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MOLECULAR CLOUDS WITHOUT DETECTABLE CO

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ABSTRACT

The clouds identified by Désert, Bazell, and Boulanger (DBB clouds) in their search for high-latitude molecular clouds were observed in the CO ($J = 1$–0) line, but only 13% of the sample was detected. We propose that the remaining 87% are diffuse molecular clouds with CO abundances of $\sim 10^{-6}$, a typical value for diffuse clouds. This hypothesis is shown to be consistent with *Copernicus* data. The clouds are found to have mean H_2 column densities of 7.3×10^{19} cm^{-2}, corresponding to $A_v = 0.08$ mag, and masses of $\sim 10\ M_{\odot}$. If this interpretation is correct, the DBB clouds are shown to be an essentially complete catalog of diffuse molecular clouds in the solar vicinity. The total molecular surface density in the vicinity of the Sun is then only about 20% greater than the 1.3 $M_{\odot}$ pc^{-2} determined by Dame *et al.* Analysis of the CO detections indicates that there is a sharp threshold in extinction of 0.25 mag before CO is detectable and is derived from the *IRAS* I_{100} μm threshold of 4 MJy sr^{-1}. This threshold is presumably where the CO abundance exhibits a sharp increase.

Subject headings: infrared: sources — interstellar: molecules — nebulae: general

I. INTRODUCTION

The carbon monoxide molecule is the most widely used tracer of Galactic and extragalatic H_2. Its abundance is known, however, to vary by two orders of magnitude between dark clouds and diffuse interstellar clouds (e.g., Dickman 1978; Federman *et al.* 1980). Surveys of the Milky Way using millimeter-wave CO emission lines tacitly assume that nearly all of the H_2 in the Galaxy is traced by this emission, but we present evidence in this *Letter* that as much as half of the mass contained in the high-latitude molecular clouds (HLCs), and as much as 7% of all of the molecular gas within 1 kpc of the Sun is contained in clouds with CO abundances too small to be detected with present-day millimeter-wave receivers. These clouds are identified by means of their 100 μm emission from *IRAS* images and appear to be identical to the diffuse molecular clouds. The method of identifying these clouds insures that we have obtained an essentially complete inventory of molecular gas within about 100 pc of the Sun. We can therefore determine the molecular surface density near the Sun without resort to averaging distant areas on the solar circle.

II. THE PROBLEM

The discovery of the high-latitude molecular clouds (Blitz, Magnani, and Mundy 1984) resulted from the subjective identification of regions of low visual extinction from the Palomar Observatory Sky Survey prints (Magnani 1986). A blind survey by Magnani, Lada, and Blitz (1986) showed that the subjective identifications were surprisingly good: the Magnani, Blitz, and Mundy (1985, hereafter MBM) catalog is 50%–70% complete. The surface filling fraction on the sky for clouds with $|b| \geq 25°$ was found to be 0.5%.

In order to have a more objective way of finding HLCs, Désert, Bazell, and Boulanger (1988, hereafter DBB) tried to identify the clouds by means of the 100 μm emission from the associated dust using the *IRAS* low-resolution maps ($\simeq 0.°5$). Because 100 μm intensity, I_{100}, has been shown to correlate well with H I column density, N(H I) (Boulanger, Baud, and van Albada 1984; DBB), molecular clouds appear as regions of positive excess in the correlation between I_{100} and N(H I). By identifying only regions with 4 σ excesses as significant, DBB found 516 regions of infrared excess outside the Galactic plane with $|b| \geq 5°$; of these, 297 are clouds with $|b| \geq 25°$ with a mean size of 3.2 deg^2. DBB checked to see whether the clouds in the MBM molecular cloud catalog are a subset of the clouds in their infrared catalog and found only one cloud absent with an expected infrared flux high enough to be detected. Therefore, the DBB catalog does appear to be a good way to find molecular clouds. The clouds at $|b| \leq 25°$ appear to be a mixture of high-latitude extensions of known giant molecular clouds and HLCs. For this reason we limit our discussion to $|b| \geq 25°$.

However, the total area subtended by the DBB clouds at $|b| \geq 25°$ is 946 deg^2, a surface filling fraction on the sky of 4.0%. Either Magnani, Lada, and Blitz (1985) underestimated the filling fraction of HLCs by a factor of 8, or the DBB objects represent a population of interstellar molecular clouds with properties different from the HLCs.

III. OBSERVATIONS

In order to test which of these possibilities is the case, we have observed most of the clouds in the DBB catalog using the $J = 1$–0 transition of CO at the 12 m NRAO telescope on Kitt Peak. One or two positions were observed in each cloud: the two positions with the highest 100 μm fluxes. A check of a number of HLCs showed that these positions invariably fall within the lowest CO contour of the clouds mapped by MBM.

