THE DEUTERIUM ABUNDANCE IN THE GALACTIC CENTER 50 km s^{-1} MOLECULAR CLOUD: EVIDENCE FOR A COSMOLOGICAL ORIGIN OF D

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ABSTRACT

We confirm that deuterium exists in the Galactic Center (GC) and estimate that D/H = 3×10^{-6}, which is the lowest D/H ratio observed anywhere in the Galaxy and five times lower than the local ISM D/H = 1.5×10^{-5}. We used the NRAO 12m telescope and obtained $T_R^* = 0.061\pm 0.007$ K and 0.04 ± 0.02 K for the J= 1-0 and 2-1 lines of DCN at 72.414 GHz and 144.828 GHz respectively in the core of the Sgr A 50 km/s molecular cloud (M-0.02-0.07) located 10 pc from the GC. We combined a new 5192-chemical reaction model of deuteration containing 163 deuterated species with our observed $DCN/HC^{15}N = 0.36$ and $DCN/HCN = 4.0 \times10^{-4}$ (determined from the GC $^{14}N/^{15}N= 900$) to estimate D/H. We also detected DCN in four additional positions and the J=1-0 lines of $H^{15}CN$, $HC^{13}N$, HCN, DCO^+, and HNC. Our results demonstrate that D exists in the Galactic Center and are the lowest $DCN/HC^{15}N$ and DCN/HCN ratios observed in any Galactic molecular cloud.

If D were produced via any stellar or Galactic nucleosynthesis, then its abundance would be a maximum value in the GC, while chemical evolution models with no additional sources of D predict D/H = 10^{-12}. Because D exists in the GC with a relatively low D/H = 3×10^{-6}, there are no significant Galactic sources of D and the γ-ray and cosmic-ray luminosities are $L_\gamma < 10^{42}$ erg/s and $Lp < 10^{43}$ erg/s for 10^9 years. There has not been recent quasar or AGN activity in the GC for any period longer than 10^9 years. The most likely source of the GC deuterium is continuous injection probably from the infall of primordial matter with D/H $\cong$ (5-10) x 10^{-5}. The current GC D/H is determined by the subsequent astration and mixing. If the primordial D/H = 8×10^{-5}, then standard big-bang nucleosynthesis models imply that the baryon density is less than the density necessary to close the Universe; most of the baryons are in dark matter; and there are fewer than four neutrino families.

Subject headings: Galaxy: center-deuterium- interstellar molecules-ISM: abundances-Galaxy: evolution

1. INTRODUCTION

The origin of deuterium has been extensively studied because it is not produced via stellar nucleosynthesis (Burbidge, Burbidge, Fowler, and Hoyle 1957); and any non-cosmological deuterium would be a signature of high-energy astrophysical processes and a probe for analyzing, cosmic-ray physics, Galactic chemical evolution, and interstellar chemistry (with deuterated molecules). Deuterium can be produced by p(p,e^+n)D, p(n,γ)D or spallation reactions whereby nuclei heavier than D (primarily He, C, N, or O) are shattered by collisions with protons, α-particles, or γ-rays. Because D produced is easily destroyed by reactions with protons, neutrons, or deuterons, D can survive only if formed in a region of rapid expansion and cooling (big-bang or explosive nucleosynthesis) or in cool rarefied matter such as the ISM.

The D/H ratio is an important prediction of standard and non-homogeneous big-bang models (Schramm and Turner, 1998) because the abundance of D depends critically on the temperature and baryonic density during the epoch of nucleosynthesis (first 1000 seconds) and might determine if the density is sufficient to close the universe. Because D is destroyed by reactions with p, D, n, or ^{3}He, a smaller D abundance implies a larger baryon density and hence a closed Universe. Conversely, a larger D abundance implies a smaller baryon density and an open Universe (Copi, Schramn, and Turner 1995a). Thus any Galactic source of deuterium would undermine its use to estimate the baryonic density of the universe and place constraints on big-bang nucleosynthesis models. Alternatively, in homogeneous inflationary or other flat models, the D/H ratio gives the amount of dark matter.

Recent observations of Lyman D lines in QSO absorption spectra are controversial and inconsistent because the detection of the D lines requires high S/N, modeling many weak features, and accurate measurements of the H column density (Timmes *et al.* 1997). Furthermore, if an HI cloud is at the radial velocity of the spectral shift of D (-82 km/s), then it will mimic the Lyman D lines. D/H values between (2 - 57) x 10^{-5} have been reported for both low and high z quasars (Tytler *et al.* 1999; Songaila, Wampler, and Cowie, 1997; Wampler *et al.* 1996, Burles and Tytler 1998; Carswell *et al.* 1994). Thus the determination of any Galactic D abundance will provide important information that will help constrain the cosmological abundance of deuterium.

