THE ASTROPHYSICAL JOURNAL, 282:L9–L12, 1984 July 1

HIGH-LATITUDE MOLECULAR CLOUDS

LEO BLITZ AND LORIS MAGNANI
Astronomy Program, University of Maryland

AND

LEE MUNDY
Department of Astronomy, University of Texas
Received 1984 February 6; accepted 1984 March 14

ABSTRACT

We report the detection of a large number of molecular clouds at high galactic latitude, a few of which were previously cataloged as dark nebulae. We have mapped a large fraction of the clouds detected at $|b| > 30°$ in order to determine the properties of this class of objects. The clouds are nearby ($\bar{d} \sim 100$ pc) with typical diameters and masses of about 2 pc and roughly 65 $M_\odot$. Allowing for incompleteness in sky coverage, there are approximately $64/\varepsilon$ such clouds within 100 pc, where ε is the fractional completeness of our survey. A large fraction, perhaps a majority, of the clouds are not gravitationally bound. The internal velocity structure implies that many of the clouds are very young with ages $\lesssim 10^6$ yr. The clouds are invariably associated with atomic hydrogen clouds, but the molecular column densities appear to dominate in many cases. The mean molecular density of the clouds is roughly 170 cm^{-3}. The one-dimensional cloud-to-cloud velocity dispersion is 5.7 ± 1.2 km s^{-1}. The surface density of these clouds projected on the galactic plane is approximately $0.1/\varepsilon$ $M_\odot$ pc^{-2}, a small fraction of the H I surface density, but an appreciable fraction of the smoothed surface density of giant molecular clouds. Individual clouds subtend areas from a fraction of a square degree to several square degrees, implying that they may be responsible for at least some of the diffuse high-latitude infrared emission detected by *IRAS*.

Subject headings: infrared: sources — interstellar: molecules — radio sources: lines

I. INTRODUCTION

This *Letter* presents the first results of a program to detect high-latitude, local molecular gas. Millimeter-wave observations at the frequency of the $J = 1$–0 transition of CO were made of potentially obscured regions identified from the Palomar Observatory Sky Survey (POSS) prints. All of the POSS prints at $|b| > 20°$ were carefully examined for obscuration, and 457 candidate regions were identified. Of these, 439 were observed, and CO emission was detected from 105 (24%), a number of these in complexes of large angular extent. More than half of the clouds at $|b| > 30°$ have been mapped. These local high-latitude clouds have not previously been included in inventories of local gas (e.g., Lequeux 1981). The observed properties of the clouds are presented and used to derive their various physical properties. It should be noted that many of the derived properties are only as accurate as the conversion factors used to obtain them.

II. OBSERVATIONS

The vast majority of objects in our source list are previously uncataloged, but some are Lynds (1962) objects. The observations were carried out at the Millimeter Wave Observatory[1] near Fort Davis, Texas, in 1983 November and December. The receiver uses a helium-cooled Schottky-barrier diode mixer and has a single-sideband (SSB) noise temperature of 220 K. Typical SSB system temperatures referred outside the atmosphere were 550–1000 K. The initial observations were frequency switched, generally by 4 MHz. Special care was taken to monitor the telluric CO line which was seen in every spectrum and occasionally occurred at the same velocity as a source detection. We reobserved all of the weak sources and sources with possible telluric contamination in the position-switching mode.

Signals were simultaneously processed using filter banks with 250 kHz and 62.5 kHz filters which provided a resolution of 0.65 and 0.17 km s^{-1} respectively. The spectrometer was always centered at a velocity of 0.0 km s^{-1} relative to the local standard of rest, and the velocity coverage in the 250 kHz filters was ± 89.5 km s^{-1}. Standard chopper-wheel calibrations were performed before observing every new source, and standard sources such as Orion KL were observed periodically. The variation of the antenna temperature for Orion KL was less than 5%. Most of the objects were observed with 5 minute integrations which produced typical rms noise temperatures of approximately 0.2 K in the 250 kHz resolution spectra.

Ten complexes at $|b| \geq 30°$ were mapped with a grid spacing that varied from 10′ to 20′ depending on the angular extent of the source (the beam size was 2′.3). The integration

[1]The Millimeter Wave Observatory is operated by the Electrical Engineering Research Laboratory of the University of Texas at Austin with support from the National Science Foundation and McDonald Observatory.

times were generally 3 minutes, and observations were made in either the position-switching or the frequency-switching mode depending on the location of the telluric line. Emission for which $T_A^* \geq 0.5$ K was unambiguously detected, but weaker emission could sometimes be observed.

