium analog of the 21-cm hydrogen hyperfine transition at 91.6 cm has been carefully observed by Weinreb (1962), who obtained an upper limit on N(D I)/N(H I) of 7.7×10^{-5}, and more recently by Cesarsky, Moffet, and Pasachoff (1973) who report a probable detection of this line yielding values between 3.3×10^{-5} and 5.0×10^{-4}. Radio emission lines of DCN, measured in the Orion Nebula by Jefferts, Penzias, and Wilson (1973), imply a value between 1.2×10^{-7} and 1.0×10^{-5} (Solomon and Woolf 1973). Black and Dalgarno (1973), using measurements of $N(\mathrm{HD})/N(\mathrm{H_2})$ by Spitzer *et al.* (1973), find that $N(\mathrm{D})/N(\mathrm{H})$ lies between 5×10^{-6} and 2×10^{-4} in the ζ Oph cloud.

In this *Letter* we report on a direct measurement of the interstellar deuterium abundance ratio using the *Copernicus* spectrometer. The Lyman series lines of hydrogen and deuterium from Lβ to Lζ have been scanned at 0.05 Å resolution in the spectrum of the B1 III star β Cen.

II. DATA ANALYSIS

The Lβ through Lϵ lines of deuterium are all visible, but the weak Lϵ line was excluded from the analysis due to a poor signal-to-noise ratio. The wavelengths and measured equivalent widths are given in table 1.

Theoretical curves of growth were computed for each line and for b-values of 4, 6, and 8 km s^{-1} ($b = 2^{\frac{1}{2}}$ times the atomic velocity dispersion in the line of sight to the star). The measured equivalent widths have been analyzed with these curves of growth and yield a mean column density of 4.8 ± 0.3 (m.e.) $\times 10^{14}$ cm^{-2} and a mean b-value of 6.6 ± 0.3 (m.e.) km s^{-1}.

The hydrogen column density can be derived directly from the Lβ line which is on the damping part of the curve of growth. Figure 2 shows the continuum derived by multiplying the observed counts by $\exp(+\tau_\lambda)$, where τ_λ is the optical depth of a purely damped Lβ line at a given τ_λ, for a variety of column densities. The red wing of Lβ is deeper than the blue wing, due to blends of interstellar lines of O I and Mg II (2 lines) (and possibly to very weak, hydrogen components) and probably to other stellar features. The true continuum for the interstellar line consists of the core of the broad stellar Lβ line plus whatever other lines are present; and without detailed

TABLE 1

DATA ON INTERSTELLAR HYDROGEN AND DEUTERIUM LINES

Source	λ_{lab}	$\lambda_{\text{obs}}{}^{*} - \lambda_{\text{lab}}$	W_λ (Å)
H	1025.722	−0.010	0.739 (+.031, −.055)†
D	1025.442	−0.005	0.075
H	972.537	+0.005	0.323 (+0.008, −0.011)‡
D	972.272	−0.002	0.051
H	949.743	−0.003	0.235 ± 0.020
D	949.485	−0.010 ± 0.015	0.034 ± 0.001
H	937.804	+0.001 ± 0.015	0.191 ± 0.012
H	930.748	−0.004 ± 0.008	0.117 ± 0.037

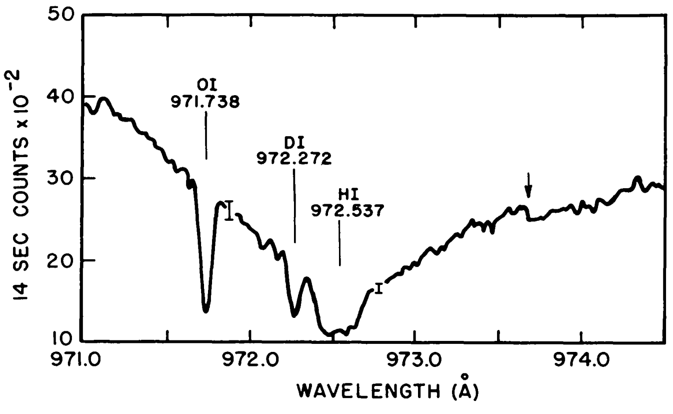
* Based on one determination except for 949.485 (2 measures), 937.805 (4 measures), and 930.748 (2 measures).