The local interstellar D/H = 1.5×10^{-5} (Linsky 1998) has been determined from HST observations of the D Lyman absorption spectra (in the wing of the H Lyman lines) towards bright stars up to 12 pc from the Sun. This value is consistent with the average Copernicus and IUE measurements of D/H= 1.5×10^{-5} for stars within 1 kpc of the Sun (McCullough 1992). Astration models predict that the early Galactic abundance of D (presumably primordial) is 8×10^{-5} (Vangioni-Flam, Olive, and Prantzos 1994) in the disk but do not apply to the GC.

Because D is completely destroyed in stellar interiors via $D(p,\gamma)^3He$ (a small amount of D may exist in the outer layer of massive stars earlier than B4), each generation of stars replenishes the interstellar medium with material deficient in D. Therefore, the abundance of D will decrease with time unless there are any additional sources of deuterium. Different Galactic D nucleosynthesis models have included supernovae, supernovae shock-waves, cosmic-ray spallation reactions, accretion disks around neutron stars or black holes, γ-ray protofission or photospallation reactions, stellar flares, and a large proton flux during an early active phase of the Galaxy as possible sources for deuterium.

The Galactic Center is the most active and heavily processed region of the Galaxy and it contains evidence of jets, bursts, winds, infalling matter, X-ray and gamma-ray sources, arcs, filaments, recent star formation, nucleosynthesis of ^{26}Al, H II regions, supernova remnants, high velocity clouds, and a supermassive object at its core (Genzel, Hollenbach, and Townes, 1994). Bursts of star formation in the Galactic Center within the past 10^7 years are inferred from the abundance of He I in Wolf-Rayet stars (Tamblyn et al. 1995), the detection of water masers (Yusef-Zadeh and Mehringer 1995), and the detection of shocked H_2 (Pak, Jaffe, and McKeller 1996) and SiO. However, with the higher metallicity, star formation rate, and steeper initial mass function (Morris 1993) in the GC, the astration rate in the GC should be considerably larger resulting in a reduced D abundance. Therefore, if D is produced by any stellar or Galactic process, then it should be more abundant in the Galactic Center and there should be a corresponding gradient in the D abundance (Ostriker and Tinsley 1975; Pasachoff and Vidal-Madjar 1989). Chemical models of the Galactic bulge (Matteucci et al. 1999) predict the total astration of deuterium (D/H = 0). The Galactic center D/H is thus determined by a combination of primordial and Galactic deuterium reduced by astration and mixing (Galli *et al.* 1995).

The Sgr A molecular clouds are the appropriate molecular clouds in which to search for D because they are 10 pc from the Galactic Center (Genzel *et al.* 1990) and are clearly related to the GC activity. Although DCN has been detected and DCN/HCN has been estimated several times for the Sgr B2 molecular cloud, the Sgr B2 cloud is 450 pc from the GC (Turner and Zuckerman 1977, Turner 1989; Penzias *et al.* 1977; Penzias 1979; Jacq *et al.* 1999). There is one reported marginal

1σ detection of D from the J = 1-0 line of DCN in the 50 km/s Sgr A molecular cloud core (Penzias 1979) with $T_a^* = 0.02 \pm 0.015$ K.

The purpose of our project is to provide a statistically significant detection of deuterium in the Galactic Center by observing DCN and estimating D/H from the DCN/HCN abundance. Although the complicated astrochemistry of D limits an accurate determination of D/H, we used DCN to trace D/H because DCN is observed in higher temperature cloud cores (50 K < T < 200 K) and the column densities of DCN and $H^{15}CN$ can be estimated from their optically thin rotational spectral lines. From measurements of $^{14}N/^{15}N$ the HCN column density and hence the DCN/HCN abundance can be determined. In §2 we present our observations, in §3 we present our results, in §4 we estimate the Galactic center D/H ratio, in §5 we the discuss the implications of our results on Galactic chemical evolution and use of the D abundance to constrain cosmological models, and in Appendix A we describe our new deuterium astrochemistry model.

2. OBSERVATIONS

We used the NRAO 12-m telescope during May 16-18, 1993, and June 29, 1993, to observe the 50 km/s Sgr A Galactic Center molecular cloud (M-0.02-0.07). We observed the DCN J=1–0 and J=2–1 lines at 72.404 GHz and 144.83 GHz in total-power mode using position switching with the 3-mm and 2-mm SIS receivers. We also observed the J=1–0 lines of DNC, $HC^{15}N$, $H^{13}CN$, HCN, and HNC at 76.3 GHz, 86.06 GHz, 86.34 GHz, 88.63 GHz, and 90.66 GHz respectively. We used 1-MHz filters with a 256 MHz bandwidth in parallel and obtained 4.14 km/s resolution with an 86 arcsec beam at 72 GHz and 2.07 km/s resolution with a 43 arcsec beam at 144 GHz. Pointing was checked using Jupiter and Uranus. The double sideband system temperature was 350 K at 72 GHz and 400 K at 144 GHz.

