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MOLECULAR CLOUDLETS EMBEDDED IN A DIFFUSE H I CLOUD WITHIN 120 PARSECS OF THE SUN

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ABSTRACT

Two molecular cloudlets have been detected and mapped in a partial survey of ^{12}CO emission in a diffuse H I cloud toward Perseus. Previous observations of K I absorption and 21 cm emission had shown that the cloud is within 120 pc of the Sun, with a diameter of 14 pc, a total mass $\sim 1500\ M_\odot$, and temperatures as low as 30 K, making it a good candidate to contain molecular gas. The two cloudlets embedded in the H I cloud have diameters ~ 1 pc, molecular densities ~ 100 cm^{-3}, and molecular masses of only 1 $M_\odot$, and lie in front of the two stars with the strongest detected K I absorption. The derived total hydrogen column density is $\sim 1 \times 10^{21}$ cm^{-2}. The molecular cores detected are not virialized but confined by the turbulent pressure of the interstellar medium. No ^{12}CO was detected along the lines of sight to eight stars showing K I absorption, or in the direction of the biggest concentration of H I.

Subject headings: ISM: abundances — ISM: clouds — ISM: molecules — radio lines: ISM

1. INTRODUCTION

Although the large-scale distribution of atomic gas, molecular clouds, and H II regions in the Galaxy is well known, the study of the ISM properties and structure on scales of the order of several parsecs is still a challenge because of the inhomogeneity of the local interstellar medium (LISM) and the complexity of the physical processes involved. In recent years very important contributions have been made by observations and models, but more questions have emerged about the distribution of the local material among the different phases, the filling factor of each phase, the geometric structure, dynamics.

By means of large-scale CO surveys, molecular cloud properties have been studied, and among the most striking results obtained are the tight relations between masses, sizes, and internal velocity dispersions of the clouds, valid over 6 orders of magnitude in mass (Larson 1981). Nevertheless, the power laws relating these magnitudes are subject to considerable scatter at the extremes of the mass spectrum. Even if the assumption of virial equilibrium under self-gravitation plus magnetic fields is reasonable for an intermediate range in cloud masses, it is more likely that cloud complexes with masses $M > 10^5\ M_\odot$ are not self-gravitating objects but temporary aggregates. At the other extreme, the smallest clouds may well be confined by external pressure.

The existence of diffuse molecular clouds has been well established in a number of surveys of high-latitude clouds in the solar neighborhood ($\simeq 100$ pc) (Blitz, Magnani, & Mundy 1984; Magnani, Blitz, & Mundy 1985; Magnani, Lada, & Blitz 1986; Keto & Myers 1986). Désert, Bazell, & Boulanger (1988), using the *IRAS* 100 μm maps, completed those previous surveys and found good positional correlation between far-infrared excess and diffuse molecular clouds. They found that the low-mass end of the spectrum of molecular clouds has characteristic sizes and masses of 1.7 pc and 40 $M_\odot$, respectively. These masses are much lower than virial masses, and these clouds must be confined by the surrounding warmer interstellar gas at lower density (Hobbs, Blitz, & Magnani 1986).

In an exploration of the cold ($T \sim 100$ K) phase of the ISM in the solar neighborhood, we identified and examined a set of dense H I clouds using the K I resonance line at 7699 Å (Trapero et al. 1992, hereafter Paper I). Typical parameters estimated for these clouds are diameter ~ 5 pc, $n_{\rm H} \sim 50$ cm^{-3}, $T \sim 70$ K, and mass of $\sim 150\ M_\odot$. Although occupying only some 5% of the local volume, the mass fraction in the LISM in these clouds was calculated to be at least 80%. Among the clouds studied, one was exceptionally large in size (~ 14 pc in diameter), and in mass ($\sim 1500\ M_\odot$) and low in temperature ($T \sim 60$ K). More comprehensive mapping of the cloud in H I at 21 cm, supplemented by K I observations toward eight more stars, confirmed the peculiarity of this very close ($d < 120$ pc) massive cloud (Trapero et al. 1995, hereafter Paper II). The high column densities measured [N(H I + H_2) $\sim 2 \times 10^{21}$ cm^{-2}], the high-density ($n_{\rm H} \sim 70$ cm^{-3}), and kinetic temperatures as low as 30 K in the densest regions suggested that this cloud would be a good candidate to contain a molecular core.