† Obtained by fitting a damping profile.

‡ Obtained by fitting a Voigt profile (see text). Unless otherwise noted, equivalent widths were measured directly from the plotted data.

model fits, the true continuum cannot be determined. However, as shown in figure 2, the derived continua for $N(\text{H I}) > 4.5 \times 10^{19}$ and $N(\text{H I}) < 3 \times 10^{19}$ imply structure that would in fact be smeared out by the 160 km s^{-1} rotational velocity of β Cen (Uesugi and Fukuda 1970). The adopted value is $N(\text{H I}) = 3.5 \pm 0.5 \times 10^{19}$. The distance to β Cen, based on the spectroscopic parallax, is 81 pc, yielding a mean volume density of 0.14 cm^{-3}.

Table 1 shows the wavelengths, equivalent widths, and method of determination of the equivalent widths. Fitting the quoted equivalent width of Lϵ to the relevant curve of growth yields a b-value of 8.8 ± 1.0 km s^{-1}, for $N = 3.5 \times 10^{19}$. Using a Voigt profile, the best fit to the L$_\gamma$ line, assuming $N(\text{H I}) = 3.5 \times 10^{19}$ gives $b = 10.2$ (+0.5, −1.0) km s^{-1}. The average of these two b-values, $b = 9.5$ (+1.1, −1.4) km s^{-1}, is in good agreement with the deuterium b-value quoted above, if the Doppler velocity is assumed to be entirely thermal, since then $b(\text{deuterium}) = b(\text{hydrogen})/\sqrt{2}$. The deuterium value then scales to a hydrogen b-value of 9.4 ± 0.4.



INTERSTELLAR LINES NEAR Ly γ IN BETA CENTAURI

FIG. 1.—The wavelength region near Lγ in the far-ultraviolet spectrum of β Cen. The stellar Lγ line dominates the figure. Wavelengths of interstellar lines are marked. Interpolation between points in the raw data yielded a point for every 0.012 Å, and two scans have been averaged in some places. The arrow marks a discontinuity in baseline for data taken in separate orbits.

