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Letter to the Editor

DI in the outer Galaxy

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Abstract. We report on a deep search with the Westerbork Synthesis Radio Telescope towards the galactic anticenter for the 327 MHz hyperfine transition of DI. This is a favorable direction for a search because: (i) the HI optical depth is high due to velocity crowding; (ii) the observed molecular column density is low (implying that most of the deuterium would probably be in atomic form, rather than in HD); and (iii) the stellar reprocessing should be minimal.

Our observations are about a factor of two more sensitive than previous searches for DI in this direction. We detect a low significance ($\sim 4\ \sigma$) feature, consistent in both amplitude and center frequency with an emission feature reported previously (Blitz & Heiles 1987). If this is the DI line, then the implied $N_{\rm D}/N_{\rm H}$ of $3.9 \pm 1.0 \times 10^{-5}$ is comparable to the inferred pre-solar deuterium abundance. Our observation is consistent with the recent low measurements of D/H towards high-redshift Lyman-limit systems. On the other hand, if the reports of high DI abundance ($\sim 24 \times 10^{-5}$) in such systems are confirmed, then our observations imply that even in regions of reduced star formation within the outer Galaxy, the DI abundance has been reduced by a factor of ~ 6 from the primordial abundance.

Key words: Cosmology: observations – ISM: abundances – Galaxy: abundances – Radio lines: ISM

1. Introduction

In the standard big bang model, the primordial abundance of deuterium is a sensitive function of the baryon to photon ratio, (e.g. Walker et al. 1991) making it a quantity of great cosmological interest. Further, since all known astrophysical processes (apart from the big bang itself, of course) result in a net destruction of deuterium, the currently observed value of the deuterium abundance is a strict lower limit to its primordial abundance.

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HST observations of the DI Lyman$-\alpha$ line in the local solar neighborhood (Linsky et al. 1993) yield a deuterium abundance of $N_{\rm D}/N_{\rm H} = 1.65^{+0.07}_{-0.18} \times 10^{-5}$. Conversion from this local current abundance to the primordial abundance depends on less well understood details of the history of the stellar reprocessing of matter in the local ISM. In order to circumvent this problem a number of groups have been attempting to measure the deuterium abundance in high-redshift Lyman-limit systems. Since these systems are less chemically evolved than the local ISM, conversion from the measured to the primordial abundance should be more straightforward. However, the results of these observations are conflicting, with different groups (Carswell et al. 1994, Songalia et al. 1994, Tytler et al. 1996) measuring abundances which differ by more than an order of magnitude. Part of the problem is that the DI Lyman$-\alpha$ line is separated from the HI Lyman$-\alpha$ line by only 82 km s^{-1}, making the chance of contamination of the DI line by absorption from a small parcel of HI at a slightly different velocity from that of the main Lyman-limit system non-negligible.

There have also been several attempts to observe the hyperfine transition of DI at radio frequencies. Since the frequency of this line is more than a factor of 4 lower than the frequency of the corresponding transition in HI, the question of HI contamination does not arise. Two kinds of lines-of-sight have been favored in the past, the first towards bright radio sources (Sgr A & Cas A; Weinreb 1962, Anantharamiah & Radhakrishnan 1979, Heiles et al. 1993), where the hydrogen column density is known to be high. The disadvantages of these lines of sight are that: (i) the bright radio sources contribute significantly to the system temperature, making detection more difficult; (ii) any measurement refers only to the thin pencil beam subtended by the absorber; and (iii) the molecular column density is also high, making it likely that most of the deuterium is in molecular rather than atomic form (Heiles et al. 1993). Anantharamiah & Radhakrishnan (1979) placed an upper limit of 5.8×10^{-5} on the DI abundance towards Sgr A. Heiles et al. (1993) reached similar limits towards Sgr A as well as Cas A.

The other promising direction for a search for the radio emission from DI is that towards the galactic anticenter, where one expects the line to be in emission. The advantages of this direction are that (i) the high optical depth of HI is due to velocity crowding along a long pathlength rather than a high volume density; (ii) the molecular column density and metallicity are low; and (iii) the observations are sensitive to the DI abundance within the entire telescope beam, and not just a narrow cone towards the background source as in the case of absorption observations.

