

A multilevel study of ammonia in star-forming regions

VI. The envelope of Sagittarius B2

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Abstract. Measurements of seven metastable NH_3 inversion transitions with $(J, K) = (8,8), (9,9), (10,10), (11,11), (12,12), (13,13)$ and $(14,14)$ are presented. These lines arise from energy levels between ~ 600 K and ~ 2000 K above the ground state, and are found in absorption toward the HII regions SgrB2(M) and (N) at v_{LSR} 's between ~ 60 and $\sim 82 \text{ km s}^{-1}$. Toward SgrB2(N), there is absorption at $v_{\text{LSR}} \sim 0 \text{ km s}^{-1}$ also. The metastable ($J = K$) inversion lines are collisionally excited, and an analysis indicates that kinetic temperatures are > 600 K. The doublet levels are very subthermally excited, with excitation temperatures < 10 K. Thus, these lines must arise from the low density, $n(\text{H}_2) < 5 \cdot 10^3 \text{ cm}^{-3}$, extended envelope of Sgr B2. In addition, we have measured absorption spectra for the $v = 0, J = 1 - 0$ transition of SiO and the $J = 4 - 3$ transition of HC_3N toward both sources. The absorptions are seen at v_{LSR} 's of ~ 0 , and between 60 and 85 km s^{-1} , although the HC_3N absorption SgrB2(N) is weak and blended with emission. LVG analyses of SiO and the HC_3N data are consistent with H_2 densities $< 5000 \text{ cm}^{-3}$. Both the NH_3 and SiO results are consistent with heating by C shocks. These data strongly indicate that the $v_{\text{LSR}} \sim 0 \text{ km s}^{-1}$ component is located close to the galactic center.

Key words: Galaxy: center – ISM: abundances – ISM: individual objects: Sgr B2 – ISM: molecules – radio lines: ISM

1. Introduction

Sgr B2 is one of the most studied molecular cloud/ionized gas complexes in the Galaxy. At a projected distance of ~ 100 pc from the galactic center (assuming that $D_\odot$ is 8.5 kpc), SgrB2 is an extraordinary giant molecular cloud with extensive ongoing star formation (see, e.g., Benson & Johnston 1984; Gaume &

Claussen 1990). From a series of molecular line and dust continuum studies (see, e.g., Lis & Goldsmith 1990, 1991; Martín-Pintado et al. 1990; Gordon et al. 1993; Hüttemeister et al. 1993a, hereafter Paper I) it has become clear that the molecular cloud consists of at least 3 components. We show a simplified sketch in Fig. 1.

The most compact, densest molecular regions are cores containing the most complex molecules (see, e.g., Cummins et al. 1986; Turner 1991). In high resolution maps with beamsizes $< 5''$, there are more than 19 high brightness NH_3 cores (Gaume & Claussen 1990). For observations with beamsizes $> 10''$, three core complexes, SgrB2(N), (M), and (S) can be distinguished. SgrB2(S) is the most extended and previously has been favored as the target of molecular line searches (see, e.g., Cummins et al. 1986). However, it is now recognized that SgrB2(N) and (M) are richer sources of complex molecular species (see, e.g., Vogel et al. 1987; Peng et al. 1993; Snyder et al. 1994); these have sizes of ~ 0.1 pc and masses of $2000 M_\odot$. In these cores, the kinetic temperatures, T_{kin} , are ~ 200 K, the local H_2 densities, $n(\text{H}_2)$, are $\sim 2 \cdot 10^7 \text{ cm}^{-3}$ and the column densities, $N(\text{H}_2)$, are $\sim 10^{25} \text{ cm}^{-2}$ (see, e.g., Paper I). From these cores highly excited transitions, including vibrationally excited lines of HC_3N and NH_3 are emitted. On the line of sight, and probably close to these dense cores are more than 19 HII regions (Gaume & Claussen 1990; Mehringer et al. 1992). Vogel et al. (1987) and Snyder et al. (1994) favor the view that SgrB2(N) is younger than SgrB2(M). However, as reported in Paper I, the $v_{\text{LSR}} \sim 55 \text{ km s}^{-1}$ component of NH_3 , seen in absorption toward SgrB2(M), shows properties similar to those of the clumps found in SgrB2(N). On this basis, there may be no large difference in cloud ages between SgrB2(M) and (N). The observations of the cores are confusing because in addition to molecular excitation effects and differences in cloud parameters, geometry is important. That is, the relative position of the molecular cores and HII regions, their angular sizes, and the angular resolution used determines whether lines are observed in emission or absorption (see, e.g., Paper I, van Dishoeck et al. 1993)

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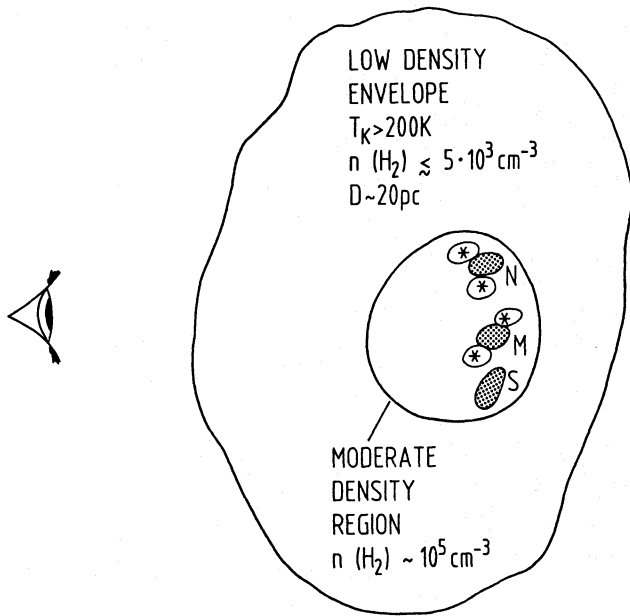


Fig. 1. A sketch of the different components present in the Sgr B2 complex. The HII regions are denoted by ellipses enclosing the stars. The compact molecular cores are shown shaded. We emphasize here the parameters of the envelope, discussed in the text. The moderate density region has a size of ~ 2.5 by ~ 5 pc ($\alpha \times \delta$), and has $T_{\text{kin}} \sim 100$ K. The dimensions are not to scale

From the NH_3 data in Paper I, the cores are embedded in a more extended, moderate density region. This has a size of 2.5 pc (α) by 5 pc (δ), T_{kin} of ~ 100 K, $n(\text{H}_2)$ of $\sim 10^5 \text{ cm}^{-3}$ and $N(\text{H}_2)$ of $\sim 10^{24} \text{ cm}^{-2}$. Since the T_{kin} and $n(\text{H}_2)$ values are lower, it is natural to assume that this inner envelope is farther from the HII regions and dense cores.

Still farther from the cores is the envelope of the Sgr B2 cloud. This region has a size of ~ 20 pc, T_{kin} of ~ 200 K, mass of $10^6 M_{\odot}$, $n(\text{H}_2)$ of $\sim 10^3 \text{ cm}^{-3}$ and $N(\text{H}_2)$ of $\sim 10^{23} \text{ cm}^{-2}$.