In this paper we present ^{12}CO observations in selected regions of the cloud, whose center lies near $l = 150°$, $b = -5°$. We have found two small molecular cores in the direction of maximum strength of the K I absorption lines, but no ^{12}CO emission was detected in the direction of the geometrical center of the H I cloud. In § 3 we describe the results obtained in the directions explored, and in § 4 we discuss the mapped molecular cores, the atomic and molecular column density of hydrogen estimated, and possible models for the whole cloud.

Although our sample was limited by practical observing constraints, the detection of molecular cloudlets immersed in a bigger massive H I cloud is a clue to the possible existence of further molecular cores within this nearby cloud, and in the ISM in general.

2. OBSERVATIONS

The observations were carried out in the ^{12}CO $J = 1-0$ transition with the NRAO 12 m telescope,[1] Kitt Peak, during 1994 December. The 256 channel 100 and 250 kHz filterbanks were configured in parallel mode to detect both polarizations, giving a velocity resolution of 0.26 and 0.65 km s^{-1}, respectively. The half-power beamwidth of the telescope at 115 GHz is 54″. We used the frequency switching mode, with a shift of ± 1.5 MHz. The calibration mode used was the chopper wheel method (Kutner & Ulich 1981), which gives the resulting temperatures on the T_R^* scale.

The data were reduced with the single-dish data reduction package CLASS. Spectra were averaged and baseline-corrected before folding. Special attention was paid to the possibility that the negative lines created by the frequency switching and the folding procedure were interfering with the emission from our source. We found this situation only in one of the spectra, created by the folding procedure. This spectrum ($\Delta\alpha = +20'$, $\Delta\delta = +5'$ in Fig. 2*a* below) was treated without the folding step. A Gaussian profile was assumed in inferring the intensity T_R^*, LSR radial velocity, line width, and integrated intensity I_{CO}, for each of the emission lines. No blended components were found, with single Gaussians showing good fits. The final spectra have a typical rms noise of 35 mK for a 10 minute exposure.

Because of the extent of the cloud, we could search for the ^{12}CO emission only in a limited set of directions selected on the basis of our previous results. A map of the cloud in atomic hydrogen column density from the 21 cm observations was presented in Paper II. Because of the nonuniform sampling of the cloud, we employed an interpolation technique using neural networks (Serra-Ricart et al. 1995). In Figure 1 we plot the observed positions in ^{12}CO superposed on the 21 cm map of the cloud. The first region observed was the dense cold cloud center in the interpolated H I map from Paper II. We observed in this region a cross of 17 points at intervals of 15′ (crosses in Fig. 1). In addition, grids of 5′ × 5′ were taken surrounding HD 21455 and HD 23552, the two stars with the strongest absorption at K I in Papers I and II. A total of 55 and 45 points were taken, respectively. Finally, we observed the lines of sight to the other eight stars observed in K I and reported in Paper II.

3. RESULTS

^{12}CO emission lines were detected in the LSR radial velocity range -20 to $+10$ km s^{-1} toward all of the 125 lines of sight observed. We need to distinguish here between the emission from our cloud and emission from background gas. An almost constant feature is present in all the spectra taken, at a velocity of roughly -14 km s^{-1}. Additional emissions in the range -20 to -8 km s^{-1} are present only in certain directions. The presence of gas at these velocities was already clear in the 21 cm spectra (see, e.g., Fig. 3 in Paper II). However, no absorption lines at these radial velocities were detected in any of the stars observed in K I, which indicates that the gas emitting in