The results of a long integration in the direction $(l, b) = (183^\circ\!.0, +0^\circ\!.5)$ using the Hat Creek telescope were presented by Blitz & Heiles (1987), who found an upper limit (2 σ) of 6.0×10^{-5} for $N_{\rm D}/N_{\rm H}$. Here we report on a long integration towards a partially overlapping line-of-sight, $(l, b) = (183^\circ\!.0, -0^\circ\!.5)$, with the Westerbork synthesis array. Using the 14 WSRT telescopes as independent single dishes allowed us to significantly increase the effective integration time.

2. Observations and data reduction

The observations were conducted at the WSRT during 29 sessions between 9 March and 14 May 1989, and used a special correlator configuration which provided 28 auto-correlations (14 telescopes $\times$ 2 polarizations) in addition to a number of cross-correlations between the different telescopes. The cross-correlation data were not used in the data analysis. The observations were done in a frequency switched mode, with the magnitude of the frequency throw equal to the total bandwidth of 0.156 MHz ($\sim$ 140 km s^{-1}). Each spectrum had 256 uniformly tapered channels. The ON spectrum was centered on $V_{\rm LSR}$ = 0 km s^{-1}. Either before or after each source observation (which typically lasted a few hours) a standard calibrator was observed in the same frequency switched mode for about an hour.

The data reduction was done in WASP (Chengalur 1996), a package suited to the automated reduction of large quantities of spectral data. For each observation, the data for each polarization of each telescope were reduced separately. Every 60 second ON spectrum was baselined using the corresponding OFF spectrum. Next the following flagging and baselining operations were done iteratively, until the the rms of the remaining unflagged data converged (which it typically did within 3 iterations). The rms over all channels and all time was computed, all points which exceeded 6 sigma were flagged. A linear baseline was then fit and subtracted from each spectrum (excluding these flagged points). Spectra whose rms (over channel numbers) exceeded 2.5 times the global rms were flagged, and finally channels whose rms (over time) exceeded 3 times the global rms were flagged. For all but the first iteration, the previously fit baseline was first added back to each spectrum. These criteria were selected after trial runs on a few sample observations and were tailored for efficient removal of narrow-band EMI and of spectra in which the EMI was strong enough to cause ringing effects. The data from telescopes 4, 5, 6 and 7 (which are the closest to the control building) showed a large amount of EMI, and are almost entirely flagged out. Finally, all the unflagged data were averaged together to produce one average spectrum per polarization per telescope per observation.

Since low-level intermittent EMI sometimes survived this flagging process, this average spectrum was inspected visually and telescopes with broad multi-channel EMI or with low-level ringing were flagged. All the remaining data were averaged together, separately for each polarization of each telescope. These processing steps were carried out separately for the source and the calibrator observations. A 4$^{\rm th}$ order polynomial baseline was then fit to the *calibrator* spectrum and then this *same* baseline was removed from the source observations (after allowing for a small scaling difference between the source and calibrator observation). The spectra from two telescopes (both polarizations of RTD and one polarization of RT3) showed substantial baseline structure even after this correction and were dropped from further processing. The spectra from the remaining telescopes were then averaged together and smoothed with a Gaussian smoothing function of 11.2 km s^{-1} FWHM. A few channels which still showed unresolved peaks, presumably due to EMI, were blanked before smoothing. Since the smoothing length was $\sim$ 20 channels, this had very little effect on the spectrum.

The final spectrum (excluding about 10% of the band on either edge for which the noise level is higher and the calibrator baseline is more poorly determined) is shown in Figure 1. The peak-to-peak variation is about 4 mK, approximately a factor of two smaller than that of the spectrum in Blitz & Heiles (1987). It is interesting to note that similar to Blitz & Heiles, there is a feature of low significance ($\sim$ 3 σ peak brightness) at the velocity $\sim$ 7 km s^{-1}. We have overlaid a Gaussian profile with peak brightness 2.4 mK and the same velocity centroid, +7 km s^{-1} and FWHM of 18.7 km s^{-1} as the HI emission feature in this direction. Excluding this possible feature, the noise level is 0.85 mK over 11.2 km s^{-1}, again about a factor of 2 lower than the 1.6 mK quoted in Blitz & Heiles 1987 (who also appear to have excluded the putative feature before computing the noise level). Including this feature in the calculation of the noise gives an rms of 1.06 mK, while the expected thermal noise is 0.8 mK.