The radial velocity with respect to the local standard of rest, v_{LSR} , of one distinct component of Sgr B2 (N) is $\sim 82 \text{ km s}^{-1}$. For all the other regions, including the bulk of the material seen toward Sgr B2 (N), v_{LSR} is $\sim 65 \text{ km s}^{-1}$. The FWHP linewidths, $\Delta v_{1/2}$, of all these regions are ~ 12 to 20 km s^{-1} . The similarity of v_{LSR} and $\Delta v_{1/2}$ from these components makes it difficult to separate the properties of each. For NH_3 , this can however be accomplished using inversion lines with different excitation requirements.

The transitions between inversion doublets of NH_3 can be separated into two categories, metastable ($J=K$) and non-metastable ($J>K$). Non-metastable doublet transitions require more extreme excitation conditions. Transitions between inversion doublet levels from both metastable and non-metastable levels have been measured at frequencies between 18 and 36 GHz. For the inversion transitions, the populations are characterized by two temperatures, the excitation temperature of the doublet populations and rotational temperatures between populations of different (J, K) levels. For the metastable levels, the

transitions between different (J, K) levels are first order forbidden, and occur only by means of collisions. Thus the T_{rot} values are determined mainly by collisions, and T_{rot} is an indication of T_{kin} . Across a doublet level, T_{ex} is determined by density, $n(\text{H}_2)$, and T_{kin} . For low density regions, $T_{\text{ex}} < T_{\text{rot}}$. In the case of Sgr B2, non-metastable NH_3 inversion lines are found in emission or absorption from the cores and moderate density region (see Fig. 1), but *not* the extended envelope. The envelope has been mapped in metastable lines up to (J, K)=(7,7) in Mauersberger et al. (1986) and Paper I with a $43''$ angular resolution. Toward the continuum sources Sgr B2(M) and (N), these inversion transitions are seen in absorption. One telescope beamwidth from the continuum sources, the absorption becomes emission. Net absorption will be recorded only if the value of T_{ex} is less than the main beam brightness temperature of the continuum sources, that is < 20 K. Since the rotational temperature, T_{rot} of NH_3 is ~ 200 K in the envelope, the inversion doublet transitions must be sub-thermally excited. From the application of such arguments, the low density in the envelope was deduced (see, e.g., Paper I). The extremely high T_{kin} values in the extended envelope can be further investigated with single telescopes. In order to determine the values of T_{kin} better, we have extended the measurements presented in Paper I to more highly excited lines of NH_3 . In addition, we present spectra of the $v = 0, J = 1 - 0$ transition of SiO and the $J = 4 - 3$ transition of HC_3N (see, e.g., Lovas 1991). Both are found in absorption toward Sgr B2 (M). Toward Sgr B2(N), the HC_3N absorption is not so prominent, perhaps because of the lower source continuum temperature, and is blended with emission. These molecules have large dipole moments, and are thought to be collisionally excited. When our data are combined with results from higher rotational lines, independent estimates of $n(\text{H}_2)$ can be obtained. Since SiO in the gas phase seems to be present only in very hot or shock heated regions (Ziurys et al. 1989), SiO data allow independent estimates of physical conditions in the envelope of Sgr B2.

2. Observations

All data were taken with the 100m telescope of the MPIfR. The 1 cm wavelength HEMT receiver covers a frequency range from 26.3 GHz to 36.2 GHz (1.15 cm to 0.85 cm), thus enabling measurements of metastable transitions of NH_3 between (J, K)=(8,8) and (14,14), and the $J = 4 - 3$ line of HC_3N . The (14,14) transition occurs between doublet energy levels which are nearly 2000 K above ground (see, e.g. Poynter & Kakar 1978). The HEMT amplifier is cooled to 15 K; the gain is > 30 dB. After amplification at the sky frequency, the signal passes through one of a series of waveguide filters to eliminate contribution from the image sideband. Then the signal is mixed twice: First, using one of a series of fixed frequencies from the sky frequency to an intermediate frequency of 2 – 4 GHz. The second mixing is made with a tunable local oscillator signal to take the motion of earth and Sun into account. This mixing centers the line in the spectrometer band. This process is complex because of the large HEMT amplifier bandwidth and the rather low IF frequency. Because of the three mixing stages, there were

Table 1. Log of the observations of NH₃ at 1cm wavelength

Source	(8,8)	(9,9)	(10,10)	(11,11)	(12,12)	(13,13)	(14,14)
Sgr B2 (M)	13.11.92 17.3.93 8.1.94	12.2.92 7.1.94	1.2.92	1.2.92 23.11.92	16.10.92 17.3.93	17.10.92	17.10.92
Sgr B2 (N)	17.3.93 5.1.94	12.2.92 23.11.92 6.1.94	1.2.92	1.2.92	16.10.92 23.11.92 24.11.92	17.10.92 17.3.93	17.10.92 18.10.92

some internal interferences caused by mixing products. These were recognized and eliminated by tuning one of the mixers to another frequency, and then compensating for this difference with a second mixer. The spectrometer was the MPI 1024 channel autocorrelator, used as two 512 channel receivers. Usually, one backend was set to a bandwidth of 12.5 MHz, the other to a bandwidth of 50 MHz. At the maximum elevation of SgrB2 from Effelsberg, $\sim 11^\circ$, the source is observed through >5 air masses. At such low elevations, T_{sys} is ~ 600 K, on a T_{MB} scale. This receiver noise is mostly caused by the atmosphere.

The NH₃ measurements were made in five periods between January 1992 and January 1994 (see Table 1). Except for the (10,10) and (11,11) inversion lines, all transitions were observed at least twice in different periods. All observations were carried out using the position switching mode with the off-source position at a -3 minutes of time offset in R.A. from the on-source position. Thus, in a typical 6 minute scan, 3 minutes “on”, 3 minutes “off”, the same portion of sky was covered during the “ons” and the “offs”, in order to improve the baselines of the resulting spectra.

The HC₃N measurements were made in conjunction with a map which covered a region of $\sim 2'$ by $\sim 2'$. The profiles taken toward positions away from the HII regions are found in emission; toward SgrB2(M) there are two blended absorption lines and a wider, weaker emission component. Toward SgrB2(N), there may be a weak absorption line between two emission lines. The integration times for each map spectrum were 1 to 2 minutes; for the continuum maxima, integration times were 15 to 30 minutes. Only these are presented here.

The pointing of the telescope was checked at the beginning of each SgrB2 observing session, checked again when the source was close to transit at 11.5° elevation and usually a third time at the end of the period. Sgr B2 (M) itself was used both as a pointing and calibration source, with the peak main beam brightness temperature, T_{MB} , taken to be 20 K (Martín-Pintado et al. 1990). The calibration, potentially difficult for a source at such low elevations, was established by analysing the individual continuum cross scans for each period and applying the calibration to the spectral line data.

