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A SEARCH FOR LOCALIZED SOURCES OF NONCOSMOLOGICAL DEUTERIUM NEAR THE GALACTIC CENTER

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ABSTRACT

If deuterium is not primarily cosmological in origin but is rather produced in the Galaxy through some process related to stellar activity, a significant enhancement of the deuterium abundance would be expected near the Galactic center as predicted by some nucleosynthesis models. To test this hypothesis, we have used the high angular resolution (5'.6 × 3'.4) now available at the Very Large Array (VLA) at the 92 cm D I hyperfine transition to search for a possible localized concentration of atomic deuterium near the Galactic center over a velocity range of ±180 km s^{-1}, with a velocity resolution of 5.6 km s^{-1}. This search has yielded an upper limit for the deuterium column density N_D of $7.8 \times 10^{16} T_s$ cm^{-2}, where T_s is the spin temperature of the D I hyperfine lines. For the smaller velocity range ±30 km s^{-1}, we have used the previous limit on the deuterium optical depth in conjunction with the continuum distribution observed with the VLA to obtain a more sensitive upper limit of $N_D \leq 3.1 \times 10^{16} T_s$ cm^{-2}.

If deuterium is associated with the H I clouds to the Galactic center, we obtain an upper limit for the D/H ratio of 4.3×10^{-3} for the clouds at $V = 20$ km s^{-1} and 50 km s^{-1}. If a significant fraction of the deuterium exists in atomic form in molecular clouds as predicted by some chemical models, we obtain an upper limit for the D/H ratio of 1.2×10^{-7} for the $V = 20$ km s^{-1} molecular cloud near the Galactic center and 8.3×10^{-7} for the $V = 50$ km s^{-1} molecular cloud near the Galactic center. These limits impose constraints on any model requiring localized production of deuterium near the Galactic center. Our results are consistent with the model that the deuterium observed in the Galactic center and the interstellar medium is primarily cosmological in origin.

Subject headings: deuterium — galaxies: The Galaxy — galaxies: nuclei — interstellar: abundances — radio sources: lines

I. INTRODUCTION

The origin and abundance of deuterium and the other light elements—lithium, beryllium, and boron—have been actively studied since it was realized that these light elements are not produced during ordinary stellar nucleosynthesis (Burbidge, Burbidge, Fowler, and Hoyle 1957). The conditions suitable for the production and survival of deuterium are believed to have existed during the epoch of nucleosynthesis in the standard big-bang model (Wagoner, Fowler, and Hoyle 1967) or in particle-theory models of the early universe (Audouze 1987). The primordial abundance of deuterium is a sensitive constraint on nucleosynthesis in the standard big-bang cosmology and could also provide an estimate of the baryon density in the universe (Wagoner 1973; Yang *et al.* 1984), which might determine if the baryon density is sufficient to close the universe (see Boesgaard and Steigman 1985; Audouze 1986; Vainer and Shchekinov 1985 for reviews of deuterium and light element nucleosynthesis and Malaney and Fowler 1988 for a discussion of nonhomogeneous, nonstandard big-bang nucleosynthesis). However, the presence of any Galactic sources of deuterium would undermine the use of the measured D/H ratio to constrain big-bang nucleosynthesis models.

Interstellar atomic deuterium has been directly observed through the Lyman UV absorption lines toward nearby stars with the *Copernicus* satellite (Rogerson and York 1973) and by the *IUE* (Landsman *et al.* 1984). These observations show an unexpected scatter in the D/H ratio of over an order of magnitude about the average observed value of 1–2 × 10^{-5}. Quite apart from the observational uncertainties (Vidal-Madjar *et al.* 1986), the proper extrapolation of this ratio to the primordial abundance critically depends on the evaluation of local astration (Clayton 1984) or enrichment of deuterium over the Galactic lifetime.

If the observed interstellar D/H ratio of 10^{-5} to 10^{-6} includes contamination by deuterium production from Galactic processes rather than only deuterium formed in the early universe, the D/H ratio must be significantly larger at its source. The D/H ratio would be significantly reduced after its production as a result of astration and mixing.