Observations were made by position-switching to a reference position 1° away in azimuth and with 0.26 and 0.65 km s^{-1} resolution, simultaneously. The instantaneous bandwidth was ± 83.2 km s^{-1} centered on 0 km s^{-1} relative to the LSR. Integration times were set so that the rms noise at the lower velocity resolution was about 0.2 K (in units of T_R^*) in each resolution element.

IV. RESULTS

Of 297 cataloged clouds with infrared excesses at $|b| \geq 25°$, we observed 201, most of those observable from Kitt Peak. We detected CO from 27. Figure 1 shows a plot of the CO integrated intensity, plotted against total interstellar 100 μm flux at the observed CO position. This flux is obtained from *IRAS* sky-flux plates (resolution 4′) by subtracting the minimum flux measured in a 2° × 2° square map centered on the cloud from the peak flux, in order to get rid of the smooth zodiacal foreground emission. Also shown is a line indicating the 2 σ upper limit to the sensitivity of the CO observations. The horizontal extent of the line shows the range of values of I_{100} spanned by the nondetections.

The most striking feature of Figure 1 is the sharp cutoff in CO emission for infrared fluxes below 4 MJy sr^{-1}. Using the mean $N(\mathrm{H})/I_{100}$ found by DBB and the $N(\mathrm{H})/A_v$ relation (Savage and Mathis 1979), this cutoff is equivalent to $A_v = 0.25$ mag. Also shown in Figure 1 is the least-squares fit to the detections. The CO observations are clearly sensitive enough to detect clouds at fluxes below 4 MJy sr^{-1} if they followed the regression line. Note, however, that there is no correlation for clouds with fluxes below 10 MJy sr^{-1}.

For the nondetections, only 12 of 174 or 7% have fluxes above the 4 MJy sr^{-1} cutoff. Thus, not only do clouds that contain detectable quantities of CO in emission require extinctions of $\sim$0.25 mag, but the converse is also apparently true: clouds without detectable radio CO emission almost always have extinctions less than 0.25 mag.

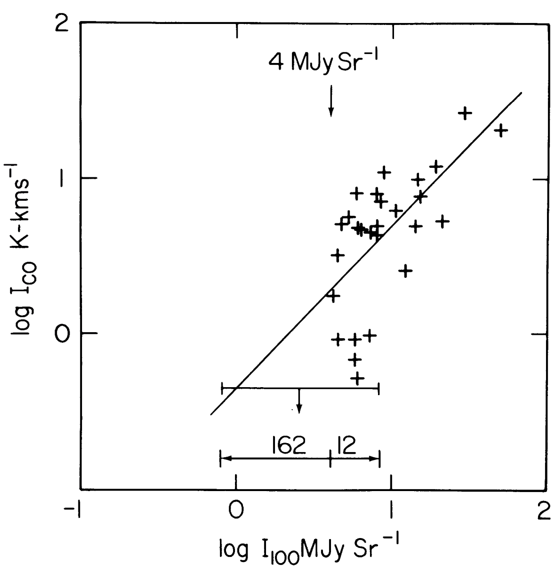

FIG. 1.—Plot of 100 μm flux density $\int T_A\, dv$ to all of the detections is shown, indicating that clouds below the I_{100} detection threshold of 4 MJy sr^{-1} should have been seen. The horizontal bar at 0.5 K km s^{-1} is the 2 σ detection limit of the CO observations; and the extent of the bar indicates the range of the I_{100} values of the nondetections. The number of nondetections above and below 4 MJy sr^{-1} is given at the bottom of the figure.

V. DISCUSSION

The detection rate of CO in the DBB clouds is 13.4%. Multiplying this fraction by the 4.0% filling fraction of DBB clouds yields a 0.53% filling fraction with detectable radio CO emission, in good agreement with the value of 0.5% derived by Magnani, Lada, and Blitz (1985). What then are the remaining 87% of the objects?

We propose that they are ordinary diffuse molecular clouds seen in infrared emission, and because the method of identification is both sensitive and unbiased, that the clouds represent an almost complete sample of diffuse molecular clouds close to the Sun. Let us examine the evidence for this conclusion.

If the DBB clouds without detectable CO are H_2 clouds, then molecular lines should be observed in absorption against *Copernicus* stars. Unfortunately, no stars in the list compiled by Bohlin, Savage, and Drake (1978) lie in the direction of DBB clouds. However, *Copernicus* stars in the plane of the Galaxy at sufficiently large distances should intersect DBB–type clouds and produce the required H_2 column density, $N(\mathrm{H}_2)$.

