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HCl ABSORPTION TOWARD SAGITTARIUS B2

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ABSTRACT

We have detected the 626 GHz $J = 1 \rightarrow 0$ transition of hydrogen chloride ($H^{35}Cl$) in absorption against the dust continuum emission of the molecular cloud Sagittarius B2. The observed line shape is consistent with the blending of the three hyperfine components of this transition by the velocity profile of Sgr B2 observed in other species. The apparent optical depth of the line is $\tau \approx 1$, and the *minimum* HCl column density is 1.6×10^{14} cm^{-2}. A detailed radiative transfer model was constructed which includes collisional and radiative excitation, absorption and emission by dust, and the radial variation of temperature and density. Good agreement between the model and the data is obtained for HCl/$H_2 \sim 1.1 \times 10^{-9}$. Comparison of this result to chemical models indicates that the depletion factor of gas-phase chlorine is between 50–180 in the molecular envelope surrounding the SgrB2(N) and (M) dust cores.

Subject headings: ISM: abundances — ISM: individual (Sagittarius B2) — ISM: molecules

1. INTRODUCTION

Ultraviolet absorption-line studies (Jura & York 1978; Harris & Bromage 1984; Harris, Gry, & Bromage 1984) have shown that the depletion of chlorine in diffuse interstellar clouds is not severe, with abundances typically only a factor of 2–3 below the solar value of Cl/H $\approx 2 \times 10^{-7}$ (Anders & Grevesse 1989). Thus chlorine may also be abundant in dense molecular cloud gas. The chemistry of chlorine in molecular clouds was analyzed by Jura (1974) and Dalgarno et al. (1974), who concluded that essentially all of the gas-phase chlorine would be in the form of HCl. If this is correct, and if chlorine remains undepleted, then HCl could be very important for cooling dense ($n \geq 10^5$ cm^{-3}) molecular clouds (Dalgarno et al. 1974).

HCl was initially detected by Blake, Keene, & Phillips (1985), who observed the 626 GHz transition in emission in OMC-1 and deduced a range for the fractional abundance relative to H_2 of $0.5–5.0 \times 10^{-8}$. This corresponds to a depletion factor between 10 to 100 if HCl accounts for all of the gas-phase chlorine. However, Blake et al. (1985) concluded that the depletion in OMC-1 was in the range 3–30, because chlorine can also exist in atomic form (Smith & Adams 1985; Blake, Anicich, & Huntress 1986; Millar et al. 1987; Schilke, Phillips, & Wang 1994). Neufeld & Green (1994) have recently argued that lower abundances are more likely, around HCl/$H_2 \approx 2 \times 10^{-9}$. Schilke et al. (1994) have mapped the HCl emission in OMC-1, and they obtain similar values for the HCl abundance.

The large critical density of the $J = 1 \rightarrow 0$ transition (4×10^7 cm^{-3}; Neufeld & Green 1994) means that HCl will be subthermally excited in all but the densest molecular cloud cores, and so the determination of the HCl abundance from the intensity of the 626 GHz emission line will depend very strongly on the estimated mean density. On the other hand, this ground-state transition might be detectable in *absorption* against strong submillimeter dust continuum sources. This should lead to reliable estimates of the HCl abundance in the quiescent molecular envelopes surrounding the dust cores, since it is unlikely that there will be sufficient excitation in these envelopes to significantly populate the $J \geq 1$ rotational levels. In this Letter, we describe the detection of HCl in absorption against the dust emission of the Sagittarius B2 molecular cloud.

2. OBSERVATIONS

The rest frequency of the $F = 5/2 \rightarrow 3/2$ component of the HCl $J = 1 \rightarrow 0$ transition is 625.9188 GHz (DeLucia, Helminger, & Gordy 1971). We observed Sgr B2 on 1993 June 23 from the NASA Kuiper Airborne Observatory (KAO) flying at an altitude of 12.5 km, in a flight from Hickam AFB in Honolulu, HI. We used a 500–680 GHz SIS receiver, consisting of a quasioptical SIS mixer (Zmuidzinas & LeDuc 1992; Zmuidzinas et al. 1994), a multiplied (×6) Gunn oscillator, and a 350 MHz bandwidth digital autocorrelation spectrometer based on the Caltech high-speed CMOS correlator chip (the "CSO320" chip; Von Herzen 1991). The receiver noise temperature at 626 GHz was measured to be 250 K (DSB) during the flight, and the system temperature including telescope and atmospheric losses was about 600 K (DSB).