The two largest Galactic Center molecular clouds are the 50 km/s cloud (M-0.02-0.07) and the 20 km/s cloud (M-0.13-0.08). In this initial investigation we observed the 50 km/s cloud at the position of the peak CS J= 7-6 and J=5-4 emission (Serabyn, Lacy, and Achtermann 1992). This position (α=17^{h}42^{m}42^s δ= $-28^o58'00''$) insured that we were observing the densest part of this cloud (n=10^6 cm^{-3}) and were also within the 2' beam size of the 7-m Bell Laboratories telescope used by Penzias (1979).

3. RESULTS

We analyzed the data using the NRAO UNIPOPS data analysis program. We detected both the J= 1-0 and J= 2-1 lines of DCN and obtained T_R^* = 0.061±0.007 K and T_R^* = 0.042 K±0.02 K, respectively, where T_R^* is the source antenna temperature corrected for atmospheric attenuation and all telescope losses (ohmic and spillover) except for coupling of the source and beam. These results can be converted into antenna temperature (T_a^*) or brightness temperature (T_b) using $T_a^* = T_R^* \eta_{fss}$ and $T_b = T_R^*/\eta_{M*}$ (Kutner and Ulrich 1981), where the forward scattering and spillover efficiency η_{fss} = 0.68 and the corrected main-beam efficiency η_{M*} = 0.73 at 72 GHz and η_{M*} = 0.76 at 145 GHz.

We confirmed our results with simultaneous observations using the hybrid-correlator spectrometer. As an additional check we observed the Sgr B2 molecular cloud where we also detected the J = 2–1 and 1–0 lines of DCN at the (OH) position ($\alpha = 17^h 44^m 11^s$ $\delta = -28^o 22' 30''$). In Sgr B2 the DCN 1-0 line is blended with the H_2CO 5(1,4)-5(1,5) transition. Our results for DCN are shown in figure 1.

The results of our unambiguous detection of DCN in the Galactic Center are *prima facie* evidence for the existence of Galactic Center deuterium. Furthermore, we also mapped the distribution of DCN at five additional positions offset by one arcmin from our center position and one point offset by two arcmin south of our center position. We detected DCN in four of the five offset positions. The center position had the strongest DCN emission and the extended emission is similar to that observed in HCN (Fukui *et al.* 1977; Lee 1996) and other molecules (Armstrong and Barrett 1985). Our results are shown in figure 2.

We also detected the J = 1-0 lines of $HC^{15}N$, $H^{13}CN$, HCN, HCO^+ and HNC; the J = 8-7 and J = 10-9 lines of $HC^{13}CCN$; and the (7,7) – (6,6) line of C_2S. We obtained an upper limit for the J = 1-0 line of DNC of $T_R^* \leq 0.02$ K. These spectra are shown in figure 3 and the results of our observations. Tables 1, 2, and 3 list the source, molecule, molecular transition, rest frequency and peak line intensity T_R^* for all the lines identified in our spectra and list U with the frequency for lines we did not identify. We used the Turner (1989) Sgr B2 survey and the Lovas (1992) tables of rest frequencies to identify the lines. The lines were well fit by Gaussian profiles. For broad lines not fit by a Gaussian we integrated over frequency while for overlapping lines we used several Gaussians to fit the lines. We were unable to resolve the hyperfine splitting (with intensity ratios of 1:5:3) for the DCN, HCN, $H^{13}CN$, and $HC^{15}N$ lines because of our use of 1 MHz filters and the large line widths of about 30 km/s.

Because the HCN J=1–0 line is optically thick, we used the optically thin J=1-0 line of $HC^{15}N$ to estimate DCN/ $HC^{15}N$. Following the analysis of DCN/HCN in hot cores by Hatchell, Millar and Rodgers (1998), DCN/HCN = $[T_{DCN}(\Delta V)/T_{HC^{15}N}(\Delta V)](^{15}N/^{14}N)\ e^{(\Delta E/\ kT_{ex})}$, where ΔE is difference between the energies of DCN and $HC^{15}N$ transitions, T_{ex} = 75 K, and sources are extended relative to our beam for the J = 1-0 lines. We obtain DCN/$HC^{15}N$ = 0.36 and DCN/HCN = 4.0×10^{-4} using $(^{15}N/^{14}N)$ = 900 (Güsten and Ungerechts 1985) for the 50 km/s cloud. In all molecular clouds outside the GC, DCN/$HC^{15}N$ > 1. These are the smallest DCN/$HC^{15}N$ and DCN/HCN ratios observed in any Galactic molecular cloud. A short summary of our results (including the 1-0 spectra) were included a review of observational constraints on light element nucleosynthesis (Lubowich 1997).

Assuming that the DCN rotational energy levels are in LTE so that the level populations are determined by the Boltzmann equation, the lines are optically thin ($\tau < 1$), $h\nu < kT_{ex}$, and $T_{ex} = T_k$, Magnum, Plambeck, and Wootten (1991) estimate the column density $N(DCN) = 1.47 \times 10^{11} T_k \exp(3.48/T_k) \int T_b dV$ cm^{-2}. For $T_k = 75$ K we obtain $N(DCN) = 2.3 \times 10^{13}$ cm^{-2}. Although the DCN and $H^{15}CN$ lines are probably optically thin, our DCN/HCN ratio is less sensitive to deviations from LTE provided that both the DCN and $H^{15}CN$ lines have similar deviations from LTE.