Many possible mechanisms for galactic production of deuterium have been proposed. Such models include production in supernova-induced spallation reactions (Colgate 1975); by cosmic-ray–induced spallation reactions (Epstein 1977;

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Ozernoy and Chernomordik 1975); in supermassive stars (Hoyle and Fowler 1973); in accretion disks surrounding neutron stars or black holes (Vainer 1986); in stellar flares (Coleman and Worden 1976); or from the breakup of neutron stars resulting in the ejection of neutron-rich material that reacts with protons (Lattimer and Schramm 1974). To our knowledge, none of these models has received an observational test.

Ostriker and Tinsley (1975) suggested that if D production is associated with stellar activity, the abundance of deuterium should increase with decreasing radial distance from the Galactic center. On the other hand, if deuterium is only cosmological in origin, we should observe the opposite effect—a positive gradient, since deuterium is destroyed during stellar processing. A direct measurement of a possible gradient in the deuterium abundance has not been possible. Indirect evidence for a possible gradient in the deuterium abundance that comes from molecular line measurements (Penzias 1979) is uncertain because of chemical fractionation effects (Watson 1976; Dalgarno and Lepp 1985).

Audouze *et al.* (1976) have pointed out that the very presence of deuterium in the Galactic center, even in deuterated molecules, implies that deuterium must be continuously replenished in the highly processed Galactic center. They show that, when the high astration in this region is taken into account, the D/H ratio in the Galactic center should be 10^{-12} if D were primarily cosmological with no recent sources of deuterium. However, the D/H ratio in the Galactic center deduced from molecular line intensities (Penzias 1979) is at least six orders of magnitude higher than this expected value, suggesting the possible presence of localized sources of deuterium.

If the Galaxy had an initial burst of star formation, an active phase, or an increased star-formation rate in the Galactic center (Audouze *et al.* 1979), this would have increased the supernova rate in the Galactic center and enhanced any supernova-induced deuterium nucleosynthesis. For supernova shock-wave–induced spallation reactions, Epstein, Arnett, and Schramm (1974) estimate that $D/H = 4.3\epsilon^2 \times 10^{-5}$ with ϵ equal to the average energy per nucleon. For $\epsilon = 10$ MeV per nucleon, which is necessary to produce the interstellar abundances of Li, Be, and B via shock-wave–induced spallation reactions (Walker, Mathews, and Viola 1985), we obtain $D/H = 4.3 \times 10^{-3}$.

There is also evidence from gamma-ray observations (Wolfendale and Worrall 1977 combined with the *COS B* results analyzed by Bhat *et al.* 1985) and molecular-line observations (Gusten, Walmsley, and Pauls 1981) that the cosmic-ray flux is 100 times larger in the Galactic center as compared with the solar neighborhood. If correct, this higher flux would result in a corresponding increase in the cosmic-ray–induced deuterium nucleosynthesis.

If there is local production of deuterium near the Galactic center, it is reasonable to expect that there could be small-angular-diameter concentrations close to the Sgr A complex. The recent availability at the VLA of high angular resolution (5′.6 × 3′.4) at the frequency of the D I hyperfine line (327.384 MHz) now makes it possible to test the above hypothesis by searching for such a concentration of deuterium near the Galactic center. All previous "single-aperture" observations of the 92 cm line in this direction (Pasachoff and Cesarsky 1974; Anantharamaiah and Radhakrishnan 1979, referred to as AR79 hereafter) were made with coarse angular resolution (110′ circular beam and 120′ × 6′.4 beam, respectively) and were therefore not sensitive to localized sources of deuterium. Furthermore, because of the narrow bandwidth used in the previous observations, the clouds close to the Galactic center that appear at large nonzero velocities had not yet been observed.

Since this observation was completed, Boyd, Ferland, and Schramm (1989) have predicted an enhanced D/H ratio of 1×10^{-3} near the Galactic center based on a new model of galactic nucleosynthesis of light elements that involves photonuclear disintegration reactions (Boyd and Ferland 1987). They determined that a significant gradient in the D/H ratio exists toward the Galactic center. The observations presented here are useful in constraining such models.

