MOLECULAR AND ATOMIC CLOUDS ASSOCIATED WITH INFRARED CIRRUS IN URSA MAJOR

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ABSTRACT

Observations of CO and H I revealed that in Ursa Major the high-latitude far-infrared "cirrus" emission discovered by the Infrared Astronomical Satellite (IRAS) survey is the discovery of patchy far-infrared emission, or infrared "cirrus," far from the Galactic equator (Low et al. 1984). Since near the equator much of the far-infrared emission apparently comes from molecular clouds (Myers et al. 1986), we attempted to detect CO counterparts of the cirrus. To date, the best correspondence between infrared and CO that we have encountered is a complex of molecular and atomic clouds in Ursa Major (Figs. 1 and 2), whose visual counterparts were first cataloged as bright nebulae by Lynds (1965) and later termed high-latitude reflection nebulosities by Sandage (1976). A striking example of this correspondence is a long, narrow infrared filament (at $l = 142^\circ$; Fig. 1), which resembles its CO counterpart (Fig. 2) in considerable detail.

Although each molecular cloud in the observed region has a clear infrared counterpart, the converse does not hold: not all infrared cirrus clouds are associated with CO. In other complexes, diffuse infrared cirrus has been found to be associated with diffuse atomic gas (see, e.g., Boulanger, Baud, and Van Albada 1985), so we observed H I in this complex as well. Our observations (Fig. 3) show a good correspondence between the infrared and the H I for all lines of sight without CO. In particular, the infrared cloud at $l = 142^\circ$, $b = 39^\circ$, of which only the southern half and the northernmost edge contain CO, shows strong H I emission from the part without CO (Fig. 4a–c).

The Ursa Major molecular clouds are similar to the high-latitude clouds recently studied by Magnani, Blitz, and Mundy (1985) and Keto and Myers (1986) but are smaller and more diffuse than the large molecular clouds in the Galactic plane (§ IV). This raises the question whether results obtained from studies of the population of molecular clouds in the Galactic plane apply in Ursa Major. In particular, the ratio of H$_2$ column density to velocity-integrated CO radiation temperature, $N(H_2)/W_{CO}$, derived from Galactic plane surveys, may not apply to them. On the assumption of a constant gas-to-dust ratio, it is argued that the cirrus emission in Ursa Major is a good mass tracer, since both the atomic and the molecular gas are probably optically thin at visual wavelengths, and the grains are heated not by local sources but by the background field of Galactic starlight. The $N(H_2)/W_{CO}$ ratio thus derived for those diffuse clouds, $(0.5 \pm 0.3) \times 10^{20} \text{K}^{-1} \text{km}^{-1} \text{s cm}^{-2}$, is significantly lower than the ratio applicable to Galactic plane surveys.

Subject headings: infrared. sources — interstellar: molecules — nebulae: reflection

I. INTRODUCTION

One of the most interesting results of the Infrared Astronomical Satellite (IRAS) survey is the discovery of patchy far-infrared emission, or infrared "cirrus," far from the Galactic equator (Low et al. 1984). Since near the equator much of the far-infrared emission apparently comes from molecular clouds (Myers et al. 1986), we attempted to detect CO counterparts of the cirrus. To date, the best correspondence between infrared and CO that we have encountered is a complex of molecular and atomic clouds in Ursa Major (Figs. 1 and 2), whose visual counterparts were first cataloged as bright nebulae by Lynds (1965) and later termed high-latitude reflection nebulosities by Sandage (1976). A striking example of this correspondence is a long, narrow infrared filament (at $l = 142^\circ$; Fig. 1), which resembles its CO counterpart (Fig. 2) in considerable detail.

Although each molecular cloud in the observed region has a clear infrared counterpart, the converse does not hold: not all infrared cirrus clouds are associated with CO. In other complexes, diffuse infrared cirrus has been found to be associated with diffuse atomic gas (see, e.g., Boulanger, Baud, and Van Albada 1985), so we observed H I in this complex as well. Our observations (Fig. 3) show a good correspondence between the infrared and the H I for all lines of sight without CO. In particular, the infrared cloud at $l = 142^\circ$, $b = 39^\circ$, of which only the southern half and the northernmost edge contain CO, shows strong H I emission from the part without CO (Fig. 4a–c).