The $v = 0$, $J = 1 - 0$ line of SiO was observed during the night of 8 July 1993 with the 100m telescope. At the line frequency of ~ 43 GHz (see, e.g., Lovas 1991) the telescope beam is $23''$, FWHP, from continuum scans of W3(OH), at an eleva-

tion of 28° . The receiver was a cooled HEMT, normally used for VLBI experiments. At the elevation of SgrB2, the system noise (with atmosphere) was measured to be 700K, in T_{a} units, if η_b is 0.25, and the peak T_{MB} of SgrB2(M) is 14K. This peak brightness temperature is calculated in the Rayleigh-Jeans limit from the peak continuum flux densities given by Akabane et al. (1988) and Martín-Pintado et al. (1990), and the beam size.

The typical resolution of the spectra was 0.2 km s^{-1} to 0.3 km s^{-1} . During reduction, the spectra were smoothed to $\sim 1 \text{ km s}^{-1}$ resolution and a polynomial baseline of order one to three for NH₃, and one or two for SiO was subtracted.

3. Results

We show an energy level diagram of NH₃ up to the (14,14) transition in Fig. 2. The lines at 1 cm wavelength discussed in this paper are indicated by a thick bar, while the transitions at 1.3 cm wavelength analysed in Paper I are indicated by thinner bars. When combined with the results in Paper I, there are now 36 NH₃ lines from the vibrational ground state measured toward Sgr B2. All seven metastable transitions of NH₃ observable at 1 cm were detected toward both Sgr B2 (M) and (N) in absorption against the continuum sources. The line profiles observed toward Sgr B2 (M) and (N) are shown in Fig. 3 and Fig. 4, respectively.

The $(J, K) = (8,8)$ and $(9,9)$ transitions were observed by Wilson et al. (1982) toward Sgr B2 (M) with a less sensitive receiver. The intensity of the previous (8,8) line data agrees with our new measurement to within 20%, while the previous (9,9) line absorption data appear to be somewhat weaker. Toward both Sgr B2 (M) and (N), even the $(J, K) = (14,14)$ transition, from the highest lying energy levels, proved to be easily detectable. This is the clearest detection of the most highly excited NH₃ transition in the ground state so far, since the (14, 14) inversion line from the Orion KL nebula (Wilson et al. 1993b) is blended with two hydrogen recombination emission lines from Orion A. In the case of Orion A, the recombination lines, from transitions between the 107 and 101 level (the H101(6) line), and between the 113 and 106 level (the H106(7) line) are more intense than the NH₃ (14,14) emission line. This is because the HII region is much more extended than the NH₃ emission region. In the case of SgrB2, the (14,14) transitions clearly dominate, since the NH₃ lines are in absorption, while the recombination lines

Table 2. Parameters of the metastable NH_3 inversions lines, the $J = 4 - 3$ line of HC_3N and the $J = 1 - 0$ line of SiO measured in absorption toward Sgr B2

Line	energy above ground	comp. ^{a)} spatial & velocity	$\int T_{\text{MB}} dv^b$	v_{LSR}	T_{MB}	$T_{\text{L}}/T_{\text{C}}$	τ_{app}	$10^{-12} N/T_{\text{ex}}$
(J, K)	K		K km s^{-1}	km s^{-1}				$\text{cm}^{-2} \text{K}^{-1}$
(8,8)	681	(M) 60	-12.5(0.5)	60.4(0.2)	-1.43	0.072(0.004)	0.074(0.004)	4.1(0.2)
		(M) 69	-7.9(0.4)	69.0(0.3)	-0.91	0.045(0.002)	0.046(0.002)	2.6(0.2)
		(N) 65	-7.3(0.6)	64.9(0.8)	-0.57	0.054(0.004)	0.055(0.004)	5.4(0.5)
		(N) 82	-9.2(0.6)	81.1(0.4)	-0.88	0.084(0.006)	0.088(0.006)	5.0(0.5)
(9,9)	845	(M) 60	-26.7(1.3)	60.4(0.2)	-3.06	0.153(0.007)	0.166(0.008)	8.9(0.4)
		(M) 69	-22.7(1.1)	68.8(0.3)	-2.60	0.130(0.007)	0.139(0.008)	7.4(0.3)
		(N) 65	-24.7(0.9)	64.6(0.3)	-1.92	0.182(0.006)	0.202(0.007)	15.9(0.8)
		(N) 82	-9.7(0.8)	81.2(0.6)	-0.93	0.088(0.008)	0.092(0.008)	5.9(0.4)
(10,10)	1028	(M) 60	-13.4(0.7)	60.3(0.3)	-1.53	0.072(0.004)	0.075(0.005)	3.1(0.2)
		(M) 69	-5.8(0.6)	68.8(0.6)	-0.66	0.031(0.003)	0.031(0.003)	1.3(0.3)
		(N) 65	-9.0(0.7)	65.9(0.5)	-0.70	0.066(0.004)	0.068(0.004)	5.1(0.4)
		(N) 82	-10.2(0.6)	82.1(0.3)	-0.98	0.092(0.006)	0.097(0.007)	5.9(0.4)
(11,11)	1228	(M) 60	-14.7(0.9)	59.8(0.4)	-1.68	0.080(0.005)	0.083(0.005)	3.2(0.2)
		(M) 69	-9.1(0.9)	68.4(0.6)	-1.04	0.049(0.005)	0.050(0.005)	1.9(0.2)
		(N) 65	-3.5(0.6)	69.2(1.1)	-0.27	0.026(0.004)	0.026(0.002)	1.7(0.2)
		(N) 82	-8.8(0.5)	82.0(0.4)	-0.84	0.080(0.004)	0.083(0.004)	4.8(0.2)
(12,12)	1447	(M) 60	-19.3(0.5)	60.7(0.2)	-2.21	0.105(0.003)	0.111(0.003)	3.8(0.1)
		(M) 69	-14.9(0.5)	69.5(0.2)	-1.70	0.081(0.003)	0.084(0.003)	1.8(0.1)
		(N) 65	-14.3(0.3)	66.2(0.2)	-1.11	0.104(0.002)	0.110(0.002)	7.2(0.2)
		(N) 82	-11.7(0.3)	81.3(0.2)	-1.12	0.106(0.002)	0.112(0.003)	7.3(0.2)
(13,13)	1683	(M) 60	-7.9(0.5)	60.6(0.3)	-0.90	0.043(0.002)	0.044(0.002)	1.4(0.1)
		(M) 69	-5.0(0.5)	71.2(0.5)	-0.57	0.027(0.002)	0.027(0.002)	0.9(0.1)
		(N) 65	-3.6(0.5)	68.3(1.1)	-0.28	0.026(0.004)	0.026(0.004)	1.6(0.2)
		(N) 82	-3.1(0.5)	80.8(0.9)	-0.29	0.028(0.004)	0.028(0.004)	1.4(0.2)
(14,14)	1937	(M) 60	-6.8(0.5)	60.1(0.4)	-0.78	0.037(0.003)	0.038(0.003)	1.0(0.1)
		(M) 69	-5.9(0.5)	68.6(1.1)	-0.67	0.032(0.003)	0.033(0.003)	0.9(0.1)
		(N) 65	-3.6(0.4)	67.7(0.7)	-0.27	0.026(0.002)	0.026(0.001)	1.5(0.2)
		(N) 82	-5.4(0.3)	81.6(0.4)	-0.51	0.040(0.002)	0.049(0.002)	2.4(0.2)
SiO^c $v = 0$ $J = 1 - 0$	2.1	(M) 0	-26.1(2.7)	3.7(0.9)	-1.45	0.103(0.011)	0.108(0.014)	2.4(0.4) ^{d)}
		(M) 60	-46.7(9.2)	59.8(0.6)	-5.71	0.405(0.080)	0.519(0.103)	5.1(1.1)
		(M) 69	-71.8(9.7)	68.4(0.7)	-6.68	0.473(0.064)	0.640(0.126)	8.3(1.3)
		(N) 0 - 20	-10.1(1.9)	10.0(1.7)	-0.55	0.079(0.015)	0.082(0.016)	1.8(0.5)
		(N) 65	-64.1(2.6)	63.8(0.4)	-3.13	0.447(0.041)	0.592(0.054)	14.6(3.4)
		(N) 82	-13.0(1.8)	84.1(0.6)	-1.57	0.224(0.031)	0.254(0.035)	2.5(0.5)
HC_3N^c $J = 4 - 3$		(M) 0	-2.4(0.5)	2.8(0.5)	-0.38	0.018(0.004)	0.018(0.004)	0.07(0.02)
		(M) 60	-14.1(1.0)	61.9(0.2)	-2.27	0.108(0.008)	0.114(0.008)	0.44(0.04)
		(M) 69	-13.1(1.1)	69.2(0.2)	-2.28	0.109(0.009)	0.115(0.010)	0.41(0.05)
		(N) 65	7.4(0.9)	50.2(0.6)	+0.54	—	—	4.8(0.6) ^{e)}
			-2.5(1.7)	66.7(—)	-0.20	0.020(0.014)	0.020(0.014)	0.16(0.11)
			11.5(1.4)	73.3(0.5)	+1.12	—	—	8.7(1.1) ^{e)}