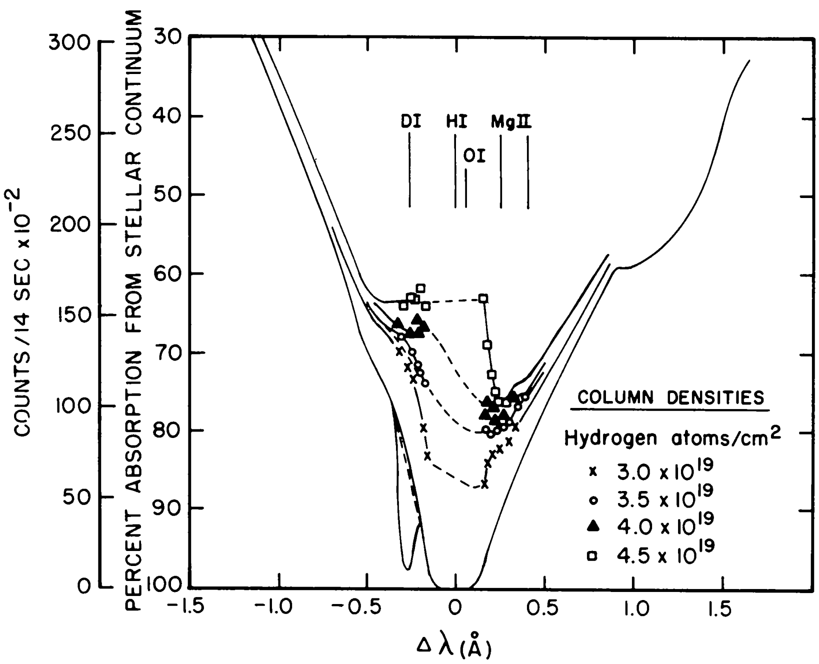


Fig. 2. Examples of continua derived from profile fitting (see text) for different values of N(H I) for the observed Lβ line. Wavelengths of interstellar lines which probably affect the long-wavelength wing are noted. Two continua are shown at the deuterium line. The solid line is the line used in the fitting; the dashed line is the lowest continuum which one could reasonably draw for the line. The dashed line between the derived continua for hydrogen (blue wing) for N(H I) equal to 3.0 and 3.5 × 10^{19} shows the effect of using a continuum intermediate between the two continua shown at the deuterium Lβ line.

The inferred temperature of 5400° (+1300°, −1500°) K may be regarded as an upper limit for this line of sight.

III. DISCUSSION

The results of the previous two sections yield a value for N(D I)/N(H I) of 1.4 ± 0.2 (m.e.) × 10^{-5}. Since lines of H_2 are not observed in this spectrum, and since the degree of ionization is likely to be the same for the two isotopes, the measured ratio is essentially identical to the deuterium abundance, N(D)/N(H). Assuming this value to be typical of the interstellar gas, we compare it with solar-system measurements.

Deuterium has not been detected in the solar photosphere or in the solar wind, but under the assumption that most if not all the ^{3}He measured in the solar wind results from the nearly complete burning of deuterium into ^{3}He in the Sun, Geiss and Reeves (1972) estimate a deuterium abundance for the protosolar gas of 2.5 × 10^{-5}. They further point out that chemical isotope fractionation during formation of at least the inner solar system can increase this value to the observed ocean-water deuterium abundance of 15.7 × 10^{-5} (Craig 1961). Trauger *et al.* (1973) report a deuterium abundance of 2.1 ± 0.4 × 10^{-5} based on measurements of HD in the spectrum of Jupiter. These results should not be compared directly with the value reported here since the interstellar deuterium has presumably decreased between the time the Sun formed and the present due to the dilution of the interstellar gas by deuterium-free matter released by evolved stars. According to the galactic evolutionary model of Truran and Cameron (1971) this decrease amounts to a factor of about 1.8, which allows us to predict a deuterium abundance for the protosolar gas of 2.5 × 10^{-5} in satisfactory agreement with the above results.

The deuterium abundance is of special interest since it is not produced in stellar nuclear processes nor (in significant quantities) by cosmic-ray spallation processes (see Reeves *et al.* 1973). Colgate (1973) has suggested that deuterium can be formed in abundance during supernova explosions, but this point of view has been strongly criticized by Reeves (1973). We infer that whatever deuterium we now see is a relic of a pregalactic phase of deuterium creation. If this phase of deuterium creation is identified with the big bang, then an estimate can be made of the present density of the Universe. Wagoner (1973) has calculated the results of element synthesis during the high-temperature phase of the big bang and (assuming zero leptonic number) gives the present density (when the temperature has fallen to 2.7° K) as a function of the mass fraction created of each element species. From the model of Truran and Cameron (1971) we find that the present mass fraction of deuterium is a factor 6.4 lower than it was at the end of the big bang. Thus the mass fraction of big-bang deuterium is 1.8×10^{-4}; and with Wagoner's results, we find a value of 1.5×10^{-31} g cm^{-3} for the present density of the Universe. Under the extreme assumption of no evolutionary deuterium depletion, the density would be 4.7×10^{-31} g cm^{-3}.

This value of the matter density does not conflict with the lower limit found by Shapiro (1971) of 5×10^{-32} g cm^{-3} (assuming a Hubble constant of 50 km s^{-1} Mpc^{-1}), but it falls a factor 27 short of the critical density for closing the Universe (4×10^{-30} g cm^{-3}).

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