LETTERS TO THE EDITOR

ASTROPHYSICS

A New Upper Limit to the Galactic Deuterium-to-Hydrogen Ratio

THE detection of the 21-cm. hydrogen line, in 1951, created interest in the possibility of detecting a similar deuterium line at a wave-length of 91·6 cm. By comparing the strengths of the two lines, the galactic deuterium-to-hydrogen ratio, N_D/N_H, could be determined. This quantity is of astrophysical interest because it will give information about the composition and nucleogenesis of the interstellar medium[1,2].

There have been four previous attempts to detect the deuterium line, and all have given negative results[3-6]. The most recent of these, at Jodrell Bank, set an upper limit on N_D/N_H of 1/4,000 in the direction of the Cassiopeia radio source; this value is slightly higher than the terrestrial abundance ratio of 1/6,700.

Our work has consisted of attempting to observe deuterium absorption in the Cassiopeia *A* radio source. The 85-ft. telescope of the National Radio Astronomy Observatory, at Green Bank, West Virginia, was used to track Cassiopeia *A* 12 hr. a day for 9 weeks. The receiving system has been described elsewhere[7]. It incorporates two techniques: (1) The autocorrelation function of the signal is determined digitally and Fourier-transformed by a computer to give the power spectrum. Use of this method gives high stability and permits multichannel operation (the spectrum is measured at many frequencies during the same time interval). (2) The effective observation time is quadrupled by using four switched receivers to monitor both polarizations all of the time. It was thus possible to have 76·5 days (6·6 × 10⁶ sec.) of effective observation time, even though the antenna was in use only 68 days.

The sensitivity of the autocorrelation system has been investigated theoretically[8], and also been checked by computer simulation. The root mean square deviation, ΔT, of the spectral measurement is given by:

$$\Delta T = \frac{2 \cdot 1}{\sqrt{Bt}} T_{tot}$$

where $B = 3 \cdot 75$ kc./s. is the frequency resolution of the measurement, $t = 6 \cdot 6 \times 10^6$ sec. is the observation time, and $T_{tot} = 2{,}000°$ is the total noise temperature referred to the receiver input. These values give $\Delta T = 0 \cdot 027°$.

The spectral dip, T_D, resulting from deuterium absorption, is given by:

$$T_D = \tau_D T_p$$

where $T_p = 0 \cdot 46\ T_{tot}$ is the contribution to the receiver input arising from the background source, Cassiopeia *A*, and τ_D is the deuterium optical depth in the angle subtended by the source.

The relation relating τ_D to N_D/N_H which we have calculated differs from those given previously by Shklovsky[9] and Adgie[10]. The peak optical depth of either gas[11] is given by:

$$\tau = \frac{hc^2}{8\pi k} \cdot \frac{A}{T_s f_0 \Delta f} \cdot \frac{g_1}{g_1 + g_0} \cdot N$$

where A is the spontaneous emission probability, T_s is the spin temperature, f_0 is the line frequency, Δf is the Doppler-broadened line-width, g_1 and g_0 are the statistical weights of the upper and lower states, and N is the total number of atoms per unit cross-section in the two states. Calculating the ratio of these quantities for deuterium and hydrogen gives:

$$\frac{\tau_D}{\tau_H} = 0 \cdot 33 \frac{N_D}{N_H}$$

The following assumptions have been made:

(1) The value $A_d = 4 \cdot 65 \times 10^{-17}$ sec.⁻¹ given by Field[12] is correct (this result has been computed independently by A. H. Barrett of this Laboratory), and the value $6 \cdot 6 \times 10^{-17}$ sec.⁻¹ given by Shklovsky is incorrect.

(2) The ratio of the Doppler-broadened line-widths $\Delta f_D/\Delta f_H$ would be equal to f_D/f_H if the atoms had the same root mean square velocities. However, approximately half the broadening is due to thermal motion in which the deuterium atoms, having twice the mass, would have $1/\sqrt{2}$ of the root mean square hydrogen velocity.

$$\text{Thus } \Delta f_D/\Delta f_H = [1/2 + 1/(2\sqrt{2})] f_D/f_H$$

(3) The spin temperatures for hydrogen and deuterium are assumed to be equal. Justification of this assumption is uncertain, since it depends on estimates of the intensity and detailed profile of the interstellar radiation field at the frequency of deuterium Lyman α-radiation[12].

The value of the peak hydrogen optical depth in the Cassiopeia *A* radio source is also the subject of some controversy, its large value being difficult to measure. The first observers, Hagen, Lilley and McClain[13], using a 50-ft. paraboloid, report $\tau_H = 2 \cdot 6$. Muller[14], using an 83-ft. reflector, gives 4·0, and observers at California Institute of Technology[15], using a single 90-ft. telescope, report $\tau_H > 4 \cdot 7$, and $3 \cdot 4 \pm 0 \cdot 4$ when using two 90-ft. telescopes as an interferometer. Accepting a value of peak hydrogen optical depth of 4, multiplying this by 0·8 to account for reduction because of the 3·75-kc./s. band-width, and assuming a detection criterion of twice the theoretical root mean square fluctuation, we obtain a minimum detectable N_D/N_H of 1/18,000.

