PHYSICAL AND DYNAMICAL CONDITIONS IN INTERSTELLAR CLOUDS

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1. INTRODUCTION

The most far-reaching result to come from the study of interstellar molecules has been the recognition of a new class of galactic structures - molecular clouds. These clouds appear to contain most of the mass of the interstellar medium and are the objects from which new stars are formed. Thus, a prerequisite for any understanding of the star formation process is a knowledge of the physical and dynamical conditions in molecular clouds.

In discussing the parameters that describe molecular clouds, it is useful to divide them into local parameters, which characterize a given location in a cloud, and global parameters, which characterize the cloud as a whole. Examples of local parameters are gas kinetic temperature (T_K), dust temperature (T_D), total density (n), magnetic field strength (B), abundance of species i ($X_i \equiv n_i/n$), volume cooling and heating rates for gas (Λ_g, Γ_g) and dust (Λ_d, Γ_d), and the thermal (V_{th}) and turbulent (V_{turb}) velocities. Global properties include the size, expressed as a length (L), or area (A), the orientation and shape, the mass (M), and the integrated heating and cooling rates. If the cloud as a whole is collapsing or rotating, then the collapse velocity (V_c) and the rotation velocity (V_r) or angular momentum are global properties. A third class of parameters are intermediate: the column density of species i (N_i), the total column density (N), and the average density ($\langle n \rangle \equiv N/L$) share some features of both local and global properties.

In the following sections, techniques for measuring these parameters will be described. Selected results will be used to illustrate the techniques. No attempt will be made to survey the entire literature of this field, since the space is inadequate. Frequent reference will be made to a recent study by Snell (1979), primarily because it illustrates many of the techniques discussed. For future reference, Snell's sample consists of 9 nearby ($\langle d \rangle$ = 170 pc) clouds selected optically as "dark clouds". Based on his maps of CO and ^{13}CO, Snell has artificially "sphericalized" his clouds by averaging all observations at the same

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distance from the cloud's density peak. While this method loses some information on cloud irregularities, it allows any underlying regularities to be examined.

2. TEMPERATURES

2.1. Gas Kinetic Temperature

The standard thermometer for measuring the gas kinetic temperature (T_K) is the carbon monoxide (CO) molecule. The absolute intensity of the radiation from transitions between several of its lowest levels may be converted into T_K. This technique assumes that the levels are thermalized ($T_{ex} = T_K$) and that the transition is optically thick, so that T_A^* is uniquely related to T_{ex}. Then,

$$T_K = T_{ex} = \frac{h\nu/k}{\ell n\left(1 + \dfrac{h\nu/k}{T_A^*/\eta_p + T_{bg}}\right)} = \frac{5.55}{\ell n\left(1 + \dfrac{5.55}{T_A^*/\eta_p + 0.83}\right)},$$

where the last expression is valid for the $J=1 \rightarrow 0$ line, and η_p is the coupling of the source to the forward antenna pattern.

Let us consider how this technique might fail. First, the density might be too low to thermalize the transition. Densities of $\sim 10^3$ cm^{-3} are sufficient to thermalize the $J=1 \rightarrow 0$ transition; thus $T_{ex} = T_K$ is a good assumption over most regions of a cloud, but the outer regions of clouds may not be thermalized. The high abundance of CO generally insures that $\tau >> 1$, with the exception of some high velocity flows. But the very large τ found in the normal case raises another question: might regions of higher T_K be hidden by a cool, but optically thick, envelope? The answer to this question depends upon the vexing issue of the proper choice of radiative transport model, and hence is coupled to the dynamics. We will defer the issue of dynamics and note only that, for reasons perhaps not fully understood, the $J=1 \rightarrow 0$ line of CO does generally "see into" the warm cores of clouds. A few exceptions have been found where self-reversed profiles indicate partial absorption by cooler foreground gas (cf. Snell and Loren 1977). Several checks on the T_K derived from the $J=1 \rightarrow 0$ line of CO exist. A partial check that the line "sees into" the cloud is afforded by observations of the $J=2 \rightarrow 1$ and, in a few clouds, the $J=3 \rightarrow 2$ lines of CO. Having higher τ, these lines should give different T_K if thick lines fail to see into the cloud. The general agreement of the T_K's derived from different CO transitions supports the reliability of CO as a thermometer.