The Ursa Major molecular clouds are similar to the high-latitude clouds recently studied by Magnani, Blitz, and Mundy (1985) and Keto and Myers (1986) but are smaller and more diffuse than the large molecular clouds in the Galactic plane (§ IV). This raises the question whether results obtained from studies of the population of molecular clouds in the Galactic plane apply in Ursa Major. In particular, the ratio of H$_2$ column density to velocity-integrated CO radiation temperature, $N(H_2)/W_{CO}$, determined from γ-ray, H I, and CO observations of the Galactic plane where large clouds dominate the CO emission (see, e.g., Bloemen et al. 1986), may not apply to the high-latitude clouds, as Keto and Myers pointed out.

As we show here, the infrared emission detected by IRAS allows us to calibrate $N(H_2)/W_{CO}$ by deriving separately the ratio of infrared flux density to $N(H_2)$ and the ratio of infrared flux density to $W_{CO}$. The resulting $N(H_2)/W_{CO}$ ratio, $(0.5 \pm 0.3) \times 10^{20} \text{K}^{-1} \text{km}^{-1} \text{s cm}^{-2}$, is significantly lower than the ratio derived by Bloemen et al. (1986). Our method of calibrating $N(H_2)/W_{CO}$ from far-infrared emission, similar to the method of calibrating $N(H_2)/W_{CO}$ from γ-rays for dense clouds by Bloemen et al., may be generally applicable to tenuous clouds.

II. OBSERVATIONS

The CO observations of the $J = 1 \rightarrow 0$ transition at 115 GHz were done during 1984 and 1985 with the Columbia 1.2 m telescope using a very sensitive SIS receiver (Pan et al. 1983) and a 256 channel spectrometer with a resolution of 250 kHz, or 0.65 km s$^{-1}$ at 115 GHz. An $8' \times 8'$ field centered at $l = 145^\circ$, $b = 38^\circ$ (Fig. 2) was observed with an rms sensitivity of 0.1 K; molecular gas when detected was sampled every beamwidth (8'), while the surrounding blank regions were generally sampled every two or three beamwidths. Only molecular clouds of very small angular size could have escaped detection.

The same region was later observed in H I (Fig. 3) with the Effelsberg 100 m telescope, which at 1.4 GHz has nearly the same angular resolution as the Columbia telescope at 115 GHz. 9.1 versus 8.7. The spectra were obtained by using a cooled, dual-channel FET amplifier with a system temperature
of about 55 K and a 1024 channel autocorrelation spectrometer in dual-channel mode with bandwidths of 0.781 and 3.125 MHz (Δν = 0.32 and 1.29 km s⁻¹); at these resolutions, the rms noise in our spectra is about 0.4 and 0.2 K, respectively. The observed line profiles were calibrated using the IAU standard position S7 and corrected for stray radiation arising from the far sidelobes of the telescope (Kalberla, Mebold, and Reich 1980).

The observations were compared with the infrared emission from this field using the IRAS Sky Flux Images (Beichman et al. 1985). By combining and smoothing three of the 100 μm images of the first sky coverage (fields 6, 17, and 18), we produced a map of the flux density measured at 100 μm (Fig. 1) with the same resolution as the CO and H I observations.

A large fraction of I₁₀₀, the flux at 100 μm, comes from a smooth "background," largely zodiacal emission. The magnitude of this emission cannot be calculated accurately because it depends on the time of observation, information not available for the Sky Flux Images (Boulanger et al. 1987). In addition to the zodiacal emission, there may be a contribution to the background from other, possibly extragalactic, sources. For our analysis we assume that in the observed region the background emission is constant, because it changes very little over distances comparable to the size of this region. Small-scale fluctuations in the background cause the total uncertainty in I₁₀₀ to be about ¼ to ½ MJy sr⁻¹ (roughly 5% of the flux in Ursa Major).