The intensity calibration was obtained by observing Jupiter at 576 GHz and making a five-point map. In addition, we compared CO(5–4) line intensities in several sources with those measured on a previous flight series in 1992 September. We deduce a net coupling efficiency between the receiver and the telescope main beam for the 1993 flights of $\eta \approx 45\%$, which includes losses due to spillover, sidelobes, transmission through a polyethylene pressure window, and reflection from the telescope optics. The Jupiter observations also give a beam width of $2'.5$ (FWHM) at 576 GHz and $2'.3$ at 626 GHz. We judge our calibration uncertainty to be around ±25%. The telescope pointing was checked during the observations of Jupiter, and was confirmed by observing the $^{13}CO(6–5)$ transition at 660 GHz toward Sgr B2. Our beam was roughly centered between the (N) and (M) dust cores which are separated in declination by about 46″ (Lis et al. 1993); therefore, both cores fall near the peak of our $2'.3$ beam. We

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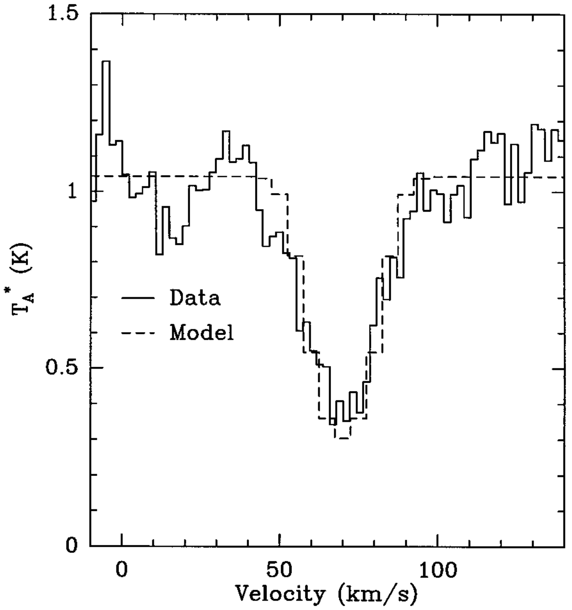

FIG. 1.—Spectrum of H^{35}Cl observed in absorption midway between the cores Sgr B2(N) and Sgr B2(M) ($\alpha_{1950} = 17^h\,44^m\,10^s.6$; $\delta_{1950} = -28°\,21'\,43''$). The dashed line is the spectrum predicted by our radiative transfer model. The model assumes an abundance of HCl/H$_2$ = 1.1×10^{-9} which is uniform throughout the cloud.

estimate that the telescope pointing errors are less than about $0'.5$. We used the standard dual-beam observing mode with the secondary mirror chopping at 4 Hz with an amplitude of 10′, which was essential for reliable measurements of the continuum level.

3. RESULTS

The spectrum shown in Figure 1 was obtained in an integration time of 32 minutes. The local oscillator frequency was shifted for half of the integration to confirm the sideband identification. The HCl line appears in absorption with an intensity of $\Delta T_A^* \approx -0.7$ K and a velocity width of ΔV(FWHM) ≈ 25 km s^{-1}. The dust continuum emission is also apparent, and has an intensity of T_A^*(dust) = 1.04 ± 0.04 K (SSB). The rotational levels of HCl have a hyperfine splitting (DeLucia et al. 1971) caused by the quadrupole moment of the ^{35}Cl nucleus ($I = 3/2$). The $J = 1 \to 0$ transition is split into three components with relative strengths of 50%, 33.3%, and 16.7%, and with velocity offsets of 0, -6.3, and $+8.2$ km s^{-1}. Our data (Fig. 1) show a single feature which results from blending in velocity. The spectrum is consistent with a background continuum source and a foreground absorbing cloud with two Gaussian velocity components centered at $V_{\rm LSR} = 66$ and 81 km s^{-1} with $\Delta V = 14$ and 12 km s^{-1} (FWHM), and whose peak optical depths in the main $F = 5/2$–$3/2$ hyperfine component are $\tau \approx 0.7$ and 0.2, respectively. Similar lineshapes are deduced for other molecular lines seen in absorption (e.g., Martín-Pintado et al. 1990; Greaves et al. 1992). There may also be weak absorption at 0–30 km s^{-1}, but higher signal-to-noise data are needed to confirm this.

4. ANALYSIS

The *minimum* HCl column density required to produce the absorption feature is easily estimated. In general, the A coefficients for the hyperfine components are

$$A(J+1\,F' \to J\,F) = (2J+3)(2F+1)\begin{Bmatrix}1 & F & F'\\ I & J+1 & J\end{Bmatrix}^2 \times A(J+1 \to J), \qquad (1)$$

which we have expressed in terms of the $A(J+1 \to J)$, the spontaneous rate for the “unsplit” transition. The A coefficients for the hyperfine components of the ground-state transition are in fact all equal to $A(1 \to 0) = 1.17 \times 10^{-3}$ s^{-1} ($\mu = 1.109$ D for HCl; Kaiser 1970).