II. OBSERVATIONS AND RESULTS

In the present observation, we searched for the D I hyperfine line from clouds close to the Galactic center that would appear in absorption against the strong Sgr A continuum source. Since we are searching for localized sources of deuterium, it might appear that this experiment would be best carried out with the highest angular resolution available with the VLA at 327 MHz. However, the sensitivity of an absorption-line experiment using a synthesis instrument such as the VLA increases directly as the unresolved continuum flux of the background source if the absorbing region completely covers the source, and if the continuum flux does not dominate the fluctuations at the output of the receivers. For the complex Galactic center region, the unresolved continuum flux is maximum in the compact D-configuration of the VLA. The central 5′ region near the Galactic center has a flux of about 200 Jy. Therefore, the D-configuration rather than the higher resolution A, B, or C-configurations is best suited for searching for a localized absorbing concentration of deuterium that extends over a few arcminutes and that would completely cover the background source.

Our observations were made in 1987 April in the D-configuration of the VLA with a synthesized beam of 5′.6 × 3′.4 (13 pc × 7.9 pc for a distance of 8 kpc between the Sun and the Galactic center), when 16 antennas were equipped with 327 MHz feeds and receivers. We used 64 channels in a single polarization covering a 390 kHz band centered at the 0 km s^{-1} LSR velocity of the D I hyperfine line. The range of velocities covered is ± 180 km s^{-1} with a velocity resolution of 5.6 km s^{-1}, which includes most of the H I clouds, molecular clouds, and ionized regions observed near the Galactic center. This velocity range is much larger than the velocity ranges used in all previous observations of deuterium toward the Galactic center. The total system temperature was ≈750 K when the antennas were pointed toward Sgr A.

The total duration of the observation was 8 hr. The flux scale was determined by observing 3C 286 and assuming its flux density at 327 MHz to be 26.9 Jy. The instrumental and ionospheric phase was determined by interspersed observations of the phase calibrator 1938 − 155. The frequency response of the instrument was determined by two 25 minute observations of the strong source Cyg A at the beginning and at the end of our observations. External interference was noticed in less than 2% of the total time. After removing stretches of time containing strong interference from the data, the total effective on-source integration is equivalent to 3.5 hr.

Figure 1 shows the deconvolved continuum map of the Galactic center region made by averaging the central three-quarters of the observed band, which has a peak continuum

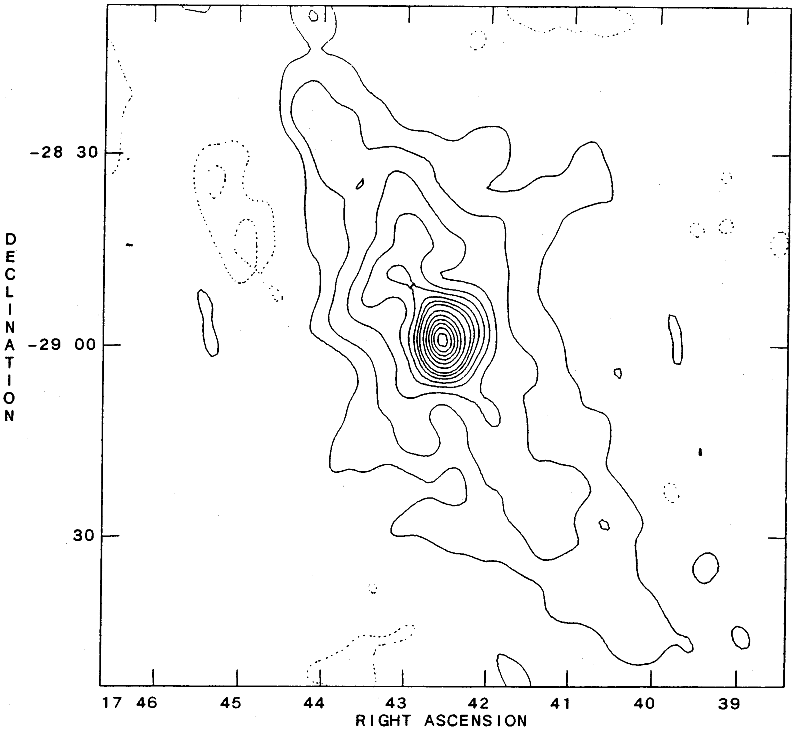

FIG. 1.—Continuum map of the Galactic center region at 327 MHz. The beam size is 5′.6 × 3′.4. The contour levels are −10, −6, −4, −2, 2, 4, 6, 10, 14, 20, 30, 40, 60, 80, 140, and 180 Jy per beam.