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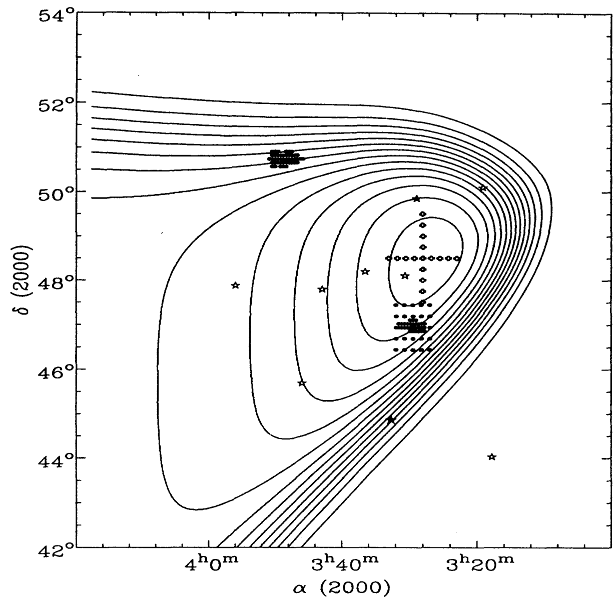

FIG. 1.—Sky directions observed in ^{12}CO plotted over the atomic hydrogen contour map obtained interpolating 21 cm data in Paper II. The contours are in units of 10^{21} cm^{-2}. Filled circles show observations toward "North" and "South" cores, crosses observations toward the center of the H I cloud, and stars show observations toward the stars observed in K I in Paper II. HD 21803 is identified by a filled star.

21 cm and ^{12}CO at these negative velocities lies behind the cloud which is the object of this study. These clouds are likely to be at more than 450 pc from the Sun, as shown by the nondetection of K I toward HD 21803, the most distant of the stars in our sample.

^{12}CO features in emission associated with our cloud were expected to show up at roughly $+2.5$ km s^{-1}, the average LSR radial velocity derived from the K I detections. Emission at this velocity was detected only in the regions surrounding the stars HD 21455 and HD 23552. In Figure 2 we show the spectra taken in those two regions. We will call "North core" the cloud on the line of sight to HD 23552 and "South core" the one in front of HD 21455. No ^{12}CO was detected with similar radial velocity in the central part of the H I map or toward the other eight stars previously observed in K I.

Contour maps of equal integrated ^{12}CO intensity, I_{CO}, were produced for the two molecular cores detected and are shown in Figure 3. The clouds, delimited in almost all directions, are two small isolated molecular cores separated by 6 pc in the H I cloud. The angular sizes of 25′ × 25′ for the "South core" and 35′ × 14′ for the "North core" correspond to $\sim 0.9 \times 0.9$ pc and 1.2×0.5 pc, respectively, at a distance of 120 pc from the Sun.

The average radial velocity in the "South core" is $+2.0$ km s^{-1}, with a dispersion of 0.36 km s^{-1} for the 22 points where ^{12}CO emission was detected. The FWHM width of the lines is ~ 1.3 km s^{-1}, and the peak intensity was measured at 1.6 K. The radial velocity measured in ^{12}CO for this cloud agrees very well with the $+1.8 \pm 1$ km s^{-1} determined toward HD 21455 with the K I absorption line.

An average radial velocity of $+4.0$ km s^{-1} is obtained for the "North core," with a dispersion of 0.31 km s^{-1}. The FWHM width of the lines is similar to that of the "South core," 1.1 km s^{-1}, and the maximum intensity measured was