The apparent optical depth $\tau(V)$ can be deduced from the line-to-continuum ratio in our observed spectrum; we calculate $\int \tau dV = 25 \pm 1$ km s^{-1} (1 σ) for the velocity interval 41–95 km s^{-1}. Because the apparent optical depth includes the contributions of the three hyperfine components, we use the expression

$$\int dV \sum_{F,F'} \tau(J\,F \to J+1\,F') = \frac{2J+3}{2J+1}\,\frac{\lambda^3 A(J+1 \to J)}{8\pi} \times N(J)(1 - e^{-h\nu/kT_x}), \qquad (2)$$

which is the same result one obtains for a transition without hyperfine splitting. If we assume that the $J \geq 1$ levels are unpopulated, which is likely given the extremely large critical density of the $J = 1 \to 0$ transition (4×10^7 cm^{-3}; Neufeld & Green 1994), the HCl column density is given by

$$N(\mathrm{HCl}) = N(J=0) = 6.52 \times 10^{12}\ \mathrm{cm^{-2}\ km^{-1}\ s} \int \tau dV, \qquad (3)$$

and so we obtain N(HCl) = $1.63 \pm 0.07 \times 10^{14}$ cm^{-2}. This result should be fairly insensitive to pointing or calibration errors since the line-to-continuum *ratio* determines the optical depth.

We need to know the H$_2$ column density of the absorbing gas to calculate the fractional abundance of HCl. With the $2'.3$ beam of the KAO, we are most likely sampling the extended envelope of the cloud rather than the dense cores. This envelope is apparent in the ^{13}CO and C^{18}O maps of Lis & Goldsmith (1989), and has an H$_2$ column density around 3×10^{23} cm^{-2}, assuming ^{13}CO/H$_2 \approx 10^{-6}$. This gives HCl/H$_2 \approx 5 \times 10^{-10}$. However, we are sampling only half of the total column density if the dust cores are embedded near the center of the extended envelope, so perhaps a better abundance estimate is HCl/H$_2 \approx 10^{-9}$.

5. RADIATIVE TRANSFER MODELING

The simple analysis given above depends on several assumptions whose validity should be checked. Questions arise about the choice of the H$_2$ column density, the excitation of HCl and the influence of the strong dust continuum radiation, and the artificial separation of the cloud into a radiating dust core and an absorbing gas envelope. Another issue to be resolved is the lack of observed *emission* from the cores. One might have expected to see HCl in emission, since the dust cores (M) and (N) are extremely massive and dense (e.g., Lis et al. 1993) and the excitation conditions appear to be ideal for HCl. Indeed, in the central 0.1 pc of these cores, the mean density is 2–3 × 10^7

TABLE 1

Sagittarius B2(N) Dust Continuum Model

Telescope	λ[a]	θ(beam)[b]	Observed Flux[c]	Model Flux[c]
CSO[d]	1300	31″	88	94
IRAM[e]	1300	12	51	52
OVRO[f]	1300	4.5 × 3.7	20	24.5
JCMT[g]	1100	60	225	237
JCMT[g]	1100	19	103	118
JCMT[g]	450	60	4323	3530
JCMT[g]	450	16	1070	1522

[a] Wavelength in μm.

[b] Telescope beam in arcseconds FWHM.

[c] Flux in units of Jy.

[d] Lis et al. 1991.

[e] Martín-Pintado et al. 1990.

[f] Lis et al. 1993.

[g] Goldsmith et al. 1990.

cm^{-3}, the gas temperature is at least 150 K, and the total mass approaches 10^4 $M_\odot$.

The physical structure of the cloud is fairly well constrained by observations. The large-scale structure over a 27.5 × 27.5 pc region was determined by Lis & Goldsmith (1989), who mapped $C^{18}O(1-0)$ at a resolution of 1.8 pc. Their data is consistent with a spherical cloud model (their model "C") whose density varies with radius according to

