

The Deuterium Abundance In The Galactic Center 50 km/s 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 $D/H = 3 \times 10^{-6}$ using a new 5192-chemical reaction model. This is the lowest D/H ratio observed in the Galaxy, five times lower than the local ISM $D/H = 1.5 \times 10^{-5}$ but $10^6 \times$ larger than D/H predicted by GC models. We detected DCN in the GC Sgr A 50 km/s molecular cloud located 10 pc from the GC with 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. The most likely source of the GC D is continuous injection from the infall of primordial matter with $D/H = 5 \times 10^{-5}$ with the D/H determined by astration and mixing. Thus there are no significant Galactic sources of D and no recent quasar or AGN activity in the GC. This primordial D/H implies 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 ν families.

1. Introduction and observations

Because D is not produced in stars, the abundance of D will decrease with time unless there are any additional sources of D. The D/H ratio is an important prediction of big-bang nucleosynthesis (Schramm & Turner, 1998) because D/H depends on the T and baryonic density during the first 1000 seconds and might determine if the density is sufficient to close the universe. Recent observations of D including QSO absorption spectra are reviewed by Vidal-Madjar (1999).

The GC is the most active and heavily processed region of the Galaxy and the Sgr A 50 km/s cloud (M-0.02-0.07), 10 pc from the GC, is related to the

GC activity and is the best place to search for Galactic D. If D is produced by any stellar or Galactic process, then it should be more abundant in the GC and there should be a corresponding gradient in the D abundance (Pasachoff & Vidal-Madjar 1989). Chemical models of the GC with no sources of D predict $D/H = 5 \times 10^{-12}$ at 12 Gyr (Audouze et al. 1976).

We used the NRAO 12-m telescope during May 16-18, 1993, and June 29, 1993, and 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 centered at $\alpha = 17^h42^m42^s$ $\delta = -28^\circ58'00''$ (the peak CS J= 7-6 and J=5-4 emission; Serabyn, Lacy, & Achtermann 1992) insuring that we observed the densest part of this cloud ($n = 10^6 \text{ cm}^{-3}$). We analyzed the data with the UNIPOPS program. We detected both the J= 1-0 and J= 2-1 lines of DCN and obtained $T_R^* = 0.061 \pm 0.007 \text{ K}$ and $T_R^* = 0.042 \pm 0.02 \text{ K}$, 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. We detected DCN at 4/5 additional positions offset by 1' and 2' S from our center position and also observed the J=1-0 lines of DNC, HC^{15}N , H^{13}CN , HCN, HCO^+ , and HNC. As a check we observed the known DCN lines in the Sgr B2 molecular at the (OH) position ($\alpha = 17^h44^m11^s$; $\delta = -28^\circ22'30''$) where the DCN 1-0 line is blended with the H_2CO 5(1,4)-5(1,5) transition.

The spectra are shown in figures 1 and 2 and our results are given in tables 1, 2, and 3 where the lines were identified from the Lovas (1992) rest frequencies (unknown lines listed with U) and fit by Gaussian profiles.

Table 1. Sgr A 50 km/s Cloud, Center Position

Molecule	Transition	ν (MHz)	T_r^* (mK)	rms(mK)	ΔV (km/s)
		U72323.9	68	7.1	22.7
		U72344.2	18	7.1	30.6
DCN	1-0	72414.9	61	7.1	30.9
HC^{13}CCN	8-7	72475.1	145	7.1	21.9
HCC^{13}CN	8-7	72482.1	120	7.1	27.9
HC^{15}N	1-0	86055.0	192	27	26.8
SO	2(2)-1(1)	86093.5	226	27	19.8
H^{13}CN	1-0	86340.2	1510	20	35.2
HCN	1-0	88631.8	5408	48	27.1
HCO^+		89188.5	3070	23	25.7
		U89204.3	532	23	11.7
		U89215.5	250	23	11.7
		U89221.8	130	23	7.8
HC^{13}CCN	10-9	90593.1	130	23	18.5
HCC^{13}CN	10-9	90601.8	120	23	25
HNC	1-0	90663.5	2198	23	41.3
C_2S	7,7-6,6	90686.4	167	23	12.4
		U144735.3	67.6	15	12.6
DCN	2-1	144828.0	38.9	15	25.2