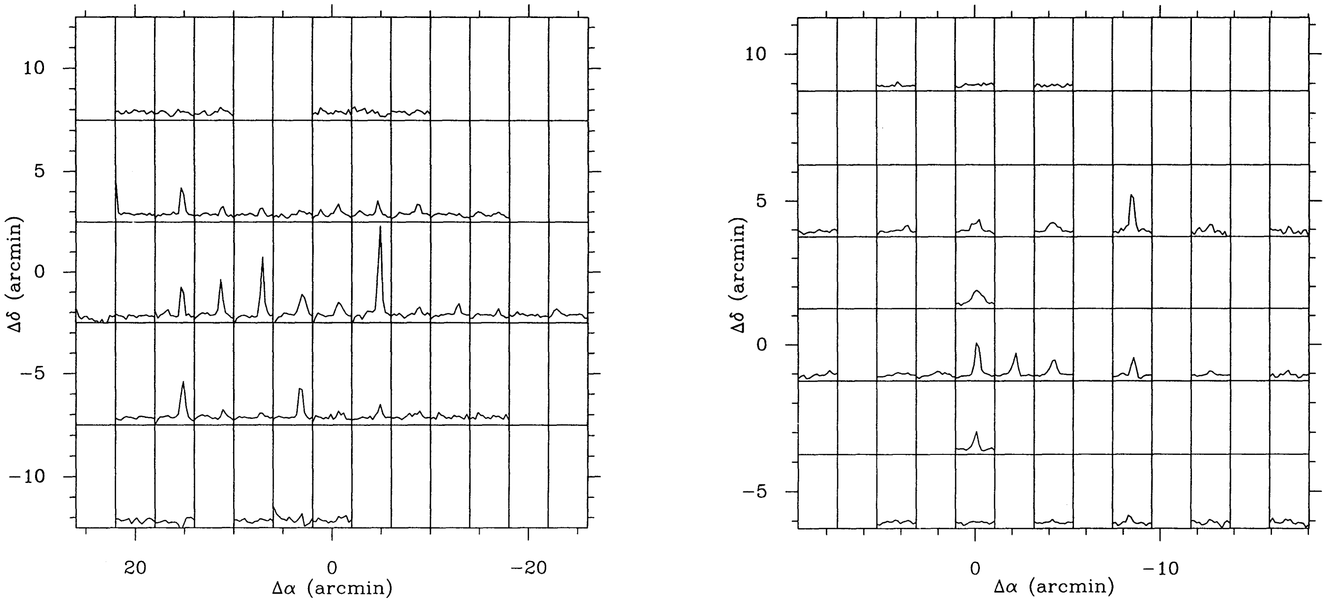

FIG. 2a FIG. 2b

FIG. 2.—Maps of the observed spectra toward "North core" (*a*) and "South core" (*b*). Offsets are relative to HD 23552 ($\alpha = 3^h48^m18^s$, $\delta = +50°44'12''$) and HD 21455 ($\alpha = 3^h29^m22^s$, $\delta = +46°56'16''$), respectively. The velocity range covered in each spectrum is −3 to +7 km s^{-1}, and the intensity range from −0.2 to 2.5 K km s^{-1}.

2.5 K. In this case, the agreement in radial velocities is not so good, as the velocity derived from the K I spectrum was $+0.7 \pm 1$ km s^{-1}. Gir, Blitz, & Magnani (1994) found similar differences of ~ 3 km s^{-1} between some MBM clouds and the H I gas associated. Moreover, no emission feature in this velocity range is found in the 21 cm spectra in this direction. A threshold for the formation of a significant molecular component was found empirically as $N(\mathrm{H\ I} + \mathrm{H_2}) \sim 5 \times 10^{20}$ cm^{-2} (Savage et al. 1977), making it very unlikely that the signal detected in ^{12}CO could have its origin in background gas not emitting at 21 cm. We therefore take the molecular gas detected here as part of the cloud situated within 120 pc of the Sun.

For the nondetections toward the other eight stars observed, and toward the center of the H I cloud, an upper limit of $I_{CO} <$ 0.07 K km s^{-1} was estimated.

4. DISCUSSION

4.1. *Molecular Cores*

Our previous observations of this nearby cloud suggested the probable presence of molecular gas within it. High total column densities $N(\mathrm{H\ I} + \mathrm{H_2})$ (roughly times 10^{21} cm^{-2}), low temperatures (~ 30 K) and high densities (> 80 cm^{-3}), all pointed in this direction. Even though the observations presented here cover a small fraction of the cloud, they have demonstrated the presence of the predicted molecular gas.

Two small (~ 1 pc diameter) molecular cores have been found embedded in the big (~ 14 pc) massive diffuse cloud already studied in Paper II. These cores are in front of the stars HD 21455 and HD 23552, at less than 120 pc from the Sun, and only ~ 10 pc below the Galactic plane.

Even in these small molecular cores internal structure is obvious in the maps (Fig. 3). Several concentrations of gas, or clumps, separated by some 0.3 pc can be distinguished: two in the "South core" and three in the "North core." The mean intensity contrast with the surrounding molecular gas is a factor of 2, with a maximum of 6.5. Evidence for the clumpiness of molecular clouds is present in studies on all observed scales, from GMC (see, e.g., Blitz & Thaddeus 1980) to diffuse molecular clouds (see, e.g., Zimmerman & Ungerechts 1990).