$$n(r) = n_1 + n_2\left(\frac{r}{1.25\ \mathrm{pc}}\right)^{-2}, \tag{7}$$

for 1.25 pc $\leq r \leq$ 22.5 pc, where $n_1 = 2.2 \times 10^3\ \mathrm{cm}^{-3}$ and $n_2 = 5.5 \times 10^4\ \mathrm{cm}^{-3}$. For $r \leq 1.25$ pc, Lis & Goldsmith (1989) assumed the density to be constant, $n(r) = n_1 + n_2$, because their data did not constrain the density at smaller scales. The structure at smaller scales can be determined by high angular resolution measurements of the dust continuum radiation (Carlstrom & Vogel 1989; Goldsmith et al. 1990; Martín-Pintado et al. 1990; Lis, Carlstrom, & Keene 1991; Lis et al. 1993). We find that a simple extension of the models of Lis & Goldsmith (1990) can reproduce the observed dust emission toward Sgr B2(N). Our model extrapolates equation (7) to smaller radii, and assumes the dust temperature distribution derived by Lis & Goldsmith (1990):

$$T_{\mathrm{dust}}(r) = 40\ \mathrm{K} \times \left(\frac{r}{1\ \mathrm{pc}}\right)^{-0.5}. \tag{8}$$

Since the dust temperature is only weakly dependent on the source luminosity, equation (8) is roughly correct for either core. Table 1 gives a comparison between our model and the fluxes measured for Sgr B2(N) for a range of wavelengths and angular resolutions. The agreement is remarkably good, especially considering that our model does not include the Sgr B2(M) core whereas the measurements made with the larger beams must contain some fraction of the flux from this source.

We developed a radiative transfer model which assumes a spherical cloud with a density distribution given by equation (7) for all $r \leq 22.5$ pc, and a dust temperature distribution given by equation (8). Obviously, this model is a simplification since Sgr B2 contains *two* cores. However, we do not expect this to be a serious problem since the two cores are unresolved by our KAO beam, and also since our chosen density distribution accounts for most of the mass in the cloud. At most, we might expect quantitative errors of a factor of 2 since the continuum fluxes from the two cores are comparable at 626 GHz. We also assume that the gas and dust temperatures are equal, which is reasonable for $r < 10$ pc, but may somewhat underestimate the gas temperature at larger radii (Lis & Goldsmith 1990).

Our radiative transfer model takes into account the excitation of HCl by collisions (Neufeld & Green 1994), line radiation, and dust continuum radiation. The dust parameters were taken from Lis et al. (1991). Our model subdivides the cloud into 200 radial shells, and uses a multilevel accelerated lambda-iteration method (e.g., Rybicki & Hummer 1991) to solve for the level populations and the transfer of the line and continuum radiation in a self-consistent fashion. The hyperfine structure of HCl is ignored in this calculation since the components are blended by the velocity profile; furthermore, the hyperfine splitting becomes less important for larger values of J (Nolt et al. 1987). Instead, the reduced peak optical depth in the $1 \rightarrow 0$ transition caused by the hyperfine splitting is taken into account in an approximate way by using a single velocity component with a width of $\Delta V = 21\ \mathrm{km\ s}^{-1}$. This velocity profile is assumed to be due to microturbulence and to be applicable throughout the cloud.

We computed the spectrum which would be observed from the KAO with its 5.7 pc FWHM Gaussian beam. The computed and measured profiles match (Fig. 1) if the HCl abundance is assumed to be $\mathrm{HCl/H_2} \approx 1.1 \times 10^{-9}$ throughout the cloud, in good agreement with our earlier estimate. The apparent agreement in the continuum levels between the model and the data in Figure 1 was obtained by multiplying the model spectrum by a factor of 1.2. This factor is well within the calibration error of our measurement and the uncertainties inherent in our model. Note that this factor does not change the line-to-continuum *ratio*, and so does not affect the determination of the HCl abundance. Our model indicates that changes of 20% in the HCl abundance lead to significant discrepancies between the predicted and observed spectra. However, note that the H_2 column density is uncertain by at least a factor of 2.

The excitation of the rotational levels of HCl in Sgr B2 appears to be dominated by the far-infrared dust radiation. Radiative rates exceed the collisional rates by large factors at all radii sampled in our model (0.05 pc $\leq r \leq$ 22.5 pc). The fractional populations for the $J = 0$, 1, and 2 levels as a function of radius are shown in Figure 2. Most of the HCl molecules reside in the $J = 0$ ground state for $r > 1$ pc,