We wish to calculate the average density along the line of sight, calculated as $\langle N(\mathrm{H}_2)\ \mathrm{kpc}^{-1}\rangle$, of the DBB clouds and compare it to the observed value from *Copernicus* stars. One expects a higher value of $\langle N(\mathrm{H}_2)\ \mathrm{kpc}^{-1}\rangle$ for the *Copernicus* stars than for the DBB clouds if the lines of sight to some of the *Copernicus* stars intersect the outer envelopes of the GMCs from which the stars formed. We first calculate the mean free path for a line of sight, $(n\sigma)^{-1}$, to the DBB clouds, and convert the mean value of I_{100} associated with the molecules to $N(\mathrm{H}_2)$. To estimate $(n\sigma)^{-1}$, we assume that the clouds at $|b| \geq 25°$ have a mean distance of 100 pc, similar to the HLCs (Magnani, Blitz, and Mundy 1986; Magnani and de Vries 1987; Hobbs, Blitz, and Magnani 1986). Thus half of the 257 clouds without detectable CO lie within a 100 pc sphere centered on the Sun. This number must be corrected upwards for the clouds at $|b| \leq 25°$, which is done by assuming a uniform distribution on the sky (probably a small underestimate). Thus the total number of DBB clouds within 100 pc is 223 and they subtend a total of 223/297 × 946 deg^2 = 710 deg^2. The value of $(n\sigma)^{-1}$ is therefore $\sim$1.9 kpc; the precise value depends on how the clouds are distributed and how accurately the mean distance has been determined.

The mean infrared excess per DBB cloud without detected CO is 1.25 MJy sr^{-1}, corresponding to $A_v = 0.08$ mag. Using $N(\mathrm{H}_2)/A_v = 9.4 \times 10^{20}$ cm^{-2} (Savage and Mathis 1979), one expects that for each 1.9 kpc, $\langle N(\mathrm{H}_2)\rangle = 7.3 \times 10^{19}$ cm^{-2}, or a mean density of 3.8×10^{19} cm^{-2} kpc^{-1}.

The compilation of Bohlin, Savage, and Drake (1978) contains 18 *Copernicus* stars with $|b| \leq 5°$ at distances more than 1 kpc from the Sun. The value of $\langle N(\mathrm{H}_2)\ \mathrm{kpc}^{-1}\rangle = 9.4 \times 10^{19}$ cm^{-2} for all 18 stars is somewhat higher than, but in reasonable agreement with, the expected value. Furthermore, of these 18 stars, 14 have $N(\mathrm{H}_2) > 4 \times 10^{19}$ cm^{-2}, consistent with the expectation that many of the stars should intersect at least 1 DDB–type cloud. The values of $E(B-V)$ for these 18 stars imply that the intervening clouds are diffuse molecular clouds (e.g., Spitzer 1978), generally defined as those clouds in which photoprocessing is important.

Thus, we have the clear implication that the DBB clouds are simply the diffuse molecular clouds seen by means of their infrared emission. The sensitivity of the DBB survey is hard to assess because it depends on the local H I background.

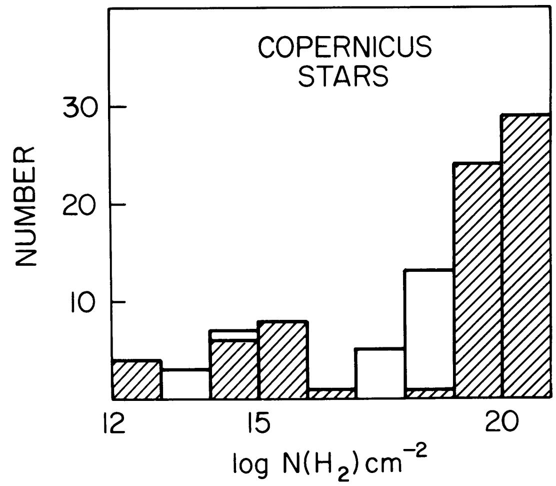

FIG. 2.—Histogram of *Copernicus* stars showing the threshold to $N(H_2)$ at $\sim 10^{19}$ cm^{-2}. Shading indicates stars toward which H_2 is detected; unshaded regions are upper limits.