The mass of a core can be estimated reasonably well using the relation between I_{CO} and $N(H_2)$ as found by Bloemen et al. (1986), $N(H_2)/I_{CO} = 2.8 \times 10^{20}$ $cm^{-2}(K\ km\ s^{-1})^{-1}$. There are well known limitations to this method, notably the fact that ^{12}CO emission can well be partially saturated, even for fairly weak lines, and the possible variations on the CO/H_2 ratio. Nevertheless, in the absence of ^{13}CO data, an estimate of this kind may be reliable to about an order of magnitude, which is satisfactory for any inference we wish to draw here. The mass values obtained using this relation were 1.3 $M_\odot$ for the "North core" and 1 $M_\odot$ for the "South core." These cloudlets are thus not only small in diameter but have low masses. With these masses neither cloud can be gravitationally bound. The line width of a virialized cloud of equal mass and radius [$\sigma_v(\mathrm{vir}) = 0.0293(M/R)^{1/2}$; Magnani et al. 1985] yields a value of 0.04 km s^{-1}, in disagreement with the line width measured, ~ 1 km s^{-1}. There is evidence (Myers 1991) that diffuse molecular clouds are confined by external pressure. The magnetic field energy and turbulent kinetic energy could be of the same order. If we estimate the internal pressure of the cores given by $P = nm(\sigma_v)^2$ (Blitz 1991), where n is the density, m is the mass of a hydrogen molecule, and σ_v is the velocity dispersion, we obtain a value of 2.4×10^4 K cm^{-3}. The same calculation for the H I cloud gives a value of $\sim 4 \times 10^4$ K cm^{-3}, in reasonable agreement with the internal pressure from the molecular cloudlets. Assuming the turbulent pressure of the interstellar medium given by Maloney (1988), 1–2 $\times 10^4$ K cm^{-3}, the clouds would be confined by the general pressure of the interstellar medium (Blitz 1991). We note the substantially smaller contribution by the thermal pressure, $P/k = nT \sim 4 \times 10^3$ cm^{-3}, in the diffuse H I gas.