The observed line strengths are given throughout this *Letter* as T_A^*, the antenna temperature corrected for atmospheric attenuation, ohmic losses, and rearward spillover (Kutner and Ulich 1981). In order to compute $N(H_2)$ in § IV, it is necessary to estimate the source radiation temperature, T_R, which is given by $T_R = T_A^*/\eta_{FSS}\eta_c$. Since the source distributions are not well known, but appear to be larger than the beam, we have used a source coupling efficiency ($\eta_{FSS}\eta_c$) of 0.7. This efficiency is appropriate for a uniform source of 4′–6′ in diameter. Since the coupling efficiency for a uniform source 30′ in diameter is only 20% larger, uncertainty in source size does not cause a large error in T_R.

III. RESULTS

We divide the results into two latitude regions: $20° \leq |b| < 30°$ and $|b| \geq 30°$. Two clouds at latitudes of 29°.98 and 29°.93 are included in the latter group.

For clouds in the lower latitude range, of 162 positions searched, 68 have detectable CO emission (42%). The strongest line has a peak antenna temperature (T_A^*) of 10.0 K; the mean of the detections is 4.3 K. The lines tend to be relatively strong: only 14 detections have peak temperatures less than 1 K; only three of these are weaker than 0.8 K. Many of the clouds appear to be parts of very large complexes covering tens of square degrees of sky. Parts of these complexes are Lynds (1962) objects, others appear to be high-latitude extensions of clouds at $|b| < 20°$, such as the Taurus and Ophiuchus molecular clouds. An especially rich region occurs between $335° < l < 345°$, the high-latitude edge of an area to which Blaauw (1982) has called attention as an area likely to contain a substantial quantity of molecular gas. Because there are so many intermediate-latitude detections in apparently related complexes, it has not yet been possible to determine with confidence which of the sources are distinct objects. The properties of the high-latitude clouds discussed in § IV are therefore based on an analysis of clouds at $|b| \geq 30°$.

Of the clouds at $|b| \geq 30°$, we detected CO emission from 37 directions of 287 observed (13%). Among this group of detections, there appear to be 29 distinct clouds, and a few of these occur in related groups. The group of five distinct clouds related to L134 mapped by Montani and Morris (unpublished observations) is the richest group of this kind.

The initial detections ranged in peak intensity from $T_A^* = 0.6$–6.8 K, with a mean of 2.6 K. Like the intermediate-latitude clouds, most show relatively strong CO lines; only four clouds have peak temperatures less than 1 K, and for only one is $T_A^* < 0.8$ K. For both the high-latitude and intermediate-latitude clouds, typical line widths (ΔV) are relatively narrow: 1–1.5 km s^{-1} FWHM. In some of the clouds that have been mapped, a few directions have line widths as small as 0.25 km s^{-1}. A few clouds at both high and intermediate latitudes have very broad lines, $\Delta V > 5$ km s^{-1}. Such broad CO lines are generally seen only in regions of active star formation.

The clouds tend to have a complex velocity structure. Seven of the ten clouds which have been mapped show multiple velocity components along at least one line of sight. All but the two smallest clouds show a rich velocity structure across the entire face of the cloud. In one cloud, the velocity components are separated by as much as 10 km s^{-1}. If the velocity dispersion of a cloud σ_v (internal) is determined from the peak velocity at each position observed in a given map, the dispersion of the ten mapped clouds ranges from 0.2 km s^{-1} to 2.2 km s^{-1} with a median value of 0.73 km s^{-1}.

In order to determine the cloud-to-cloud velocity dispersion $\sigma_v(c - c)$ of the ensemble, we have attempted to group the clouds into kinematically distinct complexes. The velocity dispersion of the ensemble is 5.7 ± 1.2 km s^{-1} and the mean velocity is 1.3 ± 0.2 km s^{-1}. These values include a correction for differential galactic rotation amounting to 0.2 km s^{-1} in the dispersion, but do not include a pathological cloud with a velocity of -24.6 km s^{-1}. The value of the dispersion derived here is midway between two recently published values (Liszt and Burton 1984; Stark 1984) for local molecular clouds and is least likely to suffer from observational biases.

If we include the data of Montani and Morris (unpublished) on the L134 complex, 16 of 29 high-latitude clouds have been mapped. Individual clouds have projected areas that range from 0.1 to 5.4 square degrees with a mean of 1.4 and a median of 0.55 square degrees. Most of the clouds are irregular in outline, and one is quite filamentary (see Fig. 1).