a): (M) 60 denotes the velocity component at $v_{\text{LSR}} \sim 60 \text{ km s}^{-1}$ in Sgr B2 (M), (M) 69 is the component at $v_{\text{LSR}} \sim 69 \text{ km s}^{-1}$ in Sgr B2 M. (N) 65 and (N) 82 indicate the two velocity components seen toward Sgr B2 N, at $v_{\text{LSR}} \sim 65 \text{ km s}^{-1}$ and 82 km s^{-1} , respectively.

b): The errors do not include calibration uncertainties, but are formal errors obtained from the gaussian fits. The column densities are obtained from the integrated line intensities.

c): For SiO and HC_3N , $\Delta v_{1/2}$ was allowed to vary freely in the gaussian fits.

d): SiO and HC_3N column densities refer to lower rotational levels; for NH_3 , the column density refers to the sum in both doublet levels.

e): Column densities for the emission components of HC_3N lines calculated assuming optically thin emission and $T_{\text{MB}} = T_{\text{ex}} \tau$

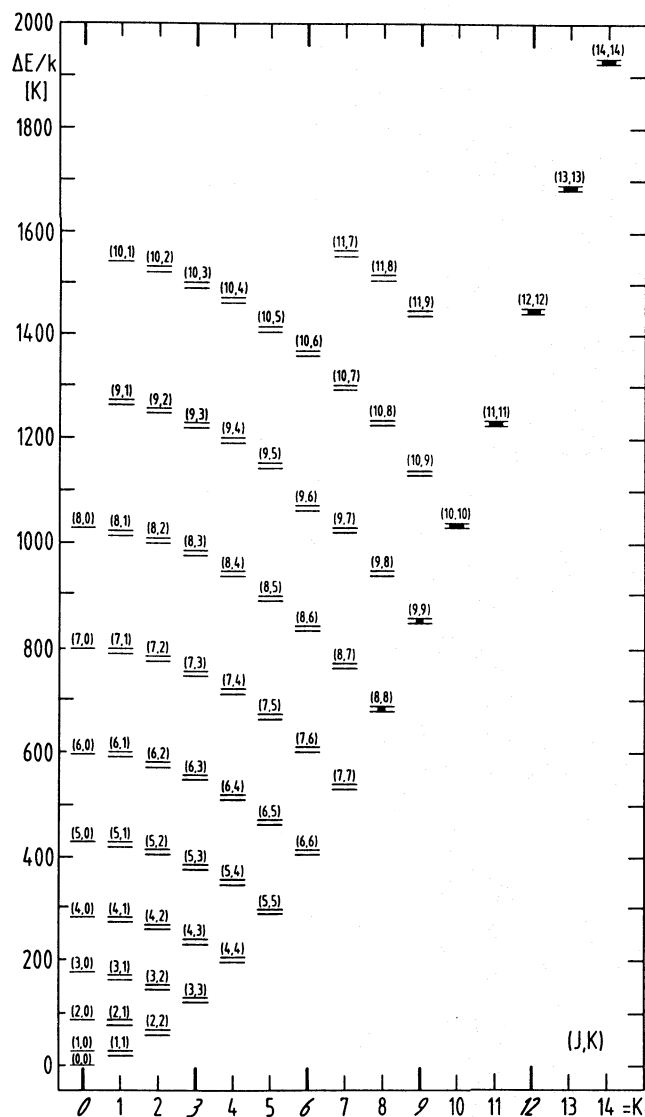


Fig. 2. This energy level diagram of NH_3 shows metastable and non-metastable transitions up to an energy above ground of 2000 K. Our data for the very highly excited metastable inversion lines at 1 cm wavelength are shown as bars connecting the doublets. The thicker bars show those transitions measured for the first time in SgrB2, the somewhat thinner bars show the two transitions previously measured by Wilson et al. (1982)

almost always found in emission. In addition, the lineshapes, v_{LSR} 's, and $\Delta v_{1/2}$'s are in agreement with other NH_3 inversion lines (see Figs. 3 and 4).