Another thermometer is provided by the NH_3 molecule. In this case T_K is determined, not from the absolute intensity of a single line, but from relative intensities, and hence populations, in the J,K = 1,1 and 2,2 inversion doublets. From studies of the transitions across both of these inversion doublets, the populations in each of the two doublets n(J,K) can be determined. Then the rotational temperature T_R is given by:

$$T_R = \frac{-41.5}{\ell n\left(\frac{3\ n(2,2)}{5\ n(1,1)}\right)}$$

To a first approximation, $T_R = T_K$ because radiative transitions are not allowed between the 2,2 and 1,1 doublets. However, $\Delta K = 1$ collisional transitions to non-metastable states (e.g. $2,2 \rightarrow 2,1$) followed by radiative decay ($2,1 \rightarrow 1,1$) can cause T_R to be less than T_K. A statistical equilibrium calculation must be performed to obtain T_K. Such calculations (Morris et al. 1973) indicate that $0.8\ T_K \leq T_R \leq T_K$. An analogous procedure may be used for other metastable inversion doublets. Generally speaking, the T_K derived from NH_3 are in reasonable agreement with those derived from CO (see Table 1). Since the NH_3 emission has been interpreted as coming from small clumps deep in the cloud, this agreement is further evidence that the CO sees into the clouds.

Table 1
T_K DETERMINATIONS

Source	$T_K(CO)$	$T_R(NH_3)$	$T_R(NH_3)$ / 0.8	$T_K(SO_2)$	$T_K(CH_3OH)$
S255	33[1]	30[2]	38[2]		
S140	30[3]	23[2]	29[2]		
NGC6334N	47[3]	19[4]	24[4]		
DR21(OH)	31[3]	22[4]	28[4]		
OMC1	94[3]			65[5]	90[6]

[1]Evans et al. 1977, [2]Ho 1977, [3]Loren, private communication, [4]Cheung 1976, [5]Pickett and Davis 1979, [6]Kutner et al. 1973

Other thermometers have been used in the specialized case of OMC1, most notably SO_2 (Pickett and Davis 1979) and CH_3OH (Kutner et al. 1973), but these probes are not useful in other regions. In summary, the accuracy of our knowledge of T_K is often limited by our ability to calibrate the CO measurements. We can determine T_K over large regions in clouds to ±10% or so, making T_K the best determined parameter in a molecular cloud.

Using CO, Dickman (1975) found that most "dark clouds" have $T_K \sim 10$ K. Maps of CO by Snell (1979) confirm that $T_A^*(CO)$ is remarkably uniform over his clouds. A more detailed analysis indicates that near the edge of the clouds, n is insufficient to thermalize CO, and the uniform or slightly declining CO emission actually translates into a rising T_K. Studies of other samples of clouds indicate the frequent presence of "hot spots", where the CO indicates $T_K > 20$ K. (cf. Blair, Peters, and

Vanden Bout 1975). Such hot spots are very often also dense and associated with recent star formation.

2.2. Dust Temperatures

The temperature of dust grains in the cloud (T_D) can be determined from far-infrared or sub-millimeter observations. Measurements of the flux density $S_\nu(\lambda)$ at two different wavelengths yields a color temperature which together with an emissivity law defines the physical grain temperature,

$$T_D = \frac{\frac{hc}{k}\left(\frac{1}{\lambda_2} - \frac{1}{\lambda_1}\right)}{(3+\beta)\,\ln\left(\frac{\lambda_1}{\lambda_2}\right) + \ln\left(\frac{S_\nu(\lambda_1)}{S_\nu(\lambda_2)}\right)} ,$$

where the grain emissivity is assumed to follow $\varepsilon(\lambda) = \varepsilon_o\lambda^{-\beta}$ and $e^{hc/kT_D\lambda} >> 1$ holds for both λ_1 and λ_2. Several factors limit the accuracy of this method. The need for spatial chopping suppresses any relatively uniform emission at low T_D and this can bias the T_D (de Muizon et al. 1979). Also, the exponent in the emissivity law is not accurately known. The range, $0 \leq \beta \leq 2$, is often used, with $\beta = 1$ or $\beta = 2$ favored by various groups. The difference between $\beta = 0$ and $\beta = 2$ translates into uncertainties in T_D of 50% or larger, depending on the exact circumstances. Once T_D has been determined, the absolute value of the flux density at either wavelength can be used to get an emissivity or optical depth at that wavelength from

$$\varepsilon(\lambda) = (1 - e^{-\tau_\lambda}) = \frac{S_\nu(\lambda)\lambda^3}{2hc}\;\frac{(e^{hc/kT_D\lambda} - 1)}{\Omega} ,$$

where Ω is the solid angle.