flux of 189 Jy per beam. A "dirty" continuum map made by averaging the outer 20 channels was subtracted from each "dirty" channel map to obtain 63 channel maps. We found no signal in either emission or absorption significantly above the noise level in any of the channel maps. The average rms noise in these maps is 115 mJy per beam, while the theoretically expected noise is 110 mJy per beam. Two of the channel maps, corresponding to velocities −67 km s^{-1} and +106 km s^{-1}, showed systematic artefacts caused by locally generated interference.

Figure 2 is the spectrum over the central one-beam area (5′.6 × 3′.4) normalized by the continuum flux measured for the same region obtained from Figure 1. The ordinate in Figure 2 is, therefore, approximately in units of optical depth. The rms noise in the spectrum is 7 × 10^{-4}. Since there are no features in this spectrum stronger than 3 σ, Figure 2 implies a 3 σ upper limit of 2.1 × 10^{-3} for the optical depth of deuterium over a region of 5′.6 × 3′.4 near the Galactic center.

III. COMPARISON WITH PREVIOUS OBSERVATIONS

Anantharamaiah and Radhakrishnan (1979) used an angular resolution of 120′ × 6′.4, 40 times larger in area than

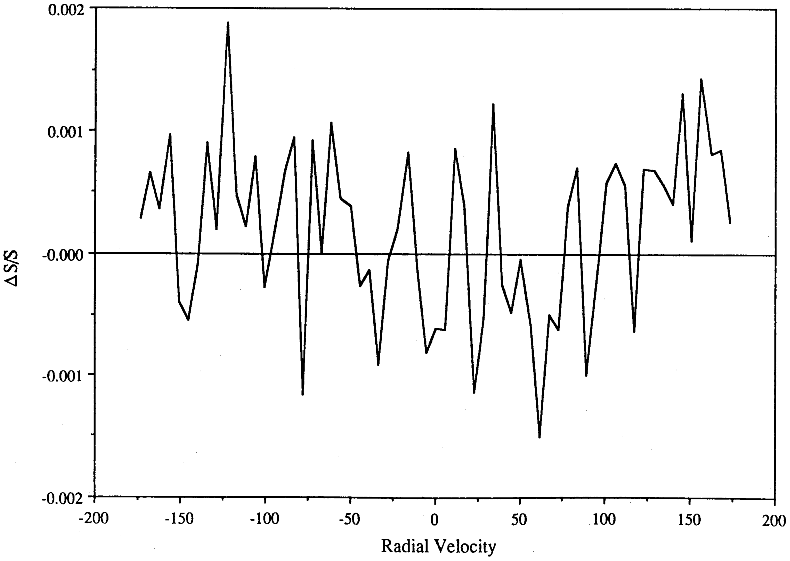

FIG. 2.—The deuterium spectrum over one beam area (5′.6 × 3′.4) centered on Sgr A. The ordinate is the flux in the line (obtained from channel maps) divided by the continuum flux obtained from Fig. 1.

our beam size, covered a velocity range of ± 30 km s^{-1}, and used an integration time of 84 hr to obtain a 3 σ limit of $\tau_{\rm DI} < 2.8 \times 10^{-4}$. In order to compare such values with our upper limit, we must analyze the continuum distribution within the beam used by AR79.

The total continuum flux within the beam of the Ooty radio telescope used by AR79 is $S = 2kT_B\Omega_b/\lambda^2$, where Ω_b is the beam solid angle and T_B is the beam-averaged brightness temperature. Using $T_B = 2300$ K as measured by Anantharamaiah and Bhattacharya (1986), we obtain $S = 564$ Jy, for a beam of $120' \times 6'.4$. From Figure 1, the central $5'.6 \times 3'.4$ area within this beam would have contributed a flux of 189 Jy. Therefore, for a deuterium-absorbing region having an angular size of $5'.6 \times 3'.4$, the results of AR79 would imply a 3 σ upper limit for $\tau_{\rm DI}$ of $2.8 \times 10^{-4}[564/189] = 8.3 \times 10^{-4}$. The equivalent upper limit of AR79 is, therefore, a factor of 2.5 times better than the limit obtained here using the VLA alone. However, it should be noted that it was possible to obtain this equivalent limit only because the detailed continuum distribution is available from the present observations (Fig. 1). Further, the above limit of AR79 applies only to deuterium in the velocity range ± 30 km s^{-1}.