III. INFRARED EMISSION AS A TRACER OF THE GAS COLUMN DENSITY

a) Qualitative Comparison

Having found that the far-infrared emission from the Ursa Major complex comes from dust associated with atomic as well as molecular gas (§ I), we now turn to a detailed comparison of the CO, H I, and far-infrared emission. The complex contains an extended infrared object, seen half in CO and half in H I (Fig. 4a–c), which is the focus of our discussion. The smoothness of the infrared emission from the object suggests that the mass distribution also is fairly smooth. It is possible that we are seeing the postulated abrupt transition (Hollenbach, Werner, and Salpeter 1971) from atomic to molecular gas or vice versa.

The "standard" mass conversion formulae for H I and CO indicate a discontinuity between the atomic mass and the molecular mass in this object. If we assume an H I spin tem-
temperature of 125 K and a ratio of \(N(H_2)\) to \(W_{\text{CO}}\) of \(2.8 \times 10^{20} \text{ K}^{-1} \text{ km}^{-1} \text{ s cm}^{-2}\) (Bloemen et al. 1986), we find that the average column density of the molecular gas is higher by roughly a factor of 7 than the average column density of the atomic gas. The smooth distribution of infrared emission, in contrast, suggests a much more uniform object, with rough equality of the atomic and the molecular mass.

There are at least three possible explanations of this apparent discontinuity. First, although the infrared clearly seems to trace both atomic and molecular gas, it may do so unequally; e.g., cooling by molecular transitions may cause the dust in molecular gas to absorb and reemit less energy than the dust in atomic gas. Second, the H I may be much colder than assumed and optically thick at 21 cm, so the H I column densities would have been underestimated. Third, \(N(H_2)/W_{\text{CO}}\) may be much lower than the value we initially adopted, so the H\(_2\) column densities were overestimated.

Simple arguments strongly suggest that the far-infrared emission is about the same per unit mass in both the atomic and the molecular gas. We assume that in Ursa Major the gas-to-dust ratio in the atomic clouds and that in the molecular clouds are similar, because the ratios \(N(\text{H I})/E_{B-V}\) and \(N(H_2)/E_{B-V}\), obtained for lines of sight distributed over a large fraction of the sky, are roughly equal (Bohlin, Savage, and Drake 1978). Next, the observed clouds are not very thick optically at visual wavelengths. Given the average \(W_{\text{CO}}\) of about 1 K km s\(^{-1}\), the extinction caused by the molecular gas, derived using \(N(H)/E_{B-V} = 5.8 \times 10^{21} \text{ cm}^{-2} \text{ mag}^{-1}\) (Bohlin, Savage, and Drake 1978), \(N(H_2)/W_{\text{CO}} = 2.8 \times 10^{20} \text{ K}^{-1} \text{ km}^{-1} \text{ s cm}^{-2}\), and \(A_V/E_{B-V} = 3.1\), is about 0.3 mag, for an optical depth of \(\sim 0.3\); there is reason to think, as we shall see, that it may be even lower. The total extinction along the line of sight caused by the atomic gas, derived using the same formulae and an average \(N(\text{H I})\) of about \(5 \times 10^{18} \text{ cm}^{-2}\), also is about 0.3 mag (cf. Sandage 1976). Owing to the small optical thickness, the absorption of light from the interstellar radiation field probably responsible for heating the dust (Mezger, Mathis, and Panagia 1982; Sandage 1976) is approximately the same for dust in the molecular gas as for dust in the atomic gas in the observed region. The dust temperature may then be assumed to be relatively uniform, because in diffuse clouds like those in Ursa Major the dust temperature is determined almost entirely by radiative processes (Spitzer 1978). Considering all these arguments, we assume that the infrared reradiation of light absorbed by dust is about the same per H atom for the molecular and the atomic gas in the Ursa Major complex.
The possibility that the H\textsc{I} is optically thick is remote. The H\textsc{I} radiation temperatures measured in the intercloud regions are comparable to those measured in most other directions at high Galactic latitudes (cf. Heiles and Habing 1974). Unless all diffuse high-latitude H\textsc{I} is conceded to be optically thick, the most diffuse H\textsc{I} in the observed region must be considered optically thin. Further, we found a good linear correlation between $I_{100}$ and the velocity-integrated H\textsc{I} radiation temperature, $W_{\text{H}\textsc{I}}$, for all lines of sight without CO and for the whole range of $W_{\text{H}\textsc{I}}$. This correlation implies that, in addition to $I_{100}$, $W_{\text{H}\textsc{I}}$ also is constant per unit mass. In the observed region, then, the H\textsc{I} is unlikely to be optically thick, so the standard $N(\text{H}\textsc{I})/W_{\text{H}\textsc{I}}$ ratio for optically thin H\textsc{I}, $1.823 \times 10^{14}$ K$^{-1}$ km$^{-1}$ s cm$^{-2}$, seems applicable.