Mapping of T_D and $\varepsilon(\lambda)$ over molecular clouds has just begun, largely because far-infrared observers have concentrated on the brighter emission from H II regions and their immediate vicinity. Such studies have already shown how molecular clouds adjacent to H II regions may be heated by the exciting stars. Maps show a decline in T_D and an increase in τ_λ as the beam moves from the H II region into the molecular cloud (cf. Gatley et al. 1979). In other cases, such as OMC1, part of the heating comes from stars or protostars embedded in the molecular cloud (cf. Werner et al. 1976). Recent observations of S140 by de Muizon et al. (1979) indicate that such embedded sources are able to raise T_D above 20 K over regions 20' in extent, comparable to the extent of the T_K > 20 K region.

3. MEASURES OF DENSITY

3.1. Column Density

It is often useful to know the total column density of material along some line-of-sight. This quantity is most conveniently expressed as $N(cm^{-2})$, the column density of gas, although a measure of the dust column density A_V, the visual extinction in magnitudes, is often used as well. Studies of diffuse clouds (Jenkins and Savage 1974) indicate that these are related by $N = 2.5 \times 10^{21} A_V$, but we are not assured that this relation will hold in molecular clouds. Indeed, neither of these quantities is directly measurable over most of the extent of molecular clouds and we are forced to use surrogate measures based on trace constituents. The most commonly used measure is $N_{13}(cm^{-2})$, the column density of ^{13}CO. This measure is useful because ^{13}CO is widely detectable, the $J=1 \rightarrow 0$ line is generally optically thin, and N_{13} can be deduced from the observations with uncertainties of no more than a factor of 2. Furthermore, Dickman (1978) showed that N_{13} and A_V were well correlated up to $A_V \sim 6$, where traditional star counting techniques begin to fail. On this basis ^{13}CO has become the standard probe of the column density of matter, using the relation, $N = 5 \times 10^5 N_{13}$ (Dickman 1978). If one also has a measure of the size (L) and assumes spherical symmetry, one may also obtain the average density $\langle n \rangle = N/L$. Over most of the extent of molecular clouds, this is the only available estimate of n.

Snell (1979) has used his sphericalized clouds to study the variation of N_{13} with radius (r). Over most of the cloud (0.2 pc $< r <$ 0.5 - 1.0 pc) he finds that $N_{13} \sim r^{-1}$, indicating that $n \sim r^{-2}$. Inside $r \sim 0.2$ pc he finds a weaker dependence of N_{13} on r. More direct measures of n (see below) inside r = 0.2 pc are consistent with a continued $n \sim r^{-2}$ law, suggesting that N_{13} fails as a probe in dense cloud cores. Snell also extended measures of A_V by using infrared colors of stars which appear to be behind the clouds. He found that the relation between N_{13} and A_V does seem to break down above $A_V \sim 5$-10.

3.2. Density

The direct determination of the total volume density (n) is much less accurate than the determination of T_K. In principle, one simply requires observations of an optically thick but unthermalized transition. Then T_A^* leads to T_{ex}, and T_{ex} can be related to n via statistical equilibrium calculations. However, the presence of radiative trapping means that T_{ex} is also a function of optical depth, or of the molecular abundance and velocity gradient in the combination $X_i(dv/dr)^{-1}$. Thus more than one line is required; the best situation exists when the two lines used respond in different ways to changes in n and $X_i(dv/dr)^{-1}$.

This situation can be seen more easily in contour plots of equal intensity in the $(n, X_i(dv/dr)^{-1})$ plane. Such plots have been made for the 2 mm and 2 cm transitions of H_2CO (Snell 1979). A given intensity of the 2 mm line alone can be fit by any $(n, X_i(dv/dr)^{-1})$ combination

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lying along a curve. Measurement of the 2 cm intensity constrains the solution to lie along another curve. If one requires a simultaneous solution, implying that both lines arise under the same conditions, then the solution is given by the intersection of the two lines. The assumption that the two lines arise under the same conditions is a critical one. First one must take care to obtain the two measurements with similar beam sizes. Second, the two transitions should be excited at comparable densities, so that density variations along the line-of-sight do not cause the transitions to arise largely in different regions of the cloud.