4. GALACTIC CENTER D/H RATIO

In this section we estimate the Galactic center D/H by comparing our results with other hot core DCN/HCN ratios and to an improved deuterium chemistry model. Chemical fractionation resulting from the lower zero-point energy for deuterated molecules due to the larger mass of the deuterated species always increases the abundance of the deuterated species. Thus the deuterated fractionation abundance ratios, $R(XD) = n(XD)/n(XH) \gg D/H$ so that $R(XD) = f_{XD}\,(D/H)$ where the degree of fractionation $f_{XD} = 10^2 - 10^5$ depending on the molecule, chemistry, and physical parameters.

In the two hot cores within 1 kpc of the Sun at $T_k = 75$ K, the average DCN/HCN $= 1.8 \times 10^{-3}$ (Hatchell, Millar, and Rodgers 1998). We make the simple assumption that D/H scales with the DCN/HCN ratio and that local molecular clouds and the GC 50 km/s molecular cloud have similar values of fractionation for similar physical conditions ($T_k = 75$ K; $n = 10^6$ cm^{-3}). If D/H in the local hot cores is the same as in the local ISM where D/H = 1.5×10^{-5}, then D/H = 3.3×10^{-6} in the GC 50 km/s molecular cloud (reduced by 4.5 times from local ISM D/H).

Our chemical model is an updated version of those of Millar, Bennet and Herbst (1989) and Rodgers and Millar (1996) containing 165 deuterated and 122 undeuterated species linked by 5192 gas-phase reactions and uses recent experimental data on the dissociative recombination of molecular ions, including H_2D^+, and incorporates sulfur chemistry for the first time. The only surface reactions included are grain formation of H_2 and HD from atomic H and D. Details of this model used in this paper are in Appendix A and the complete model will be presented in a future publication (Roberts and Millar, 1999, in preparation).

In this paper, we present the results for a model having the physical parameters typical of the 50 km/s M-0.02-0.07 cloud. We calculated the fractionation abundance ratios R(XD) for $T_k = 75$ K; $n(H_2) = 10^6$ cm^{-3}; an ionization rate of 1.3×10^{-17} sec^{-1}; fractional abundances of C, N, O equal to 9.9×10^{-4}, 3.6×10^{-4}, and 1.98×10^{-3}, respectively, approximately three times their solar abundances; and a cosmic D/H ratio of 3×10^{-6}, about 5 times less than the local value (Minh, Irving, and Friberg 1992; Serabyn, Lacy, and Actermann, 1992; Poglitsch et al. 1991; Simpson et al. 1995). The 50 km/s cloud consists of a dense molecular core surrounded by less dense atomic and molecular gas. We compared our observations of DCN/HCN in the dense core to our model and were able to obtain agreement with the observed DCN/HCN = 4.0 x 10^{-4}.

Fig. 4 shows the time evolution of the fractionation in DCN and particular species related to its formation. The curves show the deuterated fractionation abundance ratios, R(XD) = n(XD)/n(XH). For DCN, the ratio varies by only a factor of three over the period 10^4 - 10^6 yrs, after which a steady-state ratio, R(DCN) = 3.8 x10^{-4} is reached and degree of fractionation f_{DCN} equals 100. Although the column densities of DCN and HCN will be changed by varying the physical conditions, we have confirmed that R(DCN) and f_{DCN} are independent of density, metallicity, and ionization rate where a faster ionization rate resulted a shorter time to reach the steady-state values. Varying the D/H ratio also yielded f_{DCN} of about 100. Hence, our calculations show that the observed ratio of 4.0 x 10^{-4} is consistent with an underlying D/H ratio of 3 x 10^{-6} in the 50 km/s M-0.02-0.07 molecular cloud.

Our estimate of D/H is also consistent with the upper limits determined from observations of the 92 cm (327 MHz) DI hyperfine-structure line towards the Galactic Center. These upper limits are: D/H < 1x10^{-4} in the GC 20 km/s HI cloud, D/H < 1.2x10^{-5} in the 20 km/s Sgr A molecular cloud, D/H < 8.3x10^{-5} in the 50 km/s Sgr A molecular cloud (using DI/D = 0.01) (Lubowich, Anantharamaiah, and Pasachoff 1989); and D/H < 5.8x10^{-5} (Anantharamaiah and

Radhakrishnan 1979; Pasachoff and Cesarsky 1974) in the local V = 0 km/s clouds towards the GC. Our results are also consistent with the upper limits of DCN/HCN < 6×10^{-4} and D/H < 1×10^{-5} recently reported for the Sgr A 50 km/s molecular cloud (Jacq *et al.* 1999) who observed at a position away from the cloud core but near our western offset position and obtained a weak detection for the J = 2-1 DCN line; and a marginal detection for the J = 3-2 line. Jacq *et al.* (1999) did not observe the DCN J = 1-0 line and were unable to accurately estimate DCN/HCN because they did not observe $HC^{15}N$.