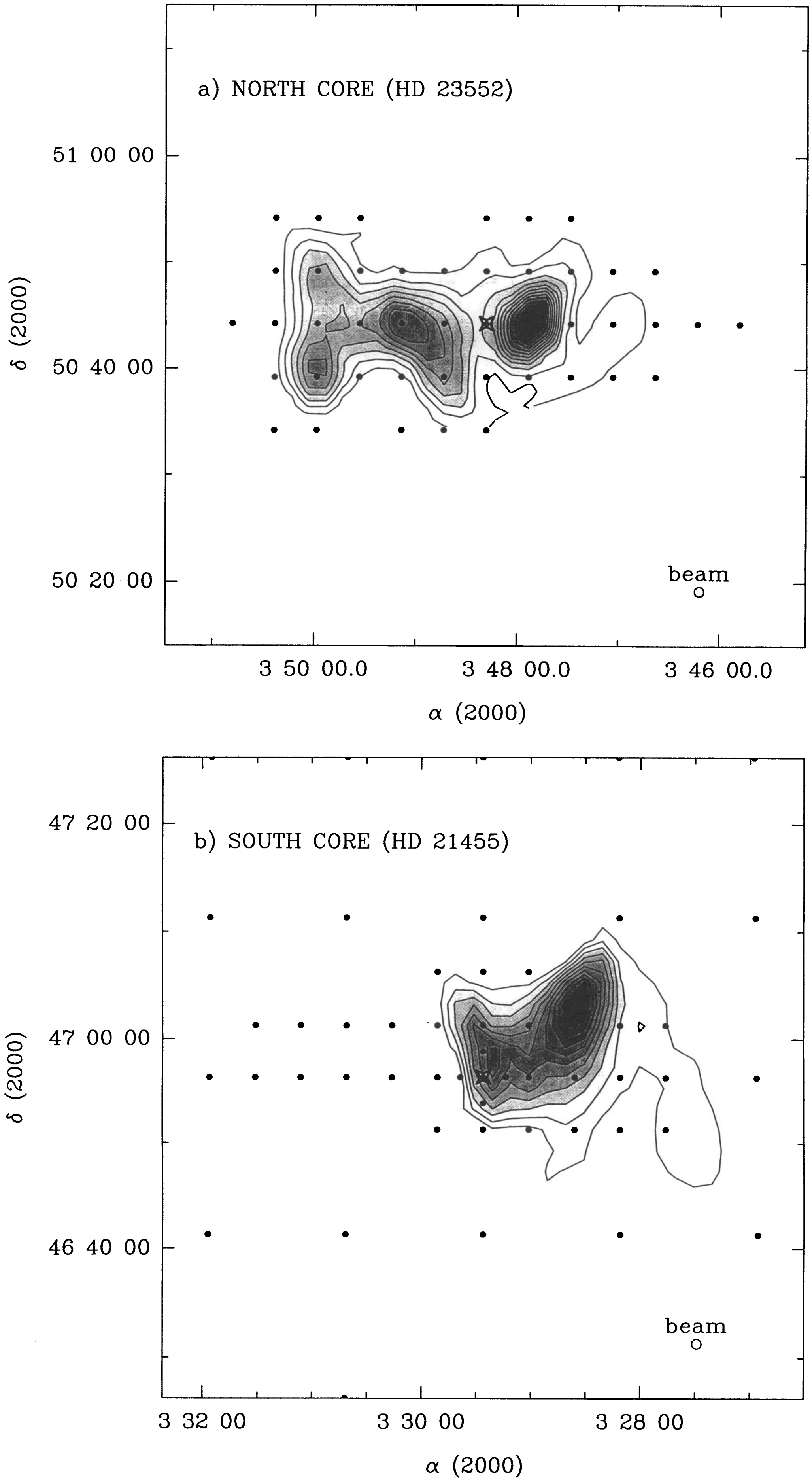

FIG. 3.—Maps of integrated emissivity $I_{CO} = \int T_R^* dV$, for (*a*) "North core" and (*b*) "South core." Contour levels are from 0.2 K km s^{-1} in steps of 0.2 K km s^{-1}. Filled circles indicate observed positions. HD 23552 and HD 21455 lines of sight are marked with starlike symbols.

Assuming that the "South core" is a sphere of diameter 0.9 pc and the "North core" is a cylindrical cloud 1.4 pc long with a base of 0.5 pc diameter, volume-averaged densities of 95 and 133 cm^{-3} are inferred for the two. Blitz (1991) obtained a mean H_2 density for the MBM clouds of 140 cm^{-3}, while Scoville (1990) estimates $n_{H_2} = 180$ cm^{-3} as a characteristic mean value for giant molecular clouds (GMCs). The cores detected here fall into the category of "diffuse molecular clouds" according to the criteria of Myers (1991), as opposed to the dark and giant molecular clouds. The MBM clouds with masses ranging from 0.6 to 300 $M_\odot$, and densities from 35 to 500 cm^{-3} (Magnani et al. 1985), belong to the same class, and our molecular cores are in the small-diameter, low-mass range of the sample.

The relations between the mass and line width and the cloud radius were first pointed out by Larson (1981) and are valid over 6 orders of magnitude in mass. The line widths and radii estimated for our cores follow this line-width radius relation rather well. However, the mass-radius relation would predict core masses of some 20 $M_\odot$ for the radii measured. Our result shows that this relation does not in fact hold for clouds with low masses (see, e.g., Combes 1991), where the assumption of virial equilibrium breaks down.

4.2. *Abundances*

We have measured K I, H I and ^{12}CO along the lines of sight toward HD 21455 and HD 23552. In Paper I we measured the equivalent width in the 7699 Å resonance line of K I and estimated the corresponding column density, N(K I). We calculated the total column density of hydrogen N(H I + H_2) from N(K I) in two steps. We first used the empirical relation N(Na I) = 60 × N(K I) by Hobbs (1976) to estimate the Na I column density. With this value we were able to infer the total column density of hydrogen using the relation log N(H I + H_2) = log [N(Na I) + 9.09]/1.04 obtained empirically by Ferlet, Vidal-Madjar, & Gry (1985).