However, clouds with $N(H_2) \geq 3 \times 10^{19}$ cm^{-2} are routinely detected, and clouds with somewhat smaller column densities are sometimes detected. Figure 2 shows a histogram of $N(H_2)$ for the *Copernicus* stars. There is a clear threshold at $N(H_2) \sim 1 \times 10^{19}$ cm^{-2}; that is, we can divide the lines of sight into categories. Those stars toward which $N(H_2) \geq 10^{19}$ cm^{-2} have sight lines which pass through diffuse molecular clouds; those with $N(H_2) \leq 10^{19}$ cm^{-2} have sight lines which pass only through intercloud gas. Only 23% of the stars with $N(H_2) \geq 10^{19}$ cm^{-2} also have $N(H_2)$ less than the conservative detection limit of 3×10^{19} cm^{-2} and therefore may not be detected in the DBB survey. One therefore expects the DBB list to be $\gtrsim$80% complete in its compilation of diffuse clouds.

We now ask, what, assuming our hypothesis is correct, is the mass fraction of molecular gas in the solar vicinity tied up in the DBB clouds without detectable CO? First, we assume, as above, that $2N(\text{H I})/I_{100} = N(H_2)/I_{100}$ as determined by DBB. The reasonableness of this assumption is supported by comparisons of I_{100}, H I, and CO for GMCs (Boulanger 1989), which show that even for clouds where the interstellar radiation field may be significantly attenuated, the equality should be in error by no more than about 25% on average. The surface density in the disk is $\langle N(H_2) \rangle$ per cloud times the probability of intersecting a cloud perpendicular to the disk: twice the scale height (H) divided by the mean free path or $2Hn\sigma$. If the scale height of these clouds is similar to the local scale height of molecular clouds ($\sim$75 pc), then the surface density in the disk is 0.07 $M_\odot$ pc^{-2}, a value consistent with the upper limit for this quantity derived by Dame *et al.* (1987). The scale height for the DBB clouds may, however, be greater than the local CO scale height, but in any event should be less than the H I scale height of 115 pc (Dickey and Lockman 1990). The surface density could therefore be 50% higher than this value. This value is to be compared with 0.2 $M_\odot$ pc^{-2} for HLCs with detectable CO (Magnani, Lada, and Blitz 1986) and 1.3 $M_\odot$ pc^{-2} for GMCs in the solar neighborhood (Dame *et al.* 1987).

The surface density of DBB clouds is therefore about one-third to one-half of the surface density attributable to the HLCs for which CO is detected. Together the small, low-extinction molecular clouds are $\sim$20% of the total molecular surface density near the Sun, a minor but not insignificant fraction of the total molecular surface density.

There are three other possible explanations for our results. The first is that the DBB clouds with excesses below the critical value of 4 MJy sr^{-1} are artifacts of the DBB analysis. We note, for example, that DBB find many infrared deficient clouds as well as infrared excess clouds. Although some of the clouds we observed from the DBB list may not be real, it seems very unlikely that the sensitivity to real clouds in their survey should be coincidentally at the level at which their survey reliably indicates the presence of CO. Another possibility is that the DBB clouds are simply hotter than the average atomic cloud in the local ISM. Although this could be the case, we consider it unlikely because, except for a latitude dependence, the DBB clouds are distributed rather uniformly about the celestial sphere. The sources of ultraviolet heating are very nonuniform in the local ISM, however, and one would expect that the DBB clouds would cluster about the nearest heating sources. They do not. The third possibility is that the clouds are identified by DBB because the dust-to-gas ratio is different in these clouds from those in the general ISM. Although we cannot rule this possibility out, the dust-to-gas ratio appears to be normal in at least some of the DBB clouds that contain CO (Weiland *et al.* 1986). That the dust-to-gas ratio should be different in only this small set of uniformly distributed clouds seems rather unreasonable.

VI. CONFIRMATION

Although we believe the evidence that the DBB clouds without CO are the diffuse molecular clouds is strong, there is still no "smoking gun." That is, there is currently no direct detection of molecules either in emission or absorption toward these clouds. We note, for example, that the molecules detected in absorption against the star HD 210121 by de Vries and van Dishoeck (1988) toward DBB 80 have been detected in the CO $J = (1\text{–}0)$ transition and is therefore not one of the CO–poor clouds. The low column densities make emission-line measurements from the DBB clouds very difficult, although detections of transitions of CH in the radio can be done. Other possibilities include looking for the CO ($J = 1\text{–}0$) in absorption against an extragalactic millimeter continuum source. Yet another possibility is to look for lines of C_2 or CH in the optical portion of the spectrum against suitable background stars. The strong CH absorption seen toward HD 210121 by de Vries and van Dishoeck shows that such observations are feasible. We are currently making a list of these stars, which will be available on request.

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