5. DISCUSSION

Using a closed-box model and a time scale for Galactic Center astration of 2 x 10^8 yr Audouze *et al.* (1976) calculate D/H = 10^{-12}, thereby requiring an additional source of deuterium such as the infall of primordial matter or a large flux of low-energy cosmic rays. Current chemical evolution models of the Galactic bulge (Matteucci et al. 1999) also predict total astration of D or a D/H of zero. Significantly, if D/H = 10^{-12}, then deuterated molecules should not exist in the Galactic Center. A kinetic analysis of the velocity gradients in the Galactic Center molecular clouds indicated that they not older 10^7 years old (Stark *et al.* 1991) and gravitationally unstable. Thus if there were no additional sources of D, the Galactic Center molecular clouds should be composed primarily of astrated material completely depleted in D and DCN should not be detectable. Thus the mere detection of D (in DCN) in the Sgr A molecular clouds constrains models of astration and requires a continuous source of deuterium to negate the effects of astration.

We have obtained the lowest DCN/$HC^{15}N$ and DCN/HCN ratios observed in any Galactic molecular cloud and the lowest D/H ratio observed anywhere in the Galaxy. Since fractionation always enhances the abundance of deuterated molecules, our results and those of Lubowich, Anantharamaiah, and Pasachoff (1989) indicate that there are no significant Galactic Center sources of D and that the Galactic Center has a lower abundance of D than the local ISM. If D is produced via any mechanism related to the nucleosynthesis of O such as massive stars or type-II supernova, then the D and O abundances will be positively correlated. Because the GC O abundance is enhanced by three times while the D abundance is reduced by 4.5 times, D is anticorrelated with the O abundance and

$[(D/O)_{GC}]/[(D/O)]_{local\text{-}ISM} = 0.075$. Thus if any D nucleosynthesis exists, it is not correlated with O nucleosynthesis or massive stars.

The negative results from a search for J= 1-0 and 2-1 lines of DCN in the shocked molecular gas associated with the IC 443 SNR (Turner, Chan, Green, and Lubowich 1992) and the young protoplanetary nebula AFGL 2688 (Lubowich, Turner, and Sahai 1999) further indicate that D is not produced via stellar processes related to supernovae or AGB stars. D is also not produced in active regions such as the Orion Nebula because the D/H $= 1.0 \times 10^{-5}$ and 7.5×10^{-6} towards the Orion molecular bar and outflow region respectively (from HD/H_2) - a reduction by 1.5 and 2 times compared to the local ISM D/H value (Wright *et al.* 1999; Bertoli *et al.* 1999).

Mullan and Linsky (1999) suggested that low mass flare stars (dM_e) may be an important source of Galactic D from H(n,γ)D and can account for local variations in D/H. However, if D production from flares contributes significantly to the local D abundance, then one should obtain an enhanced D abundance in the GC from the larger number of flare stars expected in the bulge and GC. Conversely if the reduced GC D/H is produced by flare stars, then flare stars cannot be a major source of the local ISM deuterium abundance. Deuterium cannot be produced in the GC from any large neutron flux because the 2.22 MeV neutron capture gamma-ray line was not detected and a 3 σ upper limit of $1.0 \times 10^{-4}\ \gamma\ (cm^2\ s)^{-1}$ was obtained towards the GC (Harris and Share 1991).

Combining our result of the GC D/H = $3.0\text{x}10^{-6}$ with the Sgr B2 D/H = $5.0\text{x}10^{-6}$ (Jacq *et al.* 1999), the local ISM D/H = $1.5\text{x}10^{-5}$ (Linsky 1998), and the possible detection of DI with D/H = $3.9\text{x}10^{-5}$ in the Galactic anticenter interstellar clouds

(Chengalur, Braun, and Burton, 1997), we obtain a positive abundance gradient of D (d(D/H)/dr) in the Galaxy indicating that there is no significant Galactic production of deuterium (Ostriker and Tinsley 1975). The most likely source of the Galactic Center deuterium is continuous infall of primordial matter with D/H $\approx$ (5-10) x10^{-5} with the resultant D/H ratio determined by the astration and mixing which always reduces the D abundance. This continuous replenishment would negate much of the effects of astration and inject primordial gas D enhanced but deficient in O gas into the GC. This result is in agreement with the analysis of the Galactic D/O ratio by Prantzos (1996) where he concluded that the ISM D is probably the result of infall plus astration.