Although our upper limit ($\tau_{\rm DI} \leq 2.1 \times 10^{-3}$) is a factor of 2.5 times larger than the equivalent upper limit of AR79 (8.3×10^{-4}), the VLA observations had an integration time of only 3.5 hr, a factor of 24 smaller than the 84 hr used by AR79. This difference is a consequence of the better angular resolution of the VLA, which is more suitable for detecting deuterium from localized regions. In the case of the Galactic center, this advantage is somewhat offset because of the strongly peaked continuum source in this region.

IV. DISCUSSION

Our observations provide an upper limit for the amount of deuterium present in a small region ($5'.6 \times 3'.4$) in front of the Galactic center and impose constraints on any model requiring local production of deuterium near the Galactic center (see § I).

For an optically thin deuterium hyperfine line, the peak optical depth is related to the column density by (Weinreb 1962)

$$N_D/T_s = 6.66 \times 10^{18}\tau_{\rm DI}(\Delta V \Delta V_0)^{1/2} \ {\rm cm^{-2}\ K^{-1}}\ ,$$

where ΔV is the full width at half-maximum of the line in km s^{-1}, ΔV_0 is velocity resolution, and T_s is the spin temperature of the deuterium hyperfine levels. The line profile is assumed to be Gaussian. From Figure 2, our 3 σ upper limit for τ is 2.1×10^{-3}. If the width of the deuterium line is equal to our velocity resolution of 5.6 km s^{-1}, then we obtain

$$N_D/T_s \leq 7.8 \times 10^{16}\ {\rm cm^{-2}\ K^{-1}}$$

for deuterium in the velocity range ± 180 km s^{-1}. For a smaller velocity range of ± 30 km s^{-1}, the revised upper limit of AR79 ($\tau_{\rm D} \leq 8.3 \times 10^{-4}$) derived above implies

$$N_D/T_s \leq 3.1 \times 10^{16}\ {\rm cm^{-2}\ K^{-1}}\ .$$

The above limits can be used in conjunction with the measured column density of atomic or molecular hydrogen to obtain limits for the D/H ratio in H I and molecular clouds, respectively.

a) Primordial Deuterium

The D/H ratio in the $V = 0$ km s^{-1} H I clouds present along the line of sight to the Galactic center essentially represents the primordial or early Galactic deuterium abundance reduced by astration and mixing, assuming that no subsequent Galactic nucleosynthesis of inflow primordial material occurred in these clouds since the early Galaxy. If the Galaxy had an early active phase that resulted in a D/H of 10^{-4} (Ozernoy 1987), cloud fragmentation may have resulted in some H I clouds being enhanced in D. The strong H I absorption feature ($\tau = 4.66$) observed at a velocity of 0 km s^{-1} (Schwarz, Ekers, and Goss 1982) had a FWHM of 12.7 km s^{-1} and a derived ratio of column density to spin temperature of 1.1×10^{20} cm^{-2} K^{-1}. This feature is due to the H I clouds present along the line of sight to the Galactic center. Our observations therefore imply an upper limit for the mean D/H in these clouds of D/H $\leq 1.1 \times 10^{-3}$.

This limit can be compared with the previous best upper limit of 5.6×10^{-5} obtained with a single aperture (AR79). To obtain a similar limit would require more than two orders of magnitude increase in observing time. Clearly, for this experiment, the use of a synthesis array like the VLA cannot provide an advantage over a single dish if deuterium is primarily cosmological and is associated with the H I present along the line of sight to the Galactic center. The limitations occur for two reasons: First, the optical depth of the zero-velocity 21 cm H I absorption toward the Galactic center is large and does not vary appreciably over a large region (Schwarz, Ekers, and Goss 1982) so that any increase in angular resolution provided by synthesis arrays has no effect on the measured apparent optical depth. Second, when we consider the total collecting area of the VLA, the continuum flux of the central source (≈ 189 Jy for our beam) dominates the on-source noise fluctuations. Therefore, any increase in the collecting area by increasing the number of antennas, or any increase in the continuum brightness by going to a more compact array, has no effect on the signal-to-noise ratio (Anantharamaiah *et al.* 1988). The VLA has an advantage over single dishes only if deuterium occurs on small angular scales, as would be expected from recent Galactic nucleosynthesis of deuterium.