3. Discussion

The galactic anticenter region, near $(l, b) = (183^\circ\!.0, 0^\circ)$, is particularly well-suited to a search for the DI hyperfine emission feature at λ92-cm. The HI emission brightness in this region peaks smoothly into a plateau extending spatially over several degrees with a brightness temperature 135$\pm$3 K, as can be seen in Burton (1985). Conditions should therefore be reasonably constant over the $2^\circ\!.5$ beam of the WSRT dishes. The extended region of line brightening is paired with a line narrowing due to velocity crowding. The HI emission-line profile from this region is relatively narrow, with a FWHM of 18.7 km s^{-1}. The line core is rather flat-topped, strongly suggesting a high line opacity. It also displays shallow self-absorption, indicating a

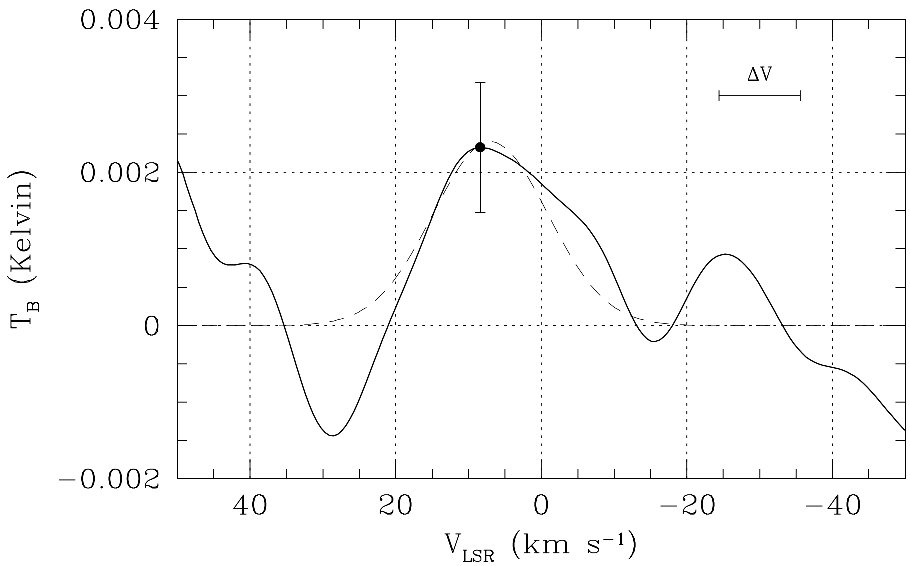

Fig. 1. Emission spectrum at the frequency of the DI λ92-cm hyperfine transition in the direction $(l, b) = (183^\circ\!.0, -0^\circ\!.5)$. The rms fluctuation level, excluding the possible feature near 7 km s^{-1}, is 0.85 mK and is consistent with the thermal noise. The velocity resolution, of 11.2 km s^{-1}, is indicated at the upper right. A Gaussian profile with peak amplitude 2.4 mK and the same velocity centroid, V_{LSR} = +7 km s^{-1} and FWHM of 18.7 km s^{-1} as the HI emission feature in this direction is overlaid.

modest amount of temperature substructure along the line-of-sight. Based on the depth of the self-absorption features and assuming a substantial line opacity, the spin temperature of the atomic gas appears to be in the range 125–135 K.

Direct measurements of the HI opacity along many lines of sight in this region have not yet been carried out. The typical sky density of moderately bright extragalactic background sources suitable for such a measurement suggests that a few tens of lines of sight could, in principle, be observed. The closest line of sight that has been observed in HI absorption (Dickey et al. 1983) is at $(l, b) = (189^\circ\!.6, -0^\circ\!.6)$. This is near the edge of the plateau in emission brightness, where the line profile is already somewhat broader than in the direction of maximum velocity crowding, with a FWHM of 23.4 km s^{-1}. The absorption profile extends smoothly over the entire velocity extent in which the emission profile exceeds a brightness of about 5–10 K, with a uniform high opacity of about 2 across the line core. This is consistent with the expectation for a gas distribution in which the column density is dominated by an approximately isothermal gas with kinetic temperature in the range 125–135 K. An absorption equivalent width, $\int \tau \, dV$ = 33.68 km s^{-1} is found. The very smooth nature of the HI emission suggests that it is plausible to expect a comparable equivalent width in the direction $(l, b) = (183^\circ\!.0, -0^\circ\!.5)$.