Comparison of the properties of the Ursa Major clouds and the properties of those clouds for which the adopted $N(\text{H}_2)/W_{\text{CO}}$ ratio was derived suggests that the ratio applicable to our clouds is indeed lower. The adopted ratio was derived by Bloemen et al. (1986) from a large-scale survey of the Galactic plane where large molecular clouds and cloud complexes with masses of at least $10^5 M_\odot$ account for most of the CO emission. The CO in these large objects is generally optically thick: the ratio of the intensity of its $J = 1 \rightarrow 0$ line to that of the corresponding line of $^{12}$CO is typically 4 to 5, while the actual abundance ratio of the two isotopes is 40 to 90 in the outer Galaxy. For optically thin CO, $N(\text{H}_2)/W_{\text{CO}}$ may therefore be expected to be lower by a factor approaching 10, and it is not surprising that in tenuous molecular clouds like those in Ursa Major the standard conversion ratio yields masses that are high.

Besides the optical thickness, one may consider other factors that may affect $W_{\text{CO}}$ and the $N(\text{H}_2)/W_{\text{CO}}$ ratio. Here we discuss here the CO abundance and the CO kinetic temperature. An increase in CO relative to H$_2$ is unlikely to be the factor responsible for the lower value of $N(\text{H}_2)/W_{\text{CO}}$, because calculations by Glassgold, Huggins, and Langer (1985) indicate that the CO abundance in clouds with a small visual extinction is significantly lower than that in dark clouds. A more likely factor seems to be the CO kinetic temperature, $T_\text{K}$. Model calculations by Kutner and Leung (1985) suggest that $N(\text{H}_2)/W_{\text{CO}} \propto T_\text{K}^{-1.3}$, which would indicate a kinetic temperature of $\sim 30$ K, a not unreasonable value.

If the lower value of $N(\text{H}_2)/W_{\text{CO}}$ is indeed caused by a higher $T_\text{K}$, we need to explain the large difference between this temperature and the peak radiation temperature, $T_{\text{R, max}}$, of the CO lines, because the detection of $^{13}$CO at $l = 142^{20}, b = 38^{22}$...
A plausible explanation of our observations, then, is that the far-infrared emission from the Ursa Major complex does trace the total mass and that the apparent mass discontinuity deduced from CO and H\textsc{i} is due mainly to an overestimate of $N(\text{H}_2)/W_{\text{CO}}$. Indeed, it is worthwhile to invert the reasoning, and to assume that the far-infrared emission is a gas column density tracer, i.e., that for tenuous clouds $N(\text{H}_2)/W_{\text{CO}}$ can be calibrated from far-infrared emission analogous to the way it was calibrated for dense clouds by Bloemen \textit{et al.} from $\gamma$-rays.

\begin{itemize}
  \item \textit{b) Calibration of $N(\text{H}_2)/W_{\text{CO}}$}
  
  To derive $N(\text{H}_2)/W_{\text{CO}}$ for the molecular gas in the Ursa Major region, we assume the cirrus in this region can be represented by a two-component infrared emission model, one component giving a contribution linearly proportional to the total hydrogen column density, $N(\text{H})$, equal to $N(\text{H}\textsc{i}) + 2N(\text{H}_2)$, the other, the background emission (§ II), a constant contribution. For each line of sight, the infrared flux density is assumed to be related to $N(\text{H}\textsc{i})$ and $W_{\text{CO}}$ by
  \begin{equation}
  I_{100} = aN(\text{H}\textsc{i}) + bW_{\text{CO}} + I_{100}(\text{BG})
  \end{equation}
  
  where $I_{100}(\text{BG})$ is the flux density of the background emission, while the $N(\text{H}_2)/W_{\text{CO}}$ ratio is equal to $b/2a$. This ratio was derived in two steps, first, derivation of the parameters $a$ and $I_{100}(\text{BG})$, and, second, determination of the relation between $I_{100}$ and $W_{\text{CO}}$.