b) Deuterium in H I *clouds near the Galactic Center*

The average column density of H I clouds close to the Galactic center, as indicated by the nonzero velocity features in the H I absorption spectrum, is a factor of 3–60 less than that of the zero-velocity feature when averaged over a $3' \times 8'$ beam (Schwarz, Ekers, and Goss 1982; see also Radhakrishnan and Sarma 1980). From the average H I profile over Sgr A (Fig. 3 of Schwarz, Ekers, and Goss 1982), we estimate for the 50 km s^{-1} cloud that $N_{\rm H}/T_s \approx 3.9 \times 10^{19}$ cm^{-2} K^{-1} with a line width $\Delta V \approx 26$ km s^{-1} and for the 20 km s^{-1} cloud $N_{\rm H}/T_s \approx 0.83 \times 10^{19}$ cm^{-2} K^{-1} with $\Delta V \approx 7.5$ km s^{-1}. Using these values, we obtain for the 50 km s^{-1} H I cloud D/H $\leq 4.3 \times 10^{-3}$ and for the 20 km s^{-1} cloud, D/H $\leq 1.1 \times 10^{-2}$ from our data and D/H $\leq 4.3 \times 10^{-3}$ from AR79 data. The upper limits for the D/H ratio in these clouds and in the -50 km s^{-1} (3 kpc arm) cloud are summarized in Table 1. For the -50 km s^{-1} cloud, our estimated $N_{\rm H}/T_s$ and ΔV, from Figure 3 of Schwarz, Ekers, and Goss (1982), are $\approx 1.9 \times 10^{19}$ cm^{-2} K^{-1} and 7.5 km s^{-1}, respectively, resulting in D/H $\leq 4.8 \times 10^{-3}$.

c) Deuterium in Molecular Clouds near the Galactic Center

If deuterium is produced by a process related to stellar activity, it may be associated with the molecular clouds, where most of the current star formation occurs. It is, therefore, interesting to determine a limit for the D/H ratio in the molecular clouds near the Galactic center.

TABLE 1

UPPER LIMITS FOR THE D/H RATIO IN H I AND H_2 CLOUDS

Type of Cloud	D/H (VLA)	D/H (VLA + AR79)
H I Clouds		
$V = 0$ km s^{-1} clouds	$\leq 1.1 \times 10^{-3}$	$\leq 4.4 \times 10^{-4}$
$V = 20$ km s^{-1} cloud	$\leq 1.1 \times 10^{-2}$	$\leq 4.3 \times 10^{-3}$
$V = 50$ km s^{-1} cloud	$\leq 4.3 \times 10^{-3}$	
$V = -50$ km s^{-1} cloud	$\leq 4.8 \times 10^{-3}$	
H_2 Clouds:		
$V = 20$ km s^{-1} cloud	$\leq 2.9 \times 10^{-7}$	$\leq 1.2 \times 10^{-7}$
$V = 50$ km s^{-1} clouds	$\leq 8.3 \times 10^{-7}$	

The two largest molecular clouds in Sgr A are the "20 km s^{-1} cloud" (M-0.13-0.08) and the 40–60 km s^{-1} cloud (the "50 km s^{-1} cloud," M-0.02-0.07) (Brown and Liszt 1984; Armstrong and Barrett 1985). Güsten and Henkel (1983) obtain H_2 column densities for these clouds of 2×10^{25} and 7×10^{24}, respectively. These estimates of column density of H_2 are somewhat uncertain because of the assumptions made in converting from column densities of observed molecules to that of H_2 (Williams 1985). Nevertheless, we use the above values and estimate the ratio of atomic deuterium to total hydrogen atoms in these clouds using $D/H \approx N(D)/2N(H_2)$. The molecular line widths are ≈ 25 km s^{-1} and the gas temperatures are estimated to be ≈ 70 K (Güsten and Henkel 1983). Using these values and our upper limit for N_D, we obtain for the 50 km s^{-1} molecular cloud $D/H \leq 8.3 \times 10^{-7}$. For the 20 km s^{-1} cloud, we obtain $D/H \leq 10^{-7}$ from our data and 1.2×10^{-7} including the data of AR79. These values are significantly lower than the solar-neighborhood interstellar D/H of $\approx 10^{-5}$ (Rogerson and York 1973) and the Galactic center D/H of $\approx 10^{-6}$ inferred from the DCN/HCN ratio (Penzias 1979). The upper limits for the D/H ratio in the Galactic center molecular clouds are summarized in Table 1 along with the D/H limits for the H I clouds.