Assuming that the DI emission is either mixed with, or lies behind, most of the galactic continuum emission, (which has the substantial brightness of about 70 K at 92 cm wavelength) the equation of radiative transfer yields simply:

$$T_B = T_S(1 - e^{-\tau_D}) \qquad (1)$$

where T_B is the differential brightness temperature on and off the line, T_S is the spin temperature of the DI and τ_D is the optical depth of the DI. For $\tau_D << 1$ this yields $T_B = T_S\tau_D$, or $\int T_B \, dV = T_S \int \tau_D dV$ for an approximately isothermal gas. The line integral of the Gaussian overlaid on the possible feature in Figure 1 is $\int T_B \, dV = 0.048 \pm 0.012$ K km s^{-1}. Assuming that the spin temperature of the DI is the same as that of HI (i.e. 130 K), this corresponds to $\int \tau_D \, dV = 3.7 \pm 0.9 \times 10^{-4}$ km s^{-1}. Hence the estimate of the ratio of the optical depths is $\tau_D/\tau_H = 1.1 \pm 0.3 \times 10^{-5}$. The relationship between the ratio of the optical depths and the ratio of the column densities of DI and HI is (Anantharamiah & Radhakrishnan 1979) $\tau_D/\tau_H = 0.28 \, N_D/N_H$, hence the estimated abundance of DI is $3.9 \pm 1.0 \times 10^{-5}$. This is comparable to the inferred pre-solar abundance (Kunde et al. 1982, Courtin et al. 1984), and about a factor of 2 above the current DI abundance in the local solar neighborhood (Linsky et al. 1993).

As discussed in the introduction, the lack of detection of DI towards the inner Galaxy suggests that most of the DI has been converted into HD within molecular clouds (Heiles et al. 1993). Towards the outer Galaxy, however, the molecular column density is low along many sight lines. In fact, the survey by Dame et al. (1987) detected very little CO emission in the galactic plane between 180 and 185 degrees longitude except for a small concentration at -10 km s^{-1}. The high optical depth in HI seems to be due to velocity crowding in diffuse gas along a pathlength of several kpc, and does not appear to arise in a single physical entity like a giant molecular cloud. It seems plausible, therefore, that a large fraction of the deuterium in this direction is still in atomic form. Further, the metallicity gradient in the Galaxy suggests that the DI abundance in the outer Galaxy would be higher than the inner. Calculations by Prantzos (1996) show that the deuterium abundance gradient is in general steeper than (and of course opposite in sign to) the oxygen gradient (because of the late ejection of metal-poor but deuterium-free gas from low mass stars formed at early times). While the exact gradient is sensitive to the assumed infall model, the current DI abundance within diffuse atomic gas in the inner and outer Galaxy could well differ by a factor of two.

Another useful comparison to make is with the range of measured DI abundances, $2.3 - 24 \times 10^{-5}$, in high redshift Lyman limit systems (Carswell et al. 1994, Songalia et al. 1994, Tytler et al. 1996). If a high primordial abundance turns out to be correct, our results indicate that even in regions with reduced star formation, the current deuterium abundance is about a factor of 6 lower than primordial. In contrast, recent model calculations of astration of deuterium suggest that the abundance evolution is modest, with current abundance only a factor ~ 2 less than primordial (Galli et al. 1995). On the other hand, the low value of D/H measured by Tytler et al. (1996), $2.3 \pm 0.3 \times 10^{-5}$, is consistent with our own possible detection and the inferred presolar value. Direct imaging of DI emission in the outer regions of nearby galaxies may provide a very effective means of addressing this issue comprehensively, once the capability for achieving sub-mK sensitivity on arcmin scales becomes available with the next generation of radio telescopes. The Giant Meterwave Radio Telescope (GMRT) should already allow a robust detection of DI emission from the Galaxy within the next few years, while DI imaging of nearby external galaxies should become possible with construction of the Square Kilometer Array Interferometer (SKAI) early in the mext millenium.

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