Our results also contrain models of Galactic Center activity. Models of Galactic Center AGN activity predict a Galactic Center D/H = 10^{-4} (at 10 pc from the GC) from γ-ray photodisintegration or photospallation reactions with a γ-ray luminosity L_γ = 10^{42} erg/s for 1 Gyr similar to that of the low-luminosity Seyfert galaxy NGC 4151 (Boyd, Ferland, and Schramm 1989) and D/H = 10^{-2} for a typical quasar L_γ = 10^{44} erg/s for 1 Gyr. Models of cosmic-ray proton spallation reactions predict D/H = 2x10^{-5} for an AGN cosmic-ray proton luminosity of Lp = 10^{43} erg/s for 1 Gyr (Ozernoi and Chernomordik 1975) while Vayner, Ozernoy and Shchekinov (1992) estimate that Lp = (3-5) x 10^{42} erg/s for 1 Gyr can explain the GC D abundance gradient if the ratio of accretion rate to star formation rate was higher in the central region of the Galaxy. The GC production of D by large fluxes of cosmic rays or γ-rays in the early Galaxy is possible only if there was rapid astration so that any D produced was destroyed in the GC but there was little astration in the local ISM. Thus, we do not believe that early AGN or quasar activity is consistent with the observed D/H ratios.

Because the current Galactic center D/H is much less than the D abundance predicted by quasar or AGN activity, there has not been recent AGN activity in the GC. The luminosities required to produce the reduced GC D/H ($L\gamma$ = 3 x 10^{40} erg/s and Lp = 4 x 10^{42} erg/s for 1 Gyr) are still many orders of magnitude larger than the observed Galactic Center $L\gamma$ = $2\text{x}10^{37}$ (Mayer-Hasselwander *et al.* 1998) or Lp = $2\text{x}10^{37}$ erg/s (Mastichades and Ozernoy 1994) and are 20 times larger than the $2\text{x}10^{41}$ erg/s cosmic-ray luminosity of the entire Milky Way (Crosas and Weisheit, 1993). Additionally, the ^{12}C 4.4 MeV and ^{16}O 6.1 MeV γ-ray de-excitation lines that are produced by cosmic-ray spallation reactions were not detected during nine years of GC observations (Harris, Share, and Messina, 1995). Thus AGN activity, γ-ray photodisintegration reactions, or cosmic-ray spallation reactions are not significant sources of Galactic deuterium.

Furthermore, almost all nucleosynthesis processes that can produce a significant abundance of D always overproduce Li or B by 10^3 - 10^5 times (Epstein, Lattimer, and Schramm 1976; Epstein 1977). The observed upper limit on the Galactic Center Li of $(\text{Li/H})_{GC}$ < 3.9 x 10^{-8} or $(\text{Li/H})_{GC}$ < 20 $(\text{Li/H})_{disk}$, (Lubowich, Turner, and Hobbs 1998) further implies that there are no Galactic Center sources of deuterium. The upper limit on the GC Li/H is also not consistent with a 100 times increase in the low-energy cosmic-ray flux inferred from the 70 K temperature of the 50 km/s Sgr A molecular cloud (Ghsten *et al.* 1981) which would significantly increase the abundance of Li to Li/H = $2\text{x}10^{-7}$. Although weak AGN activity or periodic bursts of star formation may occur, our result that D/H = 3 x 10^{-6} combined with the upper limits on Li/H, further imply that the Milky Way has not had a recent active phase nor an early active phase for any period longer than 1 Gyr.

Only a continuous source of D such as infall is able explain the Galactic D/H ratios for reasonable astration models. Therefore all the D observed in the Milky Way is primarily primordial in origin. Although unlikely, we cannot exclude low astration models with no infall or a continuous production of deuterium combined with the exact astration necessary to produce the Galactic Center D/H = 3.0 $\times 10^{-6}$, the local ISM D/H = 1.5 $\times 10^{-5}$, and the anticenter D/H = 3.9 $\times 10^{-5}$.

6. CONCLUSION

We report the first statistically significant detection of deuterium in the Galactic Center 50 km/s molecular clouds from the J = 1-0 and 2-1 lines of DCN with T_R* = 0.061± .007 K and 0.04± 0.02 K respectively. We obtained D/H = 3.0 x 10^{-6} by comparing our estimated DCN/HCN = 4.0 x 10^{-4} (determined from DCN/ $HC^{15}N$ = 0.36 and the Galactic Center $^{14}N/^{15}N$= 900) to calculations from a new 5192-chemical reaction model of deuteration containing 163 deuterated species and observations of DCN/HCN in hot cores. If there is any D nucleosynthesis it is not related to massive stars, type-II SN, AGB stars, or stellar flares. Therefore there is no significant Galactic Center nor Galactic nucleosynthesis of D. The GC has not had a strong AGN or quasar phase (L_p = 10^{42} erg/s and L_γ = 10^{43} erg/s for 1 Gyr) or there would have been evidence in enhanced D or Li abundances. Our results do not exclude weak AGN activity (L_p = 3 $\times 10^{40}$ erg/s and L_γ = 1.5×10^{42} erg/s for 1 Gyr - 1500 and 75,000 times the current GC luminosities) coupled with periodic bursts of star formation in the GC if the astration would reduce the Galactic Center D/H to match the current deuterium abundance.

The most likely source of the Galactic Center deuterium is probably continuous infall of primordial matter with D/H $\cong$ (5-10) x10^{-5}. This continuous replenishment would negate much of the effects of astration. Thus all the deuterium observed in the Galaxy is probably primordial with its abundance reduced by astration and mixing. However, we cannot exclude astration models with no infall or production from flares if the astration reduces the D/H ratio to our results.