The upper limits for the D/H ratio in the Galactic center molecular clouds are meaningful only if deuterium is present in atomic form in these clouds. A significant fraction of atomic deuterium may exist in interstellar clouds, as indicated by models of deuterium fractionation and chemistry (Dalgarno and Lepp 1984). This possibility results from the larger sensitivity of HD to photodissociation as compared with H_2 (Brusten *et al.* 1982) and also from the longer time scale for HD formation as compared to its destruction in the higher density molecular clouds (Tielens 1983). If the cosmic-ray ionization rate is sufficiently enhanced in the Galactic center (Wolfendale and Worrall 1977; Gusten, Walmsley, and Pauls 1981), most of the deuterium would also be atomic rather than in molecular form.

If only 1% of the deuterium is atomic, our upper limits would be increased by a factor of 100. This increased upper limit would still limit localized D nucleosynthesis within molecular clouds. If a significant fraction of the deuterium is atomic in dense molecular clouds, our results indicate that there is probably no localized deuterium nucleosynthesis within the Galactic center molecular clouds. Therefore, the deuterium observed in the Galactic center and the interstellar medium is probably cosmological in origin.

V. CONCLUSIONS

We have observationally addressed the question of possible localized galactic production of deuterium. If deuterium is produced in the Galaxy through some process related to stellar activity, an enhancement of deuterium abundance would be expected near the Galactic center as predicted by some nucleosynthesis models. Using the high angular resolution now available at the VLA near the D I hyperfine line (327.384 MHz), we have searched for a localized source of deuterium near the Galactic center. The search has yielded a 3 σ upper limit for the deuterium optical depth of 2.1×10^{-3} over a region of $5\rlap{.}'6 \times 3\rlap{.}'4$ near the Galactic center. This result implies an upper limit for the deuterium column density of $7.8 \times 10^{16} T_s$ cm^{-2}, where T_s is the spin temperature of the hyperfine states. The above limit applies to deuterium occurring over a velocity range of ± 180 km s^{-1}. For a smaller velocity range (± 30 km s^{-1}), the previous single-aperture result of AR79 implies $N_D \leq 3.1 \times 10^{16} T_s$ cm^{-2}. This limit will impose constraints on any model requiring local production of deuterium near the Galactic center.

Although this observation was not designed to measure the primordial deuterium abundance, we can nonetheless assess the limits these observations provide. If deuterium is primarily primordial and is associated with neutral hydrogen, we obtain an upper limit for the D/H ratio of 1.1×10^{-3}, or 4.4×10^{-4} when combined with AR79. Clearly, our observations are not sensitive to primordial deuterium and it would require more than two orders of magnitude larger integration over the present 3.5 hr in order to obtain limits comparable to the previous best single-aperture results, e.g., AR79 and Pasachoff and Cesarsky (1974) for the Galactic center and Blitz and Heiles (1987) for the anticenter.

For H I clouds near the Galactic center, we obtain upper limits for the D/H ratio of $\approx 4.3 \times 10^{-3}$. If deuterium exists primarily in atomic form in Galactic center molecular clouds, our results indicate an upper limit for the D/H ratio in the Sgr A molecular clouds of $1.1\text{–}8.3 \times 10^{-7}$.

Our observations are a first attempt to test theoretical models that propose possible noncosmological nucleosynthesis of deuterium. Our results are consistent with the model that the deuterium observed in the Galactic center and the interstellar medium is primarily cosmological in origin.

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