We used 1-MHz filters; a 256 MHz bandwidth; 4.14 km/s resolution and 86 " beam at 72 GHz, 2.07 km/s resolution and 43 " beam at 144 GHz. Pointing

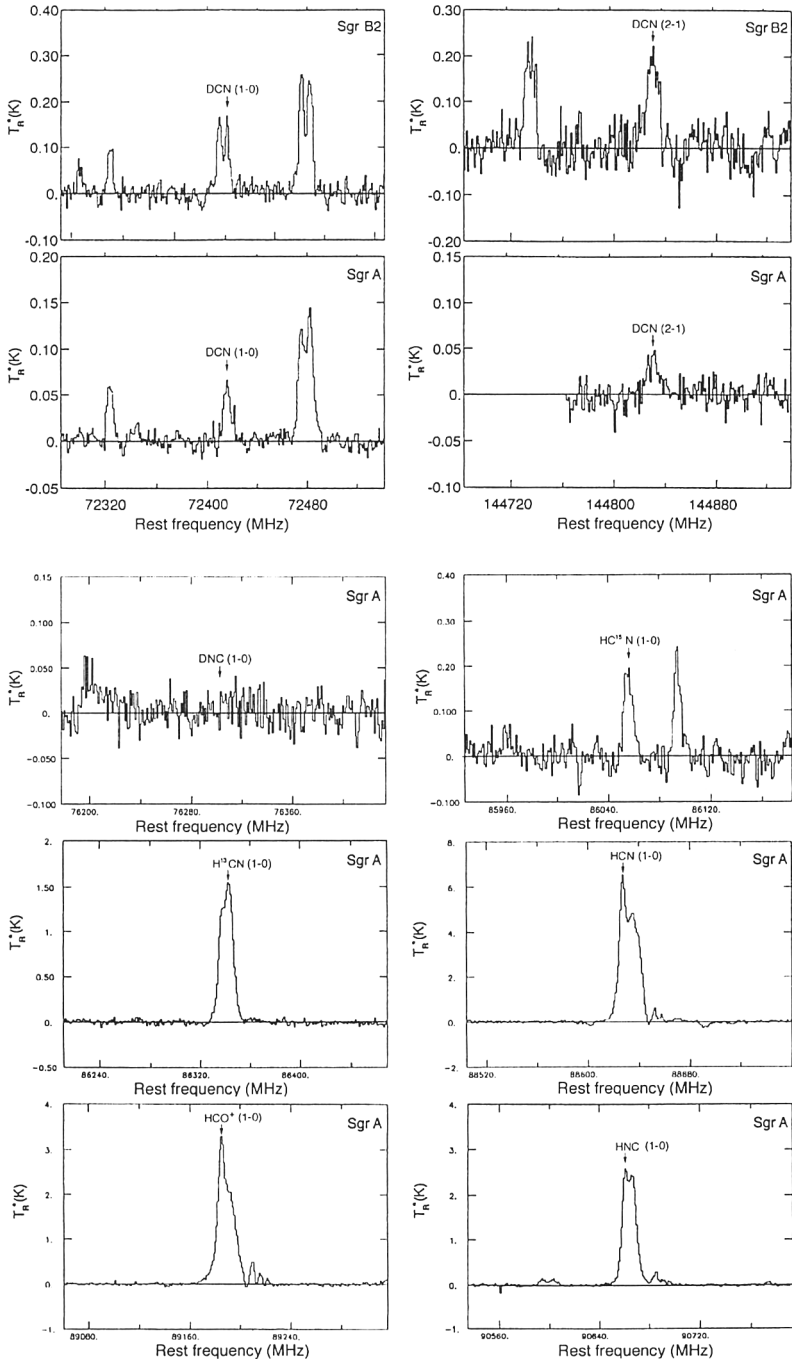


Figure 1. Spectra of the GC Sgr A 50 km/s and Sgr B2 molecular clouds. The $J = 1-0$ lines of DCN, DNC, $HC^{15}N$, $HC^{13}N$, HCN, HCO^+ , and HNC are labeled.