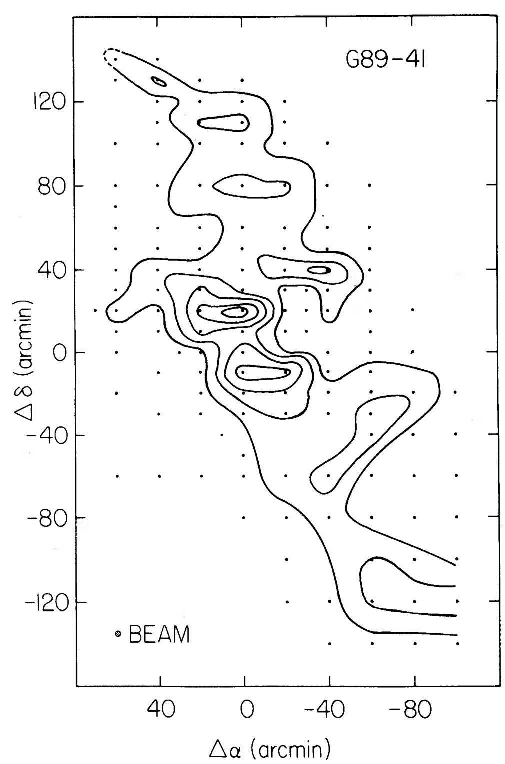

FIG. 1.—A map of the peak T_A^* of the cloud G89-41 showing its filamentary structure. The dots indicate sampled points. Coordinates are offsets in arc minutes from the peak position. The cloud is more than 5° in linear extent. The lowest contour is 0.5 K, and the contour interval is 1.0 K.

TABLE 1

PROPERTIES OF THE HIGH-LATITUDE CO CLOUDS

Quantity	Range or Value	Mean
Observed Properties		
T_A^* (CO) (K)	0.6–6.8	2.6
$\int T_A^*$ (CO) $dv / \int T_A^*$ (^{13}CO) dv	2.3–18	10.5
ΔV (CO) (FWHM) (km s^{-1})	1.0–5.7	1.9
σ_v (internal) (km s^{-1})	0.2–2.2	0.73[a]
σ_v (c − c) (km s^{-1})	5.7 ± 1.2	...
Projected area (sq. deg.)	0.1–5.4	1.3
Number detected	29	...
Derived Properties		
Distance (pc)	100[b]	...
Size (pc)	2.0[b]	...
Mass ($M_\odot$)	2.0–260	66
H_2 density (cm^{-3})	46–250	170
$N(H_2)/N$(H I)	0.2–30	5
A_v (H_2) (mag)	0.3–1.4	0.7
Age (yr)	$\lesssim 10^6$ yr	...
Number within 100 pc	$64/\epsilon$	...
Surface filling fraction within 100 pc	$2.5 \times 10^{-3}/\epsilon$	...
σ (H_2) ($M_\odot$ pc^{-2})	$0.1/\epsilon$	...

[a] Median value.
[b] Mean of ensemble.

A summary of the observed properties of the clouds as well as the derived properties discussed in the following section is given in Table 1.

IV. DERIVED PROPERTIES

a) *Distance*

The distances to the individual clouds can ultimately be derived from star counts, but a statistically determined distance to the high-latitude clouds can be obtained because the local molecular scale height is reasonably well known. In a plane-parallel, self-gravitating layer in which the gravity is produced by stars and the scale height of an isothermal gas layer is much less than that of the stars, the vertical structure of the gas is very nearly Gaussian (Spitzer 1942). For a given cloud, the expectation value of the height above the plane is 0.798 σ_Z, and the height above which half of the clouds are located is 0.674 σ_Z, where σ_Z is the Gaussian scale height of the gas.

The scale height of the gas can be estimated in several ways: (1) if the midplane deviation of the giant molecular cloud complexes is used to calculate the scale height, $\sigma_z = 76$ pc (Blitz 1978); (2) using the velocity dispersion from § III and the surface density of stars derived by van der Kruit and Shostak (1984) for the solar vicinity, $\sigma_z = 82$ pc; (3) from an extrapolation of the scale height of the molecular layer derived from the inner Galaxy, $\sigma_z = 55$–65 pc (Cohen, Tomasevich, and Thaddeus 1979; Sanders 1983). All three estimates are reasonably close, and we adopt a value of $\sigma_z = 75$ pc. The expectation value $\langle z \rangle$ for the height of a cloud above the midplane is thus 60 pc. Assuming that all of the clouds are at the expectation value, one may then calculate an expectation value $\langle d \rangle$ of the distance to a cloud from $\langle d \rangle = \langle z \rangle \csc b$. The mean $\langle \bar{d} \rangle$ for the ensemble of high-latitude clouds is 100 pc; the clouds are quite local.

b) *Size, Mass, and Density*

Using $\langle d \rangle$ to calculate the sizes of the clouds which have been mapped, the mean diameter of the clouds calculated from the square root of the projected surface area is 2.0 pc; the median is 1.2 pc. These clouds are quite small in spite of the large angular sizes projected by some of them.