The 2 mm and 2 cm transitions of H_2CO satisfy these conditions rather well and we have relied heavily on them to determine densities. Let us use them to explore various uncertainties inherent in this method. First, there is the choice of geometry and radiative transport. Spherical large-velocity gradient (LVG) models were used to construct the contour plots used to find densities. How would they differ for other choices? Snell has also calculated a less extensive set of models for turbulent slabs (TS) and compared the two models. At a given n, the TS model gives a weaker 2 mm line but there is little change in the 2 cm line. Thus a given 2 mm line strength observed from a turbulent cloud would imply a larger n; the difference depends on the conditions but seldom exceeds a factor of 2. Turbulent spheres and LVG slabs would probably give n larger or smaller by factors of 3 or less. Thus if we profess total ignorance of the cloud dynamics and geometry, we must admit uncertainties of a factor of 3-5 in either direction about the results from LVG spheres and turbulent slabs.

Secondly, the construction of these diagrams requires a knowledge of the collisional cross sections. Thanks largely to the work of S. Green and associates, we now have good theoretical collision rates for He collisions with H_2CO (Green et al. 1978) and many other molecules. Collisions with H_2, the more common collision partner, are usually assumed to be the same as those with He. This assumption, and the absence of direct laboratory tests of these rates, introduces an additional uncertainty which is hard to quantify but which should always be borne in mind.

We have used H_2CO to illustrate the technique, but the same basic method and uncertainties apply to several other molecules. Extensive studies of n have been made using H_2CO, HC_3N, CS, NH_3, and ^{13}CO. Table 2 compares the densities derived from these different molecules for the same sources. Only a few studies have been included, in order to achieve uniformity at the expense of extensiveness.

The trend in Table 2 is that the lines giving the highest n are those requiring the highest densities to excite. A measure of the density needed to excite each line (n*) was calculated by setting the collision rate equal to the spontaneous decay rate. Note that a single n* characterizes H_2CO because the 2 cm line strength is controlled by collisions between the same levels that produce the 2 mm line. The

Table 2
DENSITY DETERMINATIONS

Source	H_2CO[a]	HC_3N[b]	CS[c]	NH_3[d]	^{13}CO[f]
L134N	1.2×10^4	2×10^4	$\le 1\times10^4$	$>4\times10^3$	9×10^3
L1529	1.2×10^4	8×10^4	$\le 1\times10^4$	3.8×10^3	
NGC2264	2.5×10^5	7×10^4	6×10^4		3×10^3
DR21(OH)	7×10^5	2×10^4	6×10^4		
S255	6×10^5	4×10^4	1×10^5	1.1×10^3[e]	5×10^3
S140	5×10^5			$>3.2\times10^3$[e]	5×10^3
NGC6334N	8×10^4	3×10^4	6×10^4		
M17SW	7×10^5	4×10^4	6×10^4		2×10^3
OMC2	1.5×10^6	6×10^4	2×10^5		2×10^3
$\overline{n}$	5×10^5	5×10^4	7×10^4	3×10^3	4×10^3
n*(smaller)	1×10^6	7×10^4	8×10^4	2×10^3	3×10^3
$\langle n(H_2CO)/n \rangle$	1.0	12	6	270	230
$n^*(H_2CO)/n^*$	1.0	18	17	870	460

a. Wootten, et al. (1978) $J_{K_{-1}K_1} = 2_{12}-1_{11}$ (2mm), (1ʹ.8 beam); $J_{K_{-1}K_1} = 2_{12}-2_{11}$ (2 cm) (2' beam); spherical LVG; $n^* = 1.3 \times 10^6$.

b. Vanden Bout, et al. (1979) $J=5\rightarrow4$ (2ʹ.6 beam); $J=9\rightarrow8$ (3ʹ.1 beam); $\tau << 1$; $n^*_{54} = 7.4 \times 10^4$, $n^*_{98} = 4.5 \times 10^5$.

c. Linke and Goldsmith (1980) $J=1\rightarrow0$ (2ʹ.6 beam); $J=2\rightarrow1$ (2ʹ.1 beam); spherical LVG; $n^*_{10} = 7.6 \times 10^4$, $n^*_{21} = 4.9 \times 10^5$