The 21 cm data obtained in Paper II gave us direct measurements of the column density of atomic hydrogen, and now with the ^{12}CO spectra we can estimate the column density of the molecular hydrogen, $N(H_2)$, using the relation between I_{CO} and $N(H_2)$ in § 4.1. We can thus derive a new and independent value for the total column density of hydrogen N(H I + H_2) = N(H I) + 2$N(H_2)$ and compare it with that derived from the K I data.

In Table 1 we give all the column densities measured and derived for both stars. We show K I, H I, and H_2 column densities in columns (2)–(4) along with the total column density of hydrogen derived from K I, $N(\text{H I} + \text{H}_2)_{\text{K I}}$ (col. [5]), and $N(\text{H I} + \text{H}_2)_{\text{H}}$ derived from the H I and ^{12}CO radio observations (col. [6]).

As we can see in Table 1, the total column density estimated from the K I absorption lines was 2 × 10^{21} cm^{-2} for both stars, while the N(H I + H_2) derived from 21 cm and ^{12}CO is 1.4 × 10^{21} cm^{-2} for HD 21455, and 0.8 × 10^{21} cm^{-2} for HD 23552. The agreement is quite reasonable, taking into account the uncertainties involved. The empirical relation derived by Hobbs (1976) between N(K I) and N(Na I) was confirmed by Chaffee & White (1982), but there is an implied uncertainty of ~20%. The relation between N(Na I) and N(H I + H_2) has to be used with particular care. Welty, Hobbs, & Kulkarni (1994) note the major uncertainties introduced when using this relation for N(Na I) ≤ 10^{11} cm^{-2}, and it is clear from the original study of Ferlet et al. (1985) that the relation breaks down at N(H I + H_2) ≥ 10^{21} cm^{-2} and gives way to a roughly quadratic relation. Since our detections are over this limit, we did not use the linear fit to the data given in Ferlet et al. (1985) but made an empirical estimate based on their plotted points. We estimate a total uncertainty of 40% for $N(\text{H I} + \text{H}_2)_{\text{K I}}$. We already discussed the uncertainty implied when assuming a constant relation between I_{CO} and $N(H_2)$. Here we have used the relation given by Bloemen et al. (1986), $N(H_2)/I_{CO} = 2.8 \times 10^{20}$.

We have also derived N(H I + H_2) using a third entirely independent method via the observed dust extinction based on the relation $N(\text{H I} + \text{H}_2)/E(B-V) = 5.8 \times 10^{21}$ cm^{-2} from Bohlin, Savage, & Drake (1978). The reddening values $E(B-V) = 0.265$ and 0.17 are derived for HD 21455 and HD 23552, respectively, from the color indices and spectral classes listed in the Bright Star Catalogue (Hoffleit & Jaschek 1982). The corresponding values are N(H I + H_2) = 1.5 × 10^{21} and 9.9 × 10^{20} cm^{-2} (col. [7] in Table 1), in good agreement with the two values previously obtained for N(H I + H_2), and in especially good agreement with the more direct estimates, $N(\text{H I} + \text{H}_2)_{\text{H}}$.

Cernicharo & Guelin (1987) give an empirical relation, $I_{CO} = 5.0 \pm 0.5(A_V - 0.5 \pm 0.2)$ K km s^{-1}, between I_{CO} and the visual extinction, A_V, covering the range $0.5 \le A_V \le 3$. We can check whether our data is in agreement with this relation, which predicts 1.9 and 0.3 K km s^{-1} for HD 21455 and HD 23552, respectively. Considering the uncertainties given by the authors, the values we actually measured for the stars, 1.87 and 0.63 K km s^{-1}, are in fair agreement, although one would expect divergence for values of $A_V < 0.5$ where N(H I) is a more significant fraction of N(H I + H_2).