To estimate the masses of the clouds, we use the CO/H_2 conversion factor $N(H_2) = 2.5 \times 10^{20}\ I_{CO}$ cm^{-2} derived from γ-ray, CO, and H I observations of the inner Galaxy and the Orion molecular complex (Lebrun *et al.* 1983; Bloemen 1984). For the 10 clouds which are well sampled, the masses range from 2.0 to 260 $M_\odot$. *These are very low mass clouds with typical masses less than 100* $M_\odot$. Errors in the CO/H_2 conversion or errors in the distances will not substantially alter this conclusion.

If the volume is given by the projected area to the 3/2 power, the mean H_2 densities within these clouds range from 46 to 250 cm^{-3} with a mean value of 170 cm^{-3}. The complex velocity structure may be indicative of clumping as is true for giant molecular clouds (Blitz 1980), and local volume densities may be higher than the mean value.

We note, however, that if the local thermodynamic equilibrium approximation is used to calculate ^{13}CO column density in the directions in which it has been observed, and Dickman's (1978) ^{13}CO/H_2 conversion is used to determine $N(H_2)$, the derived values are usually lower (typically by a factor of 3) than those found using ^{12}CO data alone. All of the quantities estimated from $N(H_2)$ may therefore be high by a similar factor. Additional observations should help to settle this issue.

c) *Correlation with* H I

Using the Heiles and Habing (1974) high-latitude H I survey, it is clear that there is a strong correlation both in space and in velocity between the high-latitude CO clouds and high-latitude H I. Even the pathological −24 km s^{-1} cloud has an H I counterpart. The CO velocity does not always fall on the H I peak, however. In one case, the CO cloud is at the high-velocity edge of the H I line. A comparison of H I and H_2 column densities indicates that H_2 is usually dominant, but not in every case (although it should be remembered that N(H I) is usually determined for the entire line of sight with a much larger beam). Ratios $N(H_2)/N$(H I) are typically 3–6, but values as high as 30 and as low as 0.2 are observed.

d) *Extinction*

Of the 37 high-latitude lines of sight with CO emission, 11 were previously cataloged by Lynds (1962) and thus have substantial extinction. Some of the remainder are indistinguishable in appearance from our nondetections which are likely to be fluctuations in the stellar background. If the gas-to-extinction ratio of Savage and Mathis (1979) is used, the mean visual extinction in the clouds we mapped varies from $A_v = 0.3$ to 1.4 mag, but along some lines of sight A_v may exceed 3.0 mag. We have ignored the contribution from H I because in most cases it is small, and it is not possible with data currently available to determine how much of the H I along the line of sight is associated with a given CO cloud.

Extended sources with extinctions in this range would be readily detected by *IRAS*. Furthermore, the range of angular sizes of the CO clouds which have been mapped are comparable to those reported for the diffuse high-latitude far-infrared emission observed with *IRAS* (Low *et al.* 1984). It thus appears likely that much of the *IRAS* "infrared cirrus" is from molecular clouds of the sort described in this *Letter*.

e) *Gravitational Binding and Age*

If the clouds are virialized, the velocity dispersion of the clouds is given by $\sigma_v = 0.0657\ (M/R)^{0.5}$ km s^{-1}, if M is in $M_\odot$ and R is in pc. The velocity dispersion of four of the ten clouds we mapped exceeds this value by more than a factor of 4, one by nearly an order of magnitude. Since the dispersion determined for a virialized cloud depends on the distance to the 0.5 power, errors in the distances to the clouds are unlikely to cause this discrepancy. Furthermore, to stabilize the clouds would require that we have underestimated the mass by a factor of 20–100. If this were true, these molecular clouds would be unlike any others observed in the Milky Way, and the resulting mass surface density in the galactic plane would be unreasonably high.