The NH_3 fits in Table 2 were obtained by a two-step process. First, all line parameters were allowed to vary freely. Then, averages of the v_{LSR} and $\Delta v_{1/2}$ values were calculated. In the case of blended lines, the use of this two-step process insures that the fit parameters for different lines can be more easily compared. In Sgr B2 (M) there are two blended components with $v_{\text{LSR}} = (60.4 \pm 0.7) \text{ km s}^{-1}$ and $(69.0 \pm 1.3) \text{ km s}^{-1}$ and $\Delta v_{1/2} = (8.2 \pm 1.4) \text{ km s}^{-1}$ and $(8.2 \pm 2.5) \text{ km s}^{-1}$ respectively. There is no systematic variation in v_{LSR} or linewidth with (J, K) . Toward

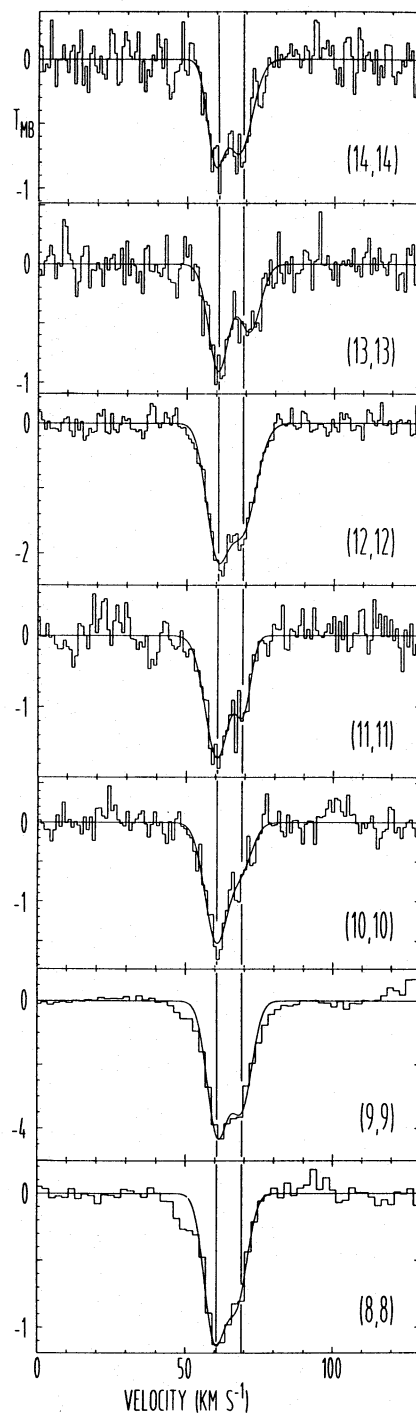


Fig. 3. The line profiles of the transitions observed at 1 cm wavelength toward Sgr B2 (M). The temperature scale is T_{MB} . Two gaussians with fixed linewidths were fitted to each spectrum. The two vertical lines mark the radial velocities of the velocity components. In the (9,9) line spectrum at $\sim 130 \text{ km s}^{-1}$, there is a positive-going feature; we tentatively attribute this to the $13_2 - 13_1\text{E}$ transition of methanol, which has a rest frequency of 27.47258 GHz, 5.36 MHz lower than the rest frequency of the $(J, K)=(9,9)$ inversion doublet transition (Poynter & Kakar 1978; Lovas 1991). This line is more convincingly seen in Fig. 4. The methanol line parameters have *not* been listed in Table 2

Sgr B2(N), two much more clearly separated velocity components are seen. These can be best distinguished in the more highly excited NH_3 inversion lines. The mean fit parameters are: $v_{\text{LSR}} = (66.7 \pm 1.0) \text{ km s}^{-1}$ and $(81.5 \pm 0.9) \text{ km s}^{-1}$ and $\Delta v_{1/2} = (12.1 \pm 4.4) \text{ km s}^{-1}$ and $(9.8 \pm 0.9) \text{ km s}^{-1}$. For the final gaussian fits, the linewidths were fixed to the mean values. The formal errors, from gaussian fits, are very small, but do not include calibration or baseline uncertainties. As can be seen from the figures, fixing the values of $\Delta v_{1/2}$ resulted in good fits in all cases; however, the ratios of the integrated intensities of the individual components toward (M) vary between 1.15 and 2.31 and are very blended. For these reasons, we used the sum of both velocity components for the calculation of T_{rot} .

Fits to the SiO and HC_3N spectra toward SgrB2(M) were made only for the absorption features. We are of the opinion that the wide weak emission line is real, since this is also present in the $J = 2 - 1$ SiO line spectrum of Greaves et al. (1992), and in our HC_3N spectrum. Toward SgrB2(N), the parameters of our SiO spectrum are in reasonable agreement with the NH_3 result. However, the HC_3N result is confusing since there is apparently weak absorption which is bracketed by emission at somewhat unusual v_{LSR} 's.

The NH_3 column density divided by T_{ex} in each level was derived for each component using the line-to-continuum ratio and the apparent optical depth. The column density given refers to the sum in both doublet levels. For absorption lines, the usual relation for optical depth is

$$\tau \equiv \tau_{\text{app}} = -\ln\left(1 - \frac{|T_L|}{T_C}\right) \quad (1)$$

For NH_3 , we have used

$$\frac{N(J, K)}{T_{\text{ex}}} = 1.61 \cdot 10^{14} \frac{J(J+1)}{K^2 \nu [\text{GHz}]} \tau_{\text{app}} \Delta v_{1/2} \quad (2)$$

The SiO data are shown in Fig. 5 and line parameters are listed in Table 2. The line T_{MB} and line-to-continuum ratios are based on a peak T_{MB} of 14.1 K for Sgr B2(M) and 7 K for Sgr B2(N). The column densities in the $J = 0$ rotational level were determined using Eq. (1) of Wilson et al. (1990), with $A = 3.1 \cdot 10^{-6} \text{ sec}^{-1}$, which corresponds to 3.1 Debyes:

$$\frac{N_1}{T_{\text{ex}}} = \frac{\nu^2 [\text{GHz}] g_1}{4.83 \cdot 10^{-4} A_{ul} g_u} \int \tau dv = 1.28 \cdot 10^{12} \tau_{\text{app}} \Delta v_{1/2} \quad (3)$$

For the $J = 4 - 3$ transition of HC_3N , for a dipole moment of 3.6 Debye, we find $A = 3.2 \cdot 10^{-6} \text{ sec}^{-1}$. Using this, the relation of column density and optical depth is

$$\frac{N_1}{T_{\text{ex}}} = 6.59 \cdot 10^{11} \tau_{\text{app}} \Delta v_{1/2} \quad (4)$$

4. Discussion

4.1. Estimates of T_{ex} and T_{rot}

If the NH_3 is uniformly distributed in a cloud large compared to the telescope beam, absorption toward compact continuum