Our results are illustrated in Fig. 1. Individual 10-hr. runs were examined for interference, corrected for any slope (typical slope correction, 0·03°/kc./s.), and averaged into 3-week lots. Examination of the 3-week averages indicates that the root mean square deviation is approximately 1·4 times the theoretical value, and thus the minimum detectable N_D/N_H should be raised to ~1/13,000. Our conclusion, then, is that the deuterium-to-hydrogen ratio in the region examined is, with probability 0·977, less than half the terrestrial value.

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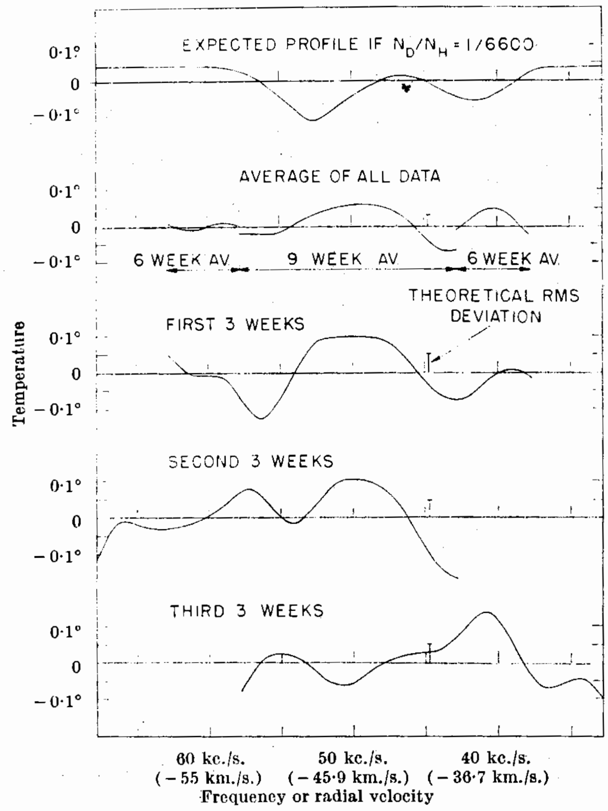

Fig. 1. Results of search for 327-mc./s. deuterium line absorption in the Cassiopeia *A* radio source

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GEOPHYSICS

Terrestrial Flow of Heat Near Flin Flon, Manitoba

Preliminary measurements of underground temperatures and thermal conductivity have been made in the Coronation Mine near Flin Flon, Manitoba. The work is part of a comprehensive geological–geophysical–geochemical investigation of the mine, made possible by the enlightened policies of the Hudson Bay Mining and Smelting Co., who has allowed free use of the mine, even when it interrupted production schedules.

Coronation is a copper sulphide orebody in basic volcanics and consists of two lenses, about 300 ft. long, which dip steeply southwards. The two lenses are separated by about 200 ft. of low-grade disseminated ore and extend 900–1,050 ft. below the surface. The mine is therefore a small one being about 300 ft. wide, 900 ft. long, and 1,050 ft. deep. The drift depths are in increments of 150 ft. from the surface down to 1,050 ft. with an exploratory drift at 1,350 ft.

There are numerous drill holes throughout the mine, but only those that were horizontal and open to at least 40 ft. from the drift wall were used. As the mine was less than 5 years old the distance of 40 ft. is well beyond the region of disturbance of temperature due to ventilation[1,2]; in some cases penetrations up to 180 ft. from the wall were made. Water was issuing from some of the holes, but in most of such cases it was possible to push the thermistor temperature sensing element beyond the point of entry of the water so that true rock temperatures could be obtained.

Not less than ten readings of temperature were obtained at each drift depth, and the average of these was taken as the temperature of a particular level. Between 550 and 600 ft. a small but significant change in gradient, which could not be correlated with a change in rock conductivity, was observed; the two gradients, together with their respective 95 per cent confidence limits, were 15·3 ± 0·8° C./km. to 600 ft. and 11·7 ± 1·2° C./km. from 600 to 1,350 ft.

The thermal conductivities (expressed in c.g.s. units) of rock samples varied from 0·0047 for an andesite to 0·0092 for a tremolite gneiss, showing extensive mineralization. The mean for the mineralized rocks is 0·008 and for unmineralized rocks is 0·006, the errors being such that use of the second figure is not warranted. Thus from 150 to 600 ft. the flow of heat lies between 0·9 and 1·2 μcal./sq. cm./sec. and from 600 to 1,350 ft. it lies between 0·7 and 0·9 μcal./sq. cm./sec.

Since the temperatures were measured in or near an ore body it is to be expected that the temperature gradient will be low and should be accompanied by a high thermal conductivity. For this reason the temperature gradients should be used with the higher value of conductivity given for the mineralized rocks, although without an extensive number of measurements it would be difficult to obtain an accurate mean value.

There are a number of factors which could have affected the value of flow of heat[3]; in this mine the most important is the probable occurrence of flows of water in the region particularly in the upper parts of the mine. The evidence for this, in addition to the flow of water from some of the drill holes, was provided by the tritium dates of two water samples which indicated that the water from the 1,050-ft. level was about 25 years older than that from the surface. Since