If all the deuterium is primordial and the astration models of Vangioni-Flam *et al.* (1994) are correct, then the primordial or early Galactic D/H = 8 x 10^{-5}. Big bang nucleosynthesis models imply that the baryon-to-photon ratio ratio η_b = 3 x 10^{-10}, there are less than four neutrino families, the baryon density of the Universe $\rho_b = 3\text{x}10^{-31}$ gm cm^{-3} < critical density $\rho_c = 3H_o{}^2/8\text{p}G$ = 1.88 h^2 x10^{-29} gm cm^{-3} = 9.2 x10^{-30} gm cm^{-3} (for a Hubble constant H_o = 70 km/s/Mpc) necessary to close the Universe for a flat Einstein-de Sitter Universe, and $\Omega_b = \rho_b/\rho_c = 0.04$ (Copi, Schramm, and Turner, 1995a,b). Thus the fraction of the critical density contributed by baryons (Ω_b) in a closed Universe requires that most of the baryons are in the form of dark matter.

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Appendix A. DEUTERIUM CHEMISTRY

In order to investigate the detailed nature of fractionation, we have calculated the deuterium chemistry of a model having the physical parameters typical of the M-0.02-0.07 cloud. Our model is an updated version of those of Millar, Bennet and Herbst (1989) and Rodgers and Millar (1996) and uses recent experimental data on the dissociative recombination of molecular ions, including H_2D^+, and incorporates sulfur chemistry for the first time. The time-dependent chemistry of some 285 species (27% more than in the previous model), including 163 deuterated species, linked by 5192 gas-phase reactions (twice as many as in the previous model) has been followed over a period of 10^9 years. The only surface reactions included are grain formation of H_2 and HD from atomic H and D.

Minh, Irving, and Friberg (1992) estimate that $T_{rot} = 75$ K for the 50 km/s molecular cloud from ten transitions of CH_3CCH (J = 6-5 and 5-4 lines). Serabyn, Lacy, and Achtermann, (1992) estimate that $n(H_2) = 10^6$ cm^{-3} from the CS J =7-6 and 5-4 transitions. The 50 km/s cloud is probably heated by shock-wave compression rather than by cosmic-ray or UV ionization (Martin-Pintado et al. 1997) and has fractional abundances of SiO and OCS, which is indicative of high temperatures or shock-wave heating (Minh, Irving, and Friberg, 1992). We believe that the ionization and electron density in the 50 km/s cloud are not significantly enhanced over other molecular clouds based on observations of 158

[CII] line (Poglitsch et al. 1991). They determined an anticorrelation between [CII] and the distribution of dense molecular gas with the brightest [CII] emission concentrated at the edge of the 50 km/s cloud. Any possible increase in the GC cosmic-ray flux will not have penetrated the 50 km/s molecular cloud core. Although the increased C, N, and O abundances in the Galactic Center (approximately two or three times; (Simpson et al. 1995) will modify the molecular cloud chemistry and column densities, both DCN and $H^{15}CN$ will be similarly modified so that DCN/$H^{15}CN$ and DCN/HCN will not be significantly changed.

In this paper, we present the results of a model calculated for $T_k = 75$ K, $n(H_2) = 10^6$ cm^{-3}, ionization rate of 1.3×10^{-17} sec^{-1}, and fractional abundances of C, N, O equal to 9.9×10^{-4}, 3.6×10^{-4}, and 1.98×10^{-3}, respectively, approximately three times their solar abundances, with a cosmic D/H ratio of 3×10^{-6}, about 5 times less than the local value. The 50 km/s cloud probably consists of a dense core surrounded by less dense molecular gas. We compared our observations for the dense core to our model.

Deuterium fractionation in interstellar clouds is driven by three primary reactions which extract deuterium from its reservoir, HD.

$$H_3^+ + HD \rightarrow H_2D^+ + H_2 + \Delta E_1 \qquad (1)$$

$$CH_3^+ + HD \rightarrow CH_2D^+ + H_2 + \Delta E_2 \quad (2)$$

$$C_2H_2^+ + HD \rightarrow C_2HD^+ + H_2 + \Delta E_3 \quad (3)$$

with the endoergicities, ΔE, given by $\approx$ 120, 370, and 550 K for reactions (1)-(3), respectively, at a temperature of 75 K. At this temperature, fractionation by H_2D^+, which dominates in cold molecular gas, is unimportant.

An estimate of the fractionation possible via reactions (2) and (3) can be found by considering the forward and reverse reactions whose rate coefficients are related by $k_r = k_f\, e^{-\Delta E/T}$. Writing $R(XD) = S(T)R(HD) = f_{XD}$ (D/H), where S(T) is the enhancement factor, $R(XD) = n(XD)/n(XH)$, and f_{XD} is the degree of fractionation, we find that $R(CH_2D^+) = e^{370/T}\, R(HD)$ and $R(C_2HD^+) = e^{550/T}\, R(HD)$, giving enhancement factors of $\approx$ 140 and $\approx$ 1500, respectively, at 75 K. Only when $R(HD) = n(HD)/n(H2) =$ (D/H) is $S(T) = f_{XD}$. These enhancement factors are only approximate because they neglect other loss mechanisms of the deuterated ions, but they are nonetheless useful in giving an indication of the enhancements possible. The actual enhancement of CH_2D^+ and C_2HD^+ are 125 and 275 respectively.