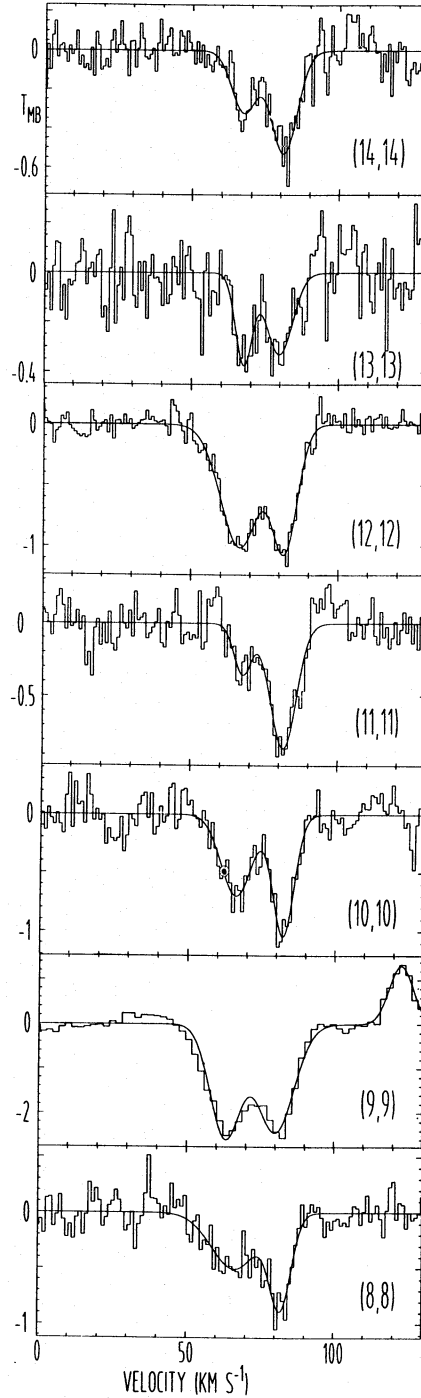


Fig. 4. The line profiles observed toward SgrB2(N). The positive feature the (9,9) line spectrum at 122.5 km s^{-1} is identified with the $13_2 - 13_1\text{E}$ transition of methanol. (See the discussion in the caption of Fig. 3)

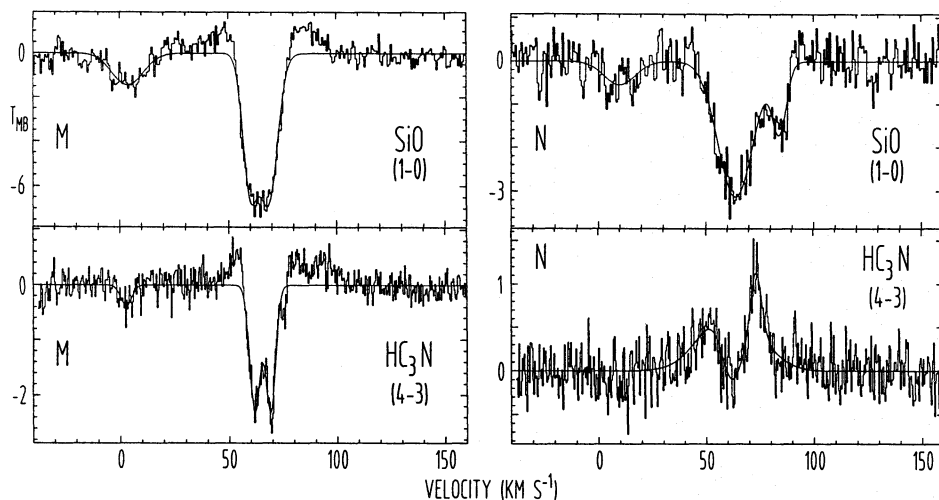


Fig. 5. The $J = 1 - 0$ SiO and the $J = 4 - 3$ HC₃N profiles observed toward Sgr B2 (M) and (N)

sources such as SgrB2(M) or SgrB2(N) necessarily implies that $T_{\text{ex}} < T_{\text{MB}}$, where T_{MB} is the main beam brightness temperature of the continuum source. This argument was applied to lower lying NH₃ metastable inversion line data in Paper I. Then, T_{ex} of the NH₃ metastable inversion lines is < 10 K. We have not mapped any of the metastable inversion lines presented here, so the assumption that the NH₃ is distributed over a wide region relies on previous mapping results: For example, in the (7,7) inversion line spectra of Mauersberger et al. (1986), or the (5,5) and (6,6) spectra in Paper I. Since the value of T_{kin} is larger than that found in Paper I, $n(\text{H}_2)$ will be lower than the previous value, estimated in Paper I, 10^4 cm^{-3} .

We follow the approach used in Paper I and Wilson et al. (1993b) to determine T_{rot} . Our data for the metastable lines has been converted into level populations per Kelvin, assuming that all lines are optically thin. We plot the normalized level populations versus energy of the levels, that is a Boltzmann plot. The results for all metastable absorption lines measured toward Sgr B2 (M) and (N) are given in Figs. 6 and 7. The 1.3 cm data (Paper I) are represented by open circles. By including the 1 cm data, the range of energy covered has been more than tripled and is now nearly 2000 K.

For Sgr B2 (M), the sum of the column densities of the two components at $\sim 60 \text{ km s}^{-1}$ and $\sim 69 \text{ km s}^{-1}$ is used since the two components are too heavily blended to be reliably separated. The more clearly separated components seen toward (N) can be analyzed individually. As can be seen from the spectra, the relative intensities of these two components show a different dependence on energy of the level.

T_{rot} derived from least squares fits to the metastable inversion lines up to (7,7), and a second fit for the 1 cm lines are also given in Figs. 6 and 7. Clearly, this simple process gives a reasonable fit to the data; this would indicate at least two regimes of *rotational* temperatures: From the 1.3 cm data, we get ~ 170 Kelvin for all velocity components toward both (M) and (N), from the 1 cm data, the rotational temperature of the 65 km s^{-1} component in both (M) and (N) is 600 Kelvin to 650 Kelvin, while the 82 km s^{-1} component seen toward (N) is

significantly hotter: we find a T_{rot} of 820 Kelvin. This component is *only* seen in metastable lines toward Sgr B2 (N). Its existence as a separate, hotter component of gas within the Sgr B2 complex, tentatively proposed in Paper I, is confirmed by these data.

The value of T_{rot} has to be very high and may be fairly well defined by the “straight line tail” of the Boltzmann plot, that is, ~ 650 K for the 65 km s^{-1} component and > 800 K for the 82 km s^{-1} component in Sgr B2 (N).

Since three values of T_{rot} represent a reasonable fit to the data, these can be used to calculate total NH₃ column densities. The column density thus calculated is only based on observed data and model independent. From $T_{\text{rot}} = 165$ K, we find toward (M), $N(\text{NH}_3)_{\text{tot}}(1) = 8 N(1,1) = 10^{16} \text{ cm}^{-2}$ (see Paper I). The second temperature component, $T_{\text{rot}} = 650$ K, yields $N(\text{NH}_3)_{\text{tot}}(2) = 17 N(12,12) = 5 \cdot 10^{14} \text{ cm}^{-2}$. In both cases, $T_{\text{ex}} = 5$ K has been assumed. As can also be seen from the Boltzmann plots, the lower levels, represented by temperature component (1), make up most of the column density. For Sgr B2 (N), the result is essentially the same.