  The first step was performed by considering all lines of sight in Figure 2 for which no CO was detected. By least-squares adjustment (cf. Jefferys 1980, 1981), we derived a value for $a$ of $(1.0 \pm 0.4) \times 10^{-20}$ MJy s$^{-1}$ cm$^{-2}$ and a value for $I_{100}(\text{BG})$ of $(4.0 \pm 0.5)$ MJy s$^{-1}$. Next, we derived $N(\text{H}_2)/W_{\text{CO}}$ by applying the derived values for $a$ and $I_{100}(\text{BG})$ to the lines of sight in Figure 2 with a CO detection above the 3σ level, $W_{\text{CO}} = 0.4$ K km$^{-1}$ s$^{-1}$, and found a value for $b$ of $1.0 \pm 0.5$ MJy s$^{-1}$ K$^{-1}$ km$^{-1}$ s, resulting in an $N(\text{H}_2)/W_{\text{CO}}$ ratio of $(0.5 \pm 0.3) \times 10^{20}$ K$^{-1}$ km$^{-1}$ s cm$^{-2}$. The uncertainties in the parameters were estimated visually from diagrams of $I_{100}$ versus $N(\text{H}\textsc{i})$ and $I_{100} - aN(\text{H}\textsc{i}) - I_{100}(\text{BG})$ versus $W_{\text{CO}}$. These diagrams and the fitted lines are shown in Figure 5.

  The derived value for $a$, the $I_{100}/N(\text{H}\textsc{i})$ ratio, agrees with the value found by Boulanger \textit{et al.} (1987), that found by Boulanger, Baud, and Van Albada (1985), that derived from a dust-gain model by Draine and Lee (1984), and that implied by the $I_{100}$ and $N(\text{H}\textsc{i})$ values given by Low \textit{et al.} (1984). Following the procedure described by Boulanger \textit{et al.}, we compared the flux densities in Figure 1 to those in a $\frac{1}{2}$ resolution, all-sky map from which the zodiacal emission had been subtracted. The slope of the relation is very nearly equal to 1, while the intercept, $3.5$ MJy s$^{-1}$, agrees with our value for $I_{100}(\text{BG})$. As expected from our qualitative examination (§ IIIa), our $N(\text{H}_2)/W_{\text{CO}}$ ratio is significantly lower than that derived by Bloemen \textit{et al.} (1986). Recently, Boulanger \textit{et al.} derived $N(\text{H}_2)/W_{\text{CO}}$ values for a number of physically different molecular clouds using a method similar to ours, and for the most diffuse objects in their observations their values agree with our value for $N(\text{H}_2)/W_{\text{CO}}$.

  To illustrate the results of our analysis, in Figure 4d we show the predicted infrared emission, derived from CO and H\textsc{i} with this analysis, for only the object shown in Figure 4a–c. The parameters derived for this object are equal within the estimated uncertainties to those derived above for the whole Ursa Major complex.

\end{itemize}
IV. PHYSICAL PROPERTIES OF THE CLOUDS

Determination of the mass and size of the high-latitude clouds in Ursa Major depends on a good estimate of the distance. Attempts to derive distances to similar, diffuse clouds from star counts have been discouraging, because at high latitudes there are few stars (Magnani, De Vries, and Blitz 1985; Mebold et al. 1985); however, reasonable upper and lower limits on the distance of the Ursa Major complex can be established. Assuming that the complex is part of the distribution of molecular material in the Galaxy, whose half-thickness is about 70 pc (Bronfman et al. 1987), the distance is not likely to be greater than 200 pc. Since studies of the interstellar medium in the immediate vicinity of the Sun indicate that the Sun is located in a hot, low-density cloud extending over a distance of ~50 pc in all directions (Kondo, Bruchweiler, and Savage 1984 [Foreword]; Bruchweiler 1984), we assume that the complex is

at least 50 pc away. For our analysis we therefore adopt a distance of 100 pc, uncertain by a factor of 2.