At a temperature of 75 K, the main routes to the formation of HCN and DCN are:

$$HCO + N \rightarrow HCN + O$$
$$DCO + N \rightarrow DCN + O$$

indicating that R(DCN) ≈ R(DCO). HCO and DCO are formed by the dissociative recombination of H_2CO^+ and $HDCO^+$, respectively, with electrons. These species are formed from the reactions

$$CH_3^+ + O \rightarrow H_2CO^+ + H$$

$$CH_2D^+ + O \rightarrow HDCO^+ + H.$$

A significant amount of DCN is also formed in the reaction

$$C_2HD^+ + N \rightarrow CH^+ + DCN$$

which can also form HCN via

$$C_2HD^+ + N \rightarrow CD^+ + HCN$$

Since C_2HD^+ is enhanced by ≈ 275 at 75 K, a significant enhancement in DCN results from this reaction. The overall enhancement in DCN is determined by the balance between these two synthetic pathways; a combination of major production (45%) from an ion, CH_2D^+, with a relatively low enhancement of ≈ 125, and minor formation (31%) from an ion, C_2HD^+, with an enhancement ≈ 275 in deuterium. The DCN degree of fractionation does not follow the exact behavior of either CH_2D^+ or C_2HD^+, but falls in between the enhancements of 42 (one-third of CH_2D^+ from statistical calculation based the number of reaction pathways) and 140 (one-half of C_2HD^+ from statistical calculation based the number of reaction pathways) which would be the case if either one of the synthetic pathways was the only route to DCN.

Fig. 4 shows the time evolution of the fractionation in DCN and particular species related to its formation. The curves show the abundance ratios, R(XD) = n(XD)/n(XH). For DCN, the ratio varies by only a factor of three over the period 10^4 - 10^6 yrs, after which a

steady-state ratio, R(DCN), of 3.8 x10^{-4} is reached. Thus, the degree of fractionation in DCN is about 100. We have confirmed that this enhancement of 100 is independent of the adopted D/H ratio. While changes in the physical conditions (metallicity and density) can drastically alter the molecular abundances of species, the fractionation is insensitive to such changes and an increased ionization rate results in reaching the steady-state R(DCN) in a shorter time. Because both the molecules studied and their corresponding deuterated species undergo the same reactions, they react to chemical changes in the same

way. Hence, our calculations show that the observed ratio of 4.0 x 10^{-4} is consistent with an underlying D/H ratio of 3 x 10^{-6} in the M-0.02-0.07 molecular cloud.

Figure Captions

Figure 1. The DCN spectra in the Sgr A 50 km s^{-1} and Sgr B2 molecular clouds. The frequency units are in MHz and the temperature units are in degrees K.

a) The J = 1-0 spectrum of DCN in the Sgr A 50 km/s molecular cloud at α = $17^h42^m42^s$ and δ = $-28^o58'00''$ and centered at 50 km s^{-1}.

b) The J = 2-1 spectrum of DCN in the Sgr A 50 km/s molecular cloud at α = $17^h42^m42^s$ and δ = $-28^o58'00''$ and centered at 50 km s^{-1}.

c) The J = 1-0 spectrum of DCN in the Sgr B2 molecular cloud at the (OH) positions ($\alpha = 17^h44^m11^s$ and $\delta = -28^o22'30''$) and centered at km s^{-1}.

d) The J = 2-1 spectrum of DCN in the Sgr B2 molecular cloud at the (OH) positions ($\alpha = 17^h44^m11^s$ and $\delta = -28^o22'30$ and centered 62 km s^{-1}.

Figure 2. Map of the J = 1-0 line of DCN at six positions in the Sgr A 50 km/s molecular cloud offset by one arcmin from our center position and one point offset by two arcmin south of our center position. Our center position is at α = $17^h42^m42^s$ and $\delta = -28^o\ 58\ '00''$ and all the spectra are centered at 50 km s^{-1}. The frequency units are in MHz and the temperature units are in degrees K.

Figure 3. The J = 1-0 spectra of DNC, $H^{15}CN$, $HC^{13}N$, HCN, HCO^+, and HNC in the Sgr A 50 km/s molecular cloud at α = $17^h42^m42^s$ and δ = $-28^o58'00''$ and centered at 50 km s^{-1}. The frequency units are in MHz and the temperature units are in degrees K.

a) DNC b) $H^{15}CN$ c) $HC^{13}N$ d) HCN e) HCO^+ f) HNC

Figure 4. The fractionation abundance ratios R(XD) vs. time in years. Figure shown is log R(XD) vs. log (time).

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