The simplest interpretation is that a large fraction of the clouds are not gravitationally bound and are expanding. If so, because the clouds are so small, their ages are less than the crossing time for the clumps: $\lesssim 10^6$ yr! *These clouds appear to be extraordinarily young* and may represent the earliest stages of molecular clouds condensing from the interstellar medium.

f) *Total Number and Surface Density*

The fraction of the sky accessible from the Millimeter Wave Observatory at $|b| \geq 30°$ is 0.381. If the fractional completeness of our catalog for the region surveyed is ε, then the total number of clouds within 100 pc of the Sun is $64/\varepsilon$.

The clouds which have been mapped subtend an area of 22.0 square degrees. We estimate the total area of the clouds in our sample to be 40.7 square degrees. The region surveyed subtends 4.79 steradians; therefore, in a blind search, only one line of sight in approximately 400 will produce a CO detection. Therefore, to get an estimate of the value of ε will require observations of at least several thousand lines of sight.

Using the column density conversions discussed above, we estimate that within 100 pc of the Sun, the small molecular clouds contribute roughly $2.9 \times 10^3/\varepsilon\ M_\odot$ which implies a mass surface density of approximately $0.1/\varepsilon\ M_\odot$ pc^{-2}. This is to be compared with roughly 4.3 $M_\odot$ pc^{-2} for H I (Liszt 1983). For the giant molecular clouds, the smoothed surface density in the solar vicinity is approximately 0.5 $M_\odot$ pc^{-2}. This value is obtained from the mean mass of giant molecular clouds in the solar neighborhood of $1.1 \times 10^5\ M_\odot$ (Stark and Blitz 1978), assuming that there is one giant molecular cloud per OB association, and taking the local density of OB associations given by Blaauw (1964). From corrections to the *Copernicus* observations, Savage *et al.* (1977) compute a local H_2 density 75% higher than the sum of the densities implied by the giant molecular clouds and high-latitude clouds. Given the uncertainties in all of the estimates, the agreement is not too bad. The main point, however, is that the small, local clouds contribute an appreciable fraction of the local molecular mass surface density.

We wish to thank Bruce Wilking for assistance with the observations, and Paul vanden Bout and Neal Evans for comments on the manuscript. We gratefully acknowledge partial support from NSF grants AST-8116403, and AST-8315276.

REFERENCES

Blaauw, A. 1964, *Ann. Rev. Astr. Ap.*, **2**, 213.
______. 1982, unpublished paper delivered at Leiden meeting on Southern Galactic Surveys, 1982 August.
Blitz, L. 1978, Ph.D. thesis, Columbia University.
______. 1980, in *Giant Molecular Clouds in the Galaxy*, ed. P. M. Solomon and M. G. Edmunds (Oxford: Pergamon), p. 1.
Bloemen, J. B. G. M. 1984, preprint.
Cohen, R. S., Tomasevich, G. R., and Thaddeus, P. 1979, in *IAU Symposium 84, The Large Scale Characteristics of the Galaxy*, ed. W. B. Burton (Dordrecht: Reidel), p. 53.
Dickman, R. L. 1978, *Ap. J. Suppl.*, **37**, 407.
Heiles, C., and Habing, H. J. 1974, *Astr. Ap. Suppl.*, **14**, 1.
Kutner, M. L., and Ulich, B. L. 1981, *Ap. J.*, **250**, 341.
Lebrun, F., *et al.* 1983, *Ap. J.*, **274**, 231.
Lequeux, J. 1981, *Comments Ap.*, **9**, 117.
Liszt, H. S. 1983, *Ap. J.*, **275**, 163.
Liszt, H. S., and Burton, W. B. 1984, preprint.
Low, F J., *et al.* 1984, *Ap. J.* (*Letters*), **278**, L19.
Lynds, B. T. 1962, *Ap. J. Suppl.*, **7**, 1.
Sanders, D. B. 1983, Ph.D. thesis, State University of New York, Stony Brook.
Savage, B. D., Bohlin, R. C., Drake, J. F., and Budich, W. 1977, *Ap. J.*, **216**, 291.
Savage, B. D., and Mathis, J. S. 1979, *Ann. Rev. Astr. Ap.*, **17**, 73.
Spitzer, L. 1942, *Ap. J.*, **95**, 329.
Stark, A. A. 1984, *Ap. J.*, **281**, in press.
Stark, A. A., and Blitz, L. 1978, *Ap. J.* (*Letters*), **225**, L15.
van der Kruit, P. C., and Shostak, G. S. 1984, *Astr. Ap.*, in press.

LEO BLITZ and LORIS MAGNANI: Astronomy Program, University of Maryland, College Park, MD 20742

LEE MUNDY: Astronomy Department, University of Texas, Austin, TX 78712