Table 2. Sgr A 50 km/s Cloud, Offset Positions

Molecule	Transition	ν (MHz)	T_r^* (mK)	rms(mK)	ΔV (km/s)
1' West					
		U72324.9	31	16	25.2
DCN	1-0	72414.9	30	16	41.5
HC ¹³ CCN	8-7	72475.1	102	16	21.4
HCC ¹³ CN	8-7	72482.1	91	16	21.4
1' North					
		U72323.1	23	14	62.9
DCN	1-0	72414.9	11	14	59.1
HC ¹³ CCN	8-7	72475.1	60	14	15.1
HCC ¹³ CN	8-7	72482.2	58	14	22.8
1' East					
DCN	1-0	72419.0	40	19	33.1
HC ¹³ CCN	8-7	72475.1	100	19	27.3
HCC ¹³ CN	8-7	72482.1	100	19	27.3
1' South					
		U72324.5	64	16	19.7
DCN	1-0	72414.9	55	16	33.9
HC ¹³ CCN	8-7	72475.1	135	16	18.8
HCC ¹³ CN	8-7	72482.1	118	16	20.1
2' South					
DCN	1-0	72414.9	32	15	27.1
HC ¹³ CCN	8-7	72475.1	80	15	18.6
HCC ¹³ CN	8-7	72482.1	79	15	27.5

Table 3. Sgr B2(OH)

Molecule	Transition	ν (MHz)	T_r^* (mK)	rms(mK)	ΔV (km/s)
CH ¹³ CCH ₃	10(1,9)-10(0,10)	72300.2	61	16	18.1
		U72324.0	106	16	17.3
H ₂ CO	5(1,4)-5(1,5)	72404.4	167	16	18.6
DCN	1-0	72414.9	167	16	16.6
HC ¹³ CCN	8-7	72475.1	226	16	20.0
HCC ¹³ CN	8-7	72482.1	260	16	20.0
		U144734.8	217	38	16.9
DCN	2-1	U144828.0	196	38	21.5

was checked using Jupiter and Uranus. The double sideband T_{sys} was 350 K at 72 GHz and 400 K at 144 GHz. We could not resolve the hyperfine splitting 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 ≈ 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/ $HC^{15}N$ and DCN/HCN (Hatchell, Millar & 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 obtained DCN/ $HC^{15}N = 0.36$ and DCN/HCN = 4.0×10^{-4} using $({}^{15}N/{}^{14}N) = 900$ (Güsten & Ungerechts 1985) which are the lowest DCN/ $HC^{15}N$ and DCN/HCN ratios observed in any molecular cloud.

2. Discussion

Chemical fractionation resulting from the lower zero-point energy for deuterated molecules due to its larger mass significantly increases these abundances. Our chemical model is an updated version of Rodgers & Millar (1996) containing 165 non-deuterated, 122 deuterated species, 5192 gas-phase reactions, recent data on the dissociative recombination of H_2D^+ , S chemistry, and grain formation of H_2 and HD. For a model with the physical parameters typical of the 50 km/s cloud ($T = 75$ K; $n(H) = 10^6$ 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 $3\times$ their solar abundances; Minh, Irving, & Friberg (1992); Serabyn, Lacy, & Actermann (1992); Poglitsch et al. (1991), Simpson et al. (1995)), we obtained a best agreement with the observed DCN/HCN for $D/H = 3 \times 10^{-6}$ (a degree of fractionation of 133).

Although the column densities of DCN and HCN will be changed by varying the physical conditions, the fractionation is independent of density, metallicity, and ionization rate where a faster ionization rate resulted a shorter time to reach the steady-state values. DCN/HCN as a function of T and n is shown in figure 3. Our D/H is also consistent with the upper limits of $D/H < 8.3 \times 10^{-5}$ (from the 92-cm hfs line; Lubowich, Anantharamaiah, & Pasachoff 1989) and DCN/HCN $< 6 \times 10^{-4}$ (Jacq et al. 1999) in GC 50 km/s molecular cloud. 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.

Using a closed-box model and a time scale for GC astration of 2×10^8 yr Audouze et al. (1976) calculate $D/H = 5 \times 10^{-12}$. If there were no additional sources of D, the GC molecular clouds should be composed of astrated material completely depleted in D and DCN should not be detectable. If D is produced via any mechanism related to the nucleosynthesis of O (massive stars or type-II SN), then the D and O abundances will be positively correlated. Because the GC O abundance is enhanced by $3\times$ while the D abundance is reduced by $4.5\times$, D is anticorrelated with the O abundance. Thus if any D nucleosynthesis exists, it is not correlated with O nucleosynthesis or massive stars.