An alternative to our LTE assumption is the approach used by Flower et al. (1994). For a very subthermally excited gas (i.e. $T_{\text{ex}} \ll T_{\text{rot}}$, or T_{kin}), a straight line fit to the data points in a Boltzmann plot is *not expected*. Flower et al. (1994) have used a non-LTE model to fit the metastable line data. In this model, the populations of different metastable (J,K) levels are linked by collisional transitions, either directly between different metastable levels, or via a transfer of population between metastable and non-metastable levels, followed by a rapid decay to metastable levels. The problem with computing the level populations in this model is the lack of collisional rates for high T_{kin} . Flower et al. (1994) have extrapolated the deexcitation rates of Danby et al. (1988) under the assumption that these rates are the same as those calculated by Danby et al. (1986) for $T_{\text{kin}} = 300$ K, and also follow the same selection rules. The collisional excitation rates can be calculated from the deexcitation rates using the principle of detailed balance. This model was then used to make a best fit

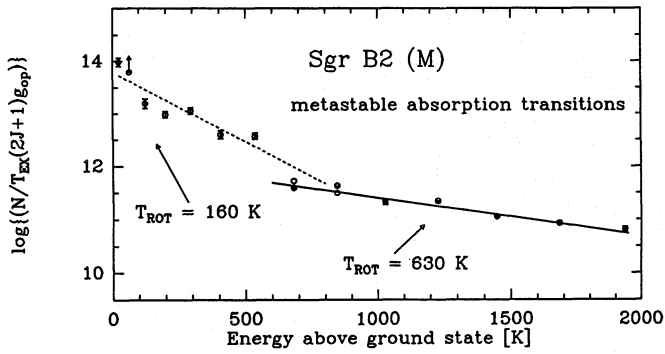


Fig. 6. Boltzmann plot for all metastable transitions of NH_3 measured toward Sgr B2 (M). The sum of the column densities of the two components at $\sim 60 \text{ km s}^{-1}$ and $\sim 69 \text{ km s}^{-1}$ is displayed since the two components cannot be reliably separated. The open circles with error bars refer to the data taken in the 1.3 cm wavelength range. To distinguish the (8,8) and (9,9) results of Wilson et al. (1982) from the present data, we have plotted the 1982 results as open circles without error bars. The filled circles represent the 1 cm data from this paper. The size of the error bars is small, and can scarcely be distinguished. Unweighted least square fits to the two data sets are also shown

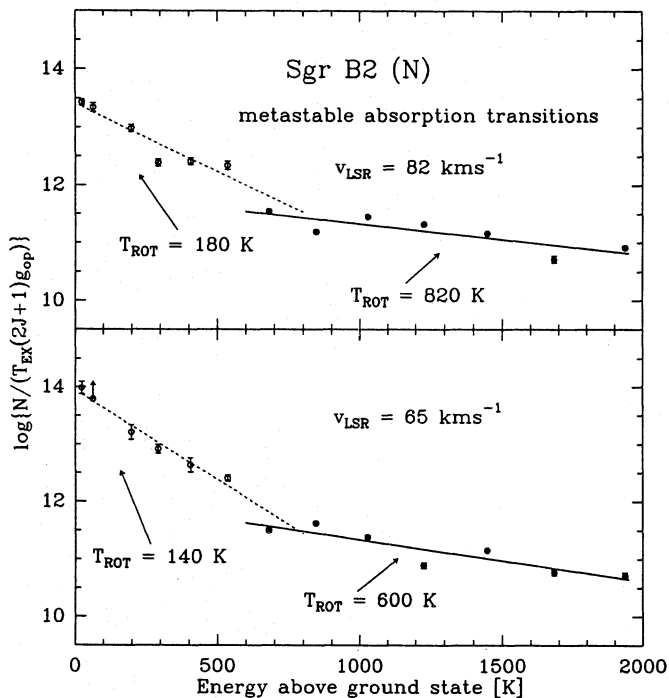


Fig. 7. Boltzmann plots for all metastable transitions observed toward Sgr B2 (N). Separate plots for the two velocity components are shown. Note that the rotational temperature derived for the 1 cm lines in the component at $\sim 82 \text{ km s}^{-1}$ (upper panel) is significantly higher than the value obtained for the more intense absorption at $\sim 65 \text{ km s}^{-1}$ lower panel

to the data for both maxima, allowing the ortho-to-para ratios to vary.

Both the LTE and the Flower et al. (1994) methods of analyzing the NH_3 data indicate that there is a component with $T_{\text{kin}} > 600 \text{ K}$ in the envelope of Sgr B2. Flower et al. (1994) have noted that energetically there is a problem of bringing large amounts of gas to such a high T_{kin} and also avoiding the presence of a great deal of cold NH_3 . As can be seen from Figs. 6 and 7, there is very little cold, i.e. $T_{\text{kin}} \sim 30 \text{ K}$ NH_3 in the envelope. Flower et al. (1994) argued that NH_3 must be produced on grains, and then liberated by shocks. In this picture, C shocks liberate the NH_3 and also heat the gas to high temperatures. The relative abundances of NH_3 are determined by the atomic N abundance. The $X(\text{NH}_3)$ could reach $\sim 10^{-5}$, $\sim 10^3$ times the usual value. The gas phase NH_3 is liberated from grain surfaces by a C shock. For a B field strength of $\sim 10 \mu\text{G}$, this shock has the strength required to free the NH_3 but not to dissociate the NH_3 .

From the virial mass of the envelope, we estimate that the average H_2 column density is $3 \cdot 10^{23} \text{ cm}^{-2}$ (Paper I). Using dust data, Gordon et al. (1993) find an even larger value, $3 \cdot 10^{24} \text{ cm}^{-2}$. Then, if we combine the column density estimates of NH_3 with the H_2 column density estimate and the relative abundance of NH_3 from shock chemistry, as estimated by Flower et al. (1994), we conclude that $\sim 10^{-4}$ of the gas in the envelope is at $T_{\text{kin}} \sim 600 \text{ K}$. A possible problem with this analysis is that we know the envelope of Sgr B2 is at least somewhat clumped (see Paper I). It is then possible that we happen to be looking at “non-typical-regions”. In this regard, there is the suggestion by Mehringer et al. (1992) that the extended HII region in Sgr B2 (N) is the result of a collision between two H_2 clouds. Even if this is the case, the hot H_2 we discuss is more extended than this HII region, since in Mauersberger et al. (1986) and Paper I, emission from the (5,5), (6,6) and (7,7) inversion lines of NH_3 are found up to $2'$ from the continuum peaks. There is evidence for H_2 gas with $T_{\text{kin}} \ll 600 \text{ K}$ in the envelope of Sgr B2: If all gas were extremely hot, one would expect to see intense emission from hot CO. This, however, is not the case. Scoville et al. (1975) report that T_{kin} of the CO is $\sim 20 \text{ K}$, almost the temperature of the dust. This strengthens the notion that there is some cooler material in the envelope. Presumably, the CO molecule, with its smaller dipole moment and higher dissociation energy, will not so easily be destroyed by shocks, and will remain in the gas phase longer, and thus have a chance to reach lower T_{kin} values.