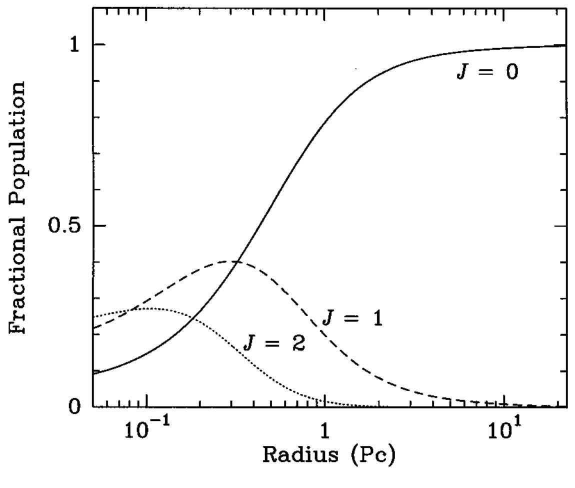

Fig. 2.—Plot of the fractional populations for the $J = 0$, 1, and 2 levels calculated by our radiative transfer model as a function of radius.

because the far-infrared continuum intensity falls off rapidly with increasing radius.

We verified that the absorption line is formed in the outer envelope of the cloud ($r > 5$ pc) by computing models with radial variations in the HCl abundance. We cannot explain our measured profile if the HCl is confined to the core, $r < 1$ pc, for in this case the model predicts that the line will be in *emission*. However, even for an abundance of $\mathrm{HCl/H_2} \approx 10^{-8}$, our model predicts that the emission line would be quite weak, perhaps $\Delta T_A^* \approx 0.2$ K. This is because the intense continuum radiation in the cores causes many rotational levels to be populated, and also because the emission from the cores will be heavily diluted in our 2′.3 KAO beam. Thus, our data probably do not set tight constraints on the HCl abundance in the Sgr B2(M) and (N) cores, since any weak emission from the core would be masked by absorption in the envelope. If we confine the HCl to $r < 5$ pc and take $\mathrm{HCl/H_2} \approx 10^{-9}$, the line is weakly in absorption, with $\Delta T_A^* \approx -0.15$ K. If the HCl is allowed to have this abundance to $r < 10$ pc, the absorption line becomes much stronger, $\Delta T_A^* \approx -0.45$ K. This confirms that the absorption arises in the envelope of Sgr B2 at radii between 5 pc to 22.5 pc. According to equation (7), the mean density in this region is in the range $2\text{–}6 \times 10^3$ cm^{-3}, and from equation (8), the dust temperature ranges from 8 to 18 K. Thus, we are sampling quiescent, relatively cool gas at moderate densities rather than the hot, dense gas whose emission lines are prominent in spectra observed at millimeter and submillimeter wavelengths using large single-dish telescopes (e.g., Turner 1991; Sutton et al. 1991). However, we note that there is observational evidence for some hot, possibly shock-excited gas (e.g., Hüttemeister et al. 1995) in the envelope of Sgr B2. Nonetheless, our estimate of the total HCl column density is secure because the hot component has a low density $n < 5000$ cm^{-3}, far below the HCl critical density. This hot component may have an enhanced HCl abundance and could be partially responsible for our absorption line, but this forces the abundance in the rest of the envelope to be even lower (below 10^{-9}).

6. CONCLUSIONS

The analysis of the chemistry of chlorine in molecular clouds by Blake et al. (1986) demonstrated that only HCl and atomic chlorine would exist in significant abundance, with HCl accounting for 25%–65% of the total gas-phase chlorine. This chemistry has been recently reanalyzed by Schilke et al. (1995), who include photodissociation of HCl by cosmic-ray induced photons. Their results are in general agreement with those of Blake et al. (1986). The new chemical model generally predicts somewhat less HCl primarily because the branching ratio of the $\mathrm{H_2Cl^+} + e^-$ reaction is assumed to be 90% in favor of $\mathrm{Cl} + \mathrm{H_2}$ and only 10% for HCl + H, instead of the 50% ratio assumed in the earlier work. For our conditions, $n \approx 2\text{–}6 \times 10^3$ cm^{-3} and $T_{\mathrm{gas}} \approx 10\text{–}30$ K, the model of Schilke et al. (1995) predicts that about 10%–30% of the gas-phase chlorine is in HCl. Combining this with our measured HCl abundance, we find that chlorine must be depleted by a factor of 50–180 below the solar abundance, which seems to confirm the correlation between mean gas density and depletion noted by Harris et al. (1984) from UV studies of diffuse clouds. However, we cannot rule out the possibility that the predictions of the chemical models are incorrect, and that chlorine has a large gas phase abundance in a form other than HCl (e.g., atomic Cl). It may be possible to resolve this question through infrared observations of the $^2P_{3/2}$–$^2P_{1/2}$ transition of Cl at $\lambda = 11.3$ μm (Dagenais, Johns, & McKellar 1976), or by searching for a feature at $\lambda = 3.5$ μm (Ault & Pimentel 1973) corresponding to HCl adsorbed on dust grains.

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