Combining our result of the GC $D/H = 3.0 \times 10^{-6}$, the Sgr B2(OH) $D/H = 5.0 \times 10^{-6}$ (Jacq et al. 1999), the local ISM $D/H = 1.5 \times 10^{-5}$ (Linsky 1998), and the possible detection of DI with $D/H = 3.9 \times 10^{-4}$ in the Galactic anticenter

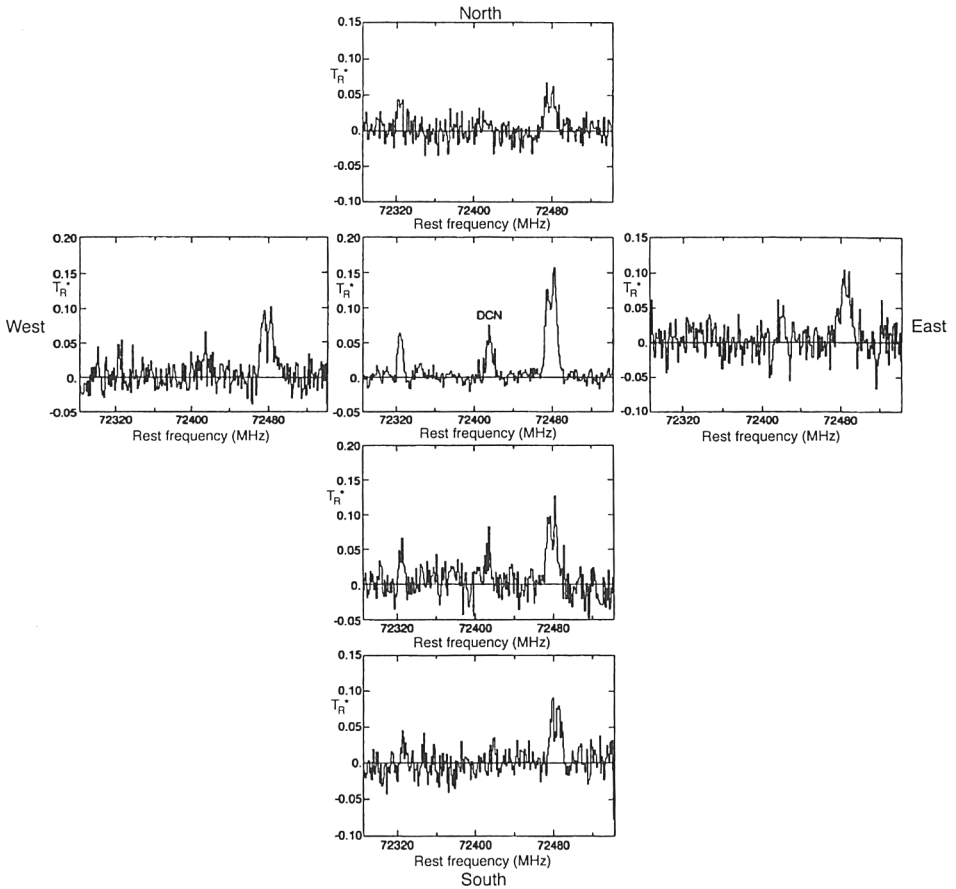


Figure 2. Spectra of the GC 50 km/s molecular cloud offset by 1' North, South, East, West and by 2' South of our center position.