4.2. SiO and HC_3N line data: additional density determinations for the envelope

The presence of SiO absorption toward Sgr B2 had been noted by Haschick & Ho (1990) and Greaves et al. (1992). The critical density for the $J = 1 - 0$ transition of SiO is $3 \cdot 10^4 \text{ cm}^{-3}$, much larger than the H_2 density estimated for the envelope of Sgr B2. The presence of absorption in the $J = 1 - 0$ line of SiO confirms the sub-thermal excitation found for NH_3 . To investigate $n(\text{H}_2)$ in more detail, we have applied an LVG radiative transfer model using our $J = 1 - 0$ line data and the $J = 2 - 1$ line data of

Greaves et al. (1992). For the $J = 2 - 1$ SiO line data, we obtained a peak optical depth of unity. We took the T_{kin} to be 200 K, and used a gradient of $1 \text{ km s}^{-1} \text{ pc}^{-1}$. We find that a high relative abundance of SiO, $X(\text{SiO}) \sim 10^{-9}$, and a H_2 density of 2 to $5 \times 10^3 \text{ cm}^{-3}$ provide a good fit to our data. The excitation temperature, T_{ex} , of the $J = 1 - 0$ transition, in this model is $\sim 3.4 \text{ K}$. In addition to the gas with v_{LSR} between 50 and 100 km s^{-1} , the absorption with v_{LSR} near 0 km s^{-1} is to be noted. This feature must be extended over $>45''$, must be hot, from NH_3 absorption up to the (6,6) inversion line detected by Gardner et al. (1988), and has a low H_2 density. Hot low density H_2 gas is a characteristic of clouds near the galactic center. On the basis of the SiO and NH_3 results, we find that this feature may be within a few hundred parsec of the galactic center.

We analyzed our HC_3N line data following the method applied to the SiO absorption. Since the dipole moment is 3.6 Debye and the frequency of the $J = 4 - 3$ line of HC_3N is 36.1 GHz, the critical density is of order 10^4 cm^{-3} . For envelope gas, absorption is to be expected. The presence of absorption shows that the H_2 density must be lower than estimates based on higher J lines of this molecule (Lis & Goldsmith 1991). In this regard, the higher J transitions of HC_3N , such as the $J = 11 - 10$ line, have completely different lineshapes (see, e.g., Mauersberger et al. 1989), and presumably arise in the denser compact cores. We have applied an LVG analysis to the HC_3N data for low J lines that is, our data, that of Morris et al. (1976) and Mangum et al. (1988). We find, for T_{kin} of $\sim 200 \text{ K}$, a H_2 of $\sim 3000 \text{ cm}^{-3}$ and a relative abundance of $\sim 10^{-10}$. For the HC_3N data, the H_2 density cannot be larger than 10^4 cm^{-3} , since then the T_{ex} of the $J = 3 - 2$ line would be larger than 20 K, and this line would appear in emission, which is certainly not the case. In summary, the SiO and HC_3N results give strong support to our interpretation of the NH_3 absorption line data.

In the SiO and HC_3N profiles, there are wider line wings which are not present in the NH_3 spectra. These are more prominent toward SgrB2(N), probably since the continuum temperature of this source is smaller. Since these lines are found in emission, we assume that these wings arise from the compact cores, which have higher H_2 densities.

4.3. Shocks in the envelope of SgrB2

On the basis of SiO, SO, H^{13}CO^+ , H^{13}CN and HN^{13}C data for three galactic regions, Martín-Pintado et al. (1992) concluded that SiO is liberated from grains by shock waves. Our data for SgrB2(M) and (N) support this interpretation, since the SiO absorption is quite strong, and the high T_{kin} in the envelope, as determined from NH_3 data, indicate a low density, hot gas. This would be the result of cloud cloud collisions, giving rise to shocks both heating the gas (but not necessarily the dust) and setting Si free from grain mantles. This data strengthen the argument that the heating of clouds in the galactic center is caused by shock waves, presumably related to cloud-cloud collisions. The alternative heating mechanisms are cosmic ray heating with an enhanced cosmic ray flux, and ambipolar diffusion. The enhanced cosmic ray flux seems unlikely since, to reach a T_{kin} of

$\sim 200 \text{ K}$, cosmic ray heating would require the dissociation of all of the H_2 . The ambipolar heating mechanism requires a B field of $\sim 100 \mu\text{Gauss}$, which might be possible, but this would not produce the observed SiO, without further extra assumptions.

4.4. Comparison with other clouds

Hüttemeister et al. (1993b) found that $T_{\text{kin}} > 200 \text{ K}$ in $\sim 25\%$ of the gas in 36 galactic center molecular clouds. The behavior of T_{kin} from NH_3 measurements is similar to that found for SgrB2. Thus, the shock heating may be a general feature of galactic center molecular clouds. For some other galaxies, probably similar to the Milky Way, there is a similar result. Toward NGC253, Mauersberger & Henkel (1991) report the detection of thermal SiO emission extended over more than several tens of pc. This is strong evidence for very hot molecular gas in this source.

5. Conclusions

From our detection of seven metastable inversion transitions of ammonia, which are emitted from doublet levels up to almost 2000 K above the ground state, and measurements of the $v = 0$, $J = 1 - 0$ rotational transition of silicon monoxide and the $J = 3 - 2$ transition of HC_3N in absorption toward the two compact HII regions in Sgr B2, we conclude the following:

- (1) The mere detection of collisionally excited, quasithermal absorption lines at $\sim 2000 \text{ K}$ toward both the middle (M) and the north (N) component of the Sgr B2 complex requires the presence of low density, hot molecular gas.
- (2) While the bulk of the gas is detected at the “standard” radial velocity of the Sgr B2 complex, $v_{\text{LSR}} \sim 65 \text{ km s}^{-1}$, both the NH_3 and the SiO data clearly show another component at $\sim 82 \text{ km s}^{-1}$ toward Sgr B2 (N). In ammonia, this component becomes more prominent in the more highly excited lines. It has no counterpart toward Sgr B2 (M) and is not seen in non-metastable NH_3 lines, indicating low densities or little IR radiation.
- (3) From simple LTE analyses of the NH_3 lines, at least part of the gas at 65 km s^{-1} has a T_{kin} of $\sim 650 \text{ K}$. The gas at 82 km s^{-1} in N is hotter still, with T_{kin} exceeding 800 K .
- (4) From the fact that all lines are seen in absorption, we conclude that the excitation temperature is below 20 K . Therefore, the lines are extremely subthermally excited and do not arise in the dense, hot, star forming cores of the Sgr B2 complex but rather in the extended envelope.
- (5) The temperatures found from the NH_3 lines suggest shocks as a likely heating mechanism of the gas. Model calculations confirm the possibility, but are not finally conclusive. From NH_3 abundance estimates, extremely high abundances provided by shock chemistry might not be required.
- (6) The presence of SiO and HC_3N absorption lines gives strong support for low H_2 densities, certainly less than 10^4 cm^{-3} . The SiO results give support for the model of shock heated gas, with the SiO being set free from dust grain mantles by shock waves generated in cloud-cloud (or rather envelope fragment envelope fragment) collisions.

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