The ratio H I/H_2 can be calculated directly from our measurements at 21 cm and ^{12}CO. Using the values from columns (4) and (5) in Table 1, we obtain N(H I)/$N(H_2)$ = 0.75 for HD 21455 and 2.7 for HD 23552. It is important to note the uncertainty introduced in the N(H I) value by the larger beamwidth of our 21 cm measurements. The FWHM beamwidth of the

TABLE 1

ATOMIC AND MOLECULAR COLUMN DENSITIES TOWARD HD 21455 AND HD 23552[a]

HD	N(K I)	N(H I)[b]	$N(H_2)$[c]	$N(\text{H I} + \text{H}_2)_{\text{K I}}$[d]	$N(\text{H I} + \text{H}_2)_{\text{H}}$[e]	$N(\text{H I} + \text{H}_2)_E$[f]
21455......	1 × 10^{12}	3.9 × 10^{20}	5.2 × 10^{20}	2 × 10^{21}	1.4 × 10^{21}	1.5 × 10^{21}
23552......	1 × 10^{12}	4.8 × 10^{20}	1.8 × 10^{20}	2 × 10^{21}	8.4 × 10^{20}	9.9 × 10^{20}

a All column densities in cm^{-2}.
b From 21 cm observations.
c Derived from ^{12}CO measurements.
d Estimated from N(K I) (see text).
e Derived from N(H I) and $N(H_2)$.
f Derived from the reddening $E(B-V)$.

76 m Lovell Telescope at Jodrell Bank was 12′, covering almost half of the cloud, and larger than the structure of the individual clumps observed in our ^{12}CO data.

No direct 21 cm observations were taken toward the other stars observed in ^{12}CO, and therefore we cannot infer values for the total column density of hydrogen. We can use the relation between the visual extinction and I_{CO} and check it against the nondetections obtained in ^{12}CO emission. The stars showing interstellar K I equivalent widths below 60 mÅ have visual extinctions lower than 0.4, out of the range of the relation given by Cernicharo & Guelin (1987). Only HD 21803, the star with K I equivalent width of 70.8 mÅ, has a visual extinction high enough (0.89 mag) within the range—in fact, even higher than in HD 21455. Therefore, according to this relation we would have expected to detect a fairly strong line in that direction. However, no signal was detected in this direction with a limit $I_{CO} < 0.1$ K km s^{-1}, equivalent to $N(H_2) < 3 \times 10^{19}$ cm^{-2}. This value, combined with the total column density N(H I + H_2) derived from the K I measurement, gives a ratio N(H I)/$N(H_2) > 60$ for the cloud toward this star, implying a wide range of physical parameters within the single large cloud.

4.3. *The Cloud*

Based on our 21 cm observations we produced an extensive, although partly interpolated map of the H I cloud, shown in Figure 1. No ^{12}CO was detected in a limited survey of the central part of that map, the part with the largest H I column densities. We know that the distributions of H I and H_2 are not necessarily monotonically related. Low H I column densities can mean either that the line of sight is poor in gas or that most of the hydrogen has been converted to molecular hydrogen. Measurements at 21 cm will then tend to give too smooth, too uniform a view of the total gas content, and hence of the structure in a cloud. In the present case, the construction technique of the H I map itself (Serra-Ricart et al. 1995) strengthened this effect. It was performed by interpolating a relatively sparse sample of data and adopting a smooth solution that could give us a general notion of the size and shape of the cloud and a tool for deriving its mass. The offset found between the ^{12}CO gas and the concentration of H I in our 21 cm map is of 3 pc for the "South core" and 8 pc for the "North core." Gir et al. (1994) found offsets CO-H I in the MBM clouds comparable with the size of the molecular component. Since the interpolator method we used was able to map only one maximum in H I, we are limited to comparing the "South core" diameter, ~ 1 pc with its offset, ~ 3 pc, higher than in the MBM clouds.

The two molecular cores mapped, with masses of $\sim 1\ M_{\odot}$, diameters of ~ 1 pc, and molecular densities of ~ 100 cm^{-3}, to order of magnitude, show how varied the internal structure of such a cloud can be. There are restricted zones where there is enough gas and dust to shield the interstellar radiation field, allowing the existence of molecular gas formed on the grains surface. As we have seen, these molecular cores have their own internal structure, comprised of clumps with a density contrast of over half an order of magnitude.

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