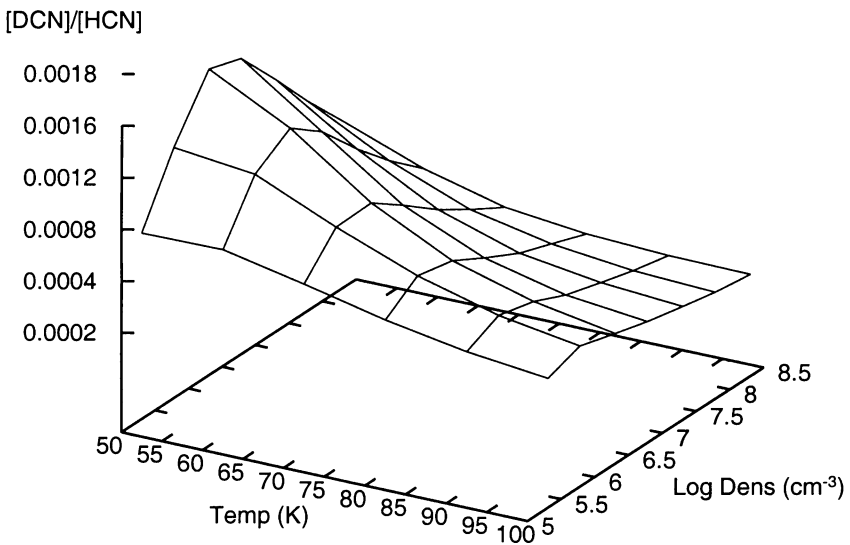


Figure 3. DCN/HCN as a function of temperature of temperature and density

(Chengalur, Braun, & Burton, 1997), we obtain a positive abundance gradient of D in the Galaxy indicating that there is no significant Galactic production of D (Pasachoff & Vidal-Madjar 1988). The most likely source of the GC D is continuous infall of primordial matter with $D/H \approx 5 \times 10^{-5}$ where the resultant D/H ratio is determined by the astration and mixing which always reduces the D/H. This replenishment would negate much of the effects of astration and inject gas enhanced in D but deficient in O gas into the GC. This is in agreement with the analysis of the Galactic D/O ratio (Prantzos 1996) where the ISM D is probably the result of infall plus astration.

Our results constrain models of GC activity that predict a GC $D/H = 10^{-4}$ (10 pc from the GC) from γ -ray photospallation reactions (Boyd, Ferland, & Schramm 1989) for an AGN or Seyfert γ -ray luminosity $L_\gamma = 10^{42}$ erg/s; $D/H = 10^{-2}$ and $L_\gamma = 10^{44}$ erg/s for a quasar; and $D/H = 2 \times 10^{-5}$ for an AGN cosmic-ray (CR) proton luminosity $L_p = 10^{43}$ erg/s for 1 Gyr (Ozernoi & Chernomordik 1975). The GC production of D by large fluxes of CRs 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. Because the current GC $D/H \ll D/H$ predicted by quasar or AGN activity, there has not been recent AGN activity in the GC. The luminosities required to produce the GC D/H are still many orders of magnitude larger than the observed GC L_γ or $L_p = 2 \times 10^{37}$ erg/s (Mayer-Hasselwander et al. 1998; Mastichades & Ozernoy 1994). The γ -rays from CR spallation reactions were not detected during 9 years of GC observations (Harris, Share, & Messina, 1995).

Thus AGN activity, (γ -ray photodisintegration reactions, or CR spallation reactions) are not significant sources of Galactic deuterium. Because almost all nucleosynthesis processes that can produce a significant abundance of D always

overproduce Li or B by $10^3 - 10^5$ times, the observed upper limit on the GC Li of $(\text{Li}/\text{H})_{GC} < 3.9 \times 10^{-8}$ or $(\text{Li}/\text{H})_{GC} < 20 (\text{Li}/\text{H})_{disk}$, (Lubowich, Turner, & Hobbs 1998) further implies that there are no Galactic Center sources of deuterium. Although weak AGN activity or periodic bursts of star formation may occur, the Milky Way has not had a recent active phase nor an early active phase for any period longer than 1 Gyr. 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, the local, and the anticenter D/H values.

If all the deuterium is primordial and the astration models Prantzos (1996) are correct, then the primordial or early Galactic D/H $\approx 5 \times 10^{-5}$. For this D/H big-bang nucleosynthesis models imply that the baryon-to-photon ratio $\eta_b = 3 \times 10^{-10}$, there are less than four neutrino families, the baryon density of the Universe $\rho_b = 3 \times 10^{-31} \text{ gm cm}^{-3} < \text{critical density of } \rho_c = 3H_0^2/8\pi G = 1.88H_0^2 \times 10^{-29} \text{ gm cm}^{-3} = 9.2 \times 10^{-30} \text{ gm cm}^{-3}$ (for a Hubble constant $H_0 = 70 \text{ km/s/Mpc}$) necessary to close the Universe for a flat Einstein-de Sitter Universe, and $\Omega_b = \rho_b/\rho_c = 0.04$ (Copi, Schramm, & Turner, 1995). 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.

Note added in proof: Based on additional modelling D/H = 1.7×10^{-6} , $9 \times$ lower than the local D/H which strengthens our conclusion that GC D is the result of infalling matter.

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