Many CO and H I objects can be found in Figures 2 and 3, but only the most conspicuous clouds are identified in Table 1. They are characterized by a mass of a few solar masses, a radius of about 1 pc, a small velocity with respect to the local standard of rest, and a small line width, indicating little turbulence—properties which agree well with those found for clouds observed in the high-latitude CO surveys by Keto and Myer (1986) and Magnani, Blitz, and Mundy (1985), whose survey included observations of the Ursa Major complex. This agreement suggests that the clouds in these surveys and the Ursa Major clouds are all part of one population, an idea supported by preliminary results of a comparison (Hauser et al. 1985) of the survey by Magnani, Blitz, and Mundy and the IRAS survey that indicates that the clouds in the former survey can be found in infrared as well.

Although whether the Ursa Major clouds are stable is not clear, they are almost certainly not gravitationally bound: the mass deduced from the virial theorem, \( M = 5R(\Delta \sigma)^2 / [8G \ln (2)] \), assuming that the clouds are spherical and uniform, is larger by at least 2 orders of magnitude than that given in Table 1. An error in the estimated distance cannot explain the difference, because to make the two masses equal would require a location many scale heights above the Galactic plane; the large difference also cannot be explained by errors in the assumptions regarding the shape and uniformity of the clouds. It is still possible, however, that the clouds are stable. Keto and Myer (1986) found that the intercloud pressure needed to maintain hydrostatic equilibrium in most of the high-latitude clouds they observed is approximately equal to the pressure measured in the local interstellar medium. The presence in our observations of a long, narrow molecular filament (at \( \ell = 142^\circ \); Fig. 2) supports the hypothesis that the clouds are fairly stable. Were the clouds diffusing into the intercloud medium, such a filament would be very unlikely; one would expect to see only the cloud cores, with little or no filamentary gas between them.

The properties of our objects do not contradict a lower value for \( N(H)/W_{CO} \). As indicated earlier (§ IIIa), the Ursa Major complex is significantly smaller and more diffuse than the large molecular complexes found in surveys of the Galactic plane (e.g., Dame 1983). These complexes generally have masses
exceeding the mass of the Ursa Major complex by several orders of magnitude, so that in the latter complex the optical depth of the CO may well be lower. Another indication of lower optical depth is the large variation in peak radiation temperature of the CO line across the projected surface of the clouds in Ursa Major. Indeed, this variation is the principal cause of variation in the integrated radiation temperature, while in the large complexes in the Galactic plane the peak temperature is roughly constant; there variation in \( W_{\text{CO}} \) is due mainly to variation in line width. Although other explanations exist, the assumption of a lower optical depth and, therefore, a lower \( \frac{N(\text{H}_2)}{W_{\text{CO}}} \) seems plausible.

V. CONCLUSION

Analysis of the CO, the H\(_1\), and the far-infrared emission from cirrus in Ursa Major suggests a new method to calibrate \( \frac{N(\text{H}_2)}{W_{\text{CO}}} \) for tenuous clouds. The optical depth at visual wavelengths of the Ursa Major clouds seems small enough for the infrared flux density to be approximately linearly proportional to the total gas column density. Indeed, since most cirrus at high Galactic latitudes has a more diffuse appearance than the Ursa Major cirrus, this proportionality should exist for a large fraction of the sky at high latitudes. The method of deriving \( \frac{N(\text{H}_2)}{W_{\text{CO}}} \) from infrared emission complements the similar method of Bloemen et al. (1986), useful for dense clouds, for deriving this ratio from \( \gamma \)-rays. The IRAS survey seems to have extended significantly the spectrum of molecular clouds for which a relatively simple calibration of \( \frac{N(\text{H}_2)}{W_{\text{CO}}} \) is possible.

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