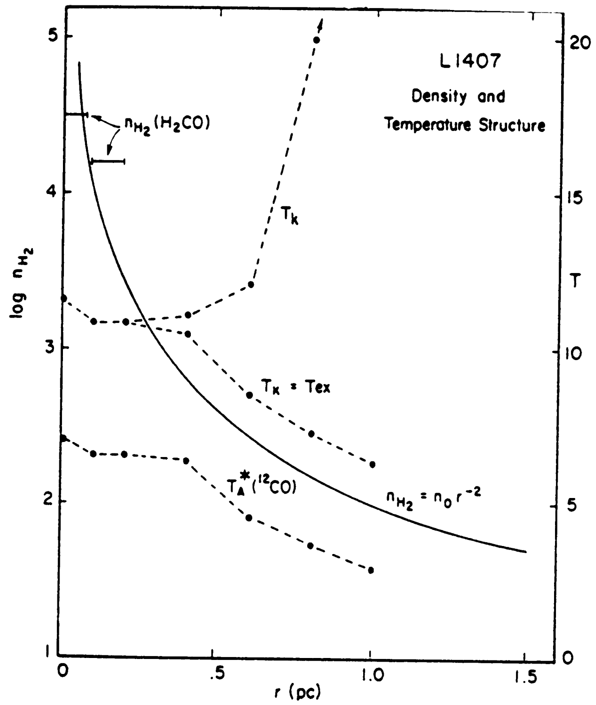
d. Ho (1977) $(J,K) = (1,1)\rightarrow(1,1)$; 1ʹ.3 beam; 2-level model; $n_*=1.5\times10^3$.

e. These values are for a filling factor $\Phi = 1$. Ho favors $\Phi = 0.1$, which gives $n = 1.4\times10^4$ for S255 and 2.0×10^5 for S140.

f. Plambeck, Snell, and Loren (1979), $J=1\rightarrow0$ (1ʹ.0 or 2ʹ.3 beam); $J=2\rightarrow1$ (1ʹ.2 beam); spherical LVG; $n^*_{10} = 2.8\times10^3$, $n^*_{21} = 1.6\times10^4$.

average n measured by a given probe ($\overline{n}$) is always close to the smaller n* of the two lines used. The ratio of n derived from H_2CO to n derived from another probe shows the same correlation as the ratio of n*'s. The most obvious explanation of this situation is that the density varies along the line-of-sight and that different lines sample different density regimes. Thus the easy-to-excite ^{13}CO samples much more of the low density envelope, while the hard-to-excite H_2CO lines arise almost entirely in much denser regions. In such a situation, the use of two lines of differing n* will bias the result toward lower n. To test this explanation, one must construct a cloud model with density gradients. We have done this for several clouds with sufficiently detailed H_2CO data, and find that $n \sim r^{-2}$ laws appear to match H_2CO data from up to five different lines reasonably well. However the ^{13}CO lines produced in the model are far too strong if Dickman's (1978) value for $X(^{13}CO) = 2x10^{-6}$ is used. Thus we found that $X(^{13}CO)$ had to be much lower in the dense core where the H_2CO lines are formed, in order to make the ^{13}CO and H_2CO observations consistent (Blair et al. 1978; Wootten et al. 1978).

This conclusion again indicates that N_{13} fails as a probe of N or $\langle n \rangle$ in dense cores. We can now pull together some of these ideas by examining the results for one of Snell's sphericalized clouds, L1407. He has used the 2 mm and 2 cm H_2CO lines to determine densities of $\sim 3 \times 10^4$ cm^{-3} in the dense core. These densities agree with the $n \sim r^{-2}$ law established from N_{13} measurements at larger r, but are more than one would predict from N_{13} measures at the dense core. Moving outward, as n falls below $\sim 10^3$ cm^{-3}, the CO line is no longer thermalized, and T_K must rise to maintain the gradual decline in $T_A^*(CO)$.



3.3. Chemical Abundance

To test theories of chemical evolution in molecular clouds, observations should provide measures of the chemical abundance of species i. The most useful measure is the density of i relative to the total density, $X_i = n_i/n$. For molecules which are probes of n, the analysis leading to n usually provides as well a measure of $X_i(dv/dr)^{-1}$. Measurement of the

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line width and extent of emission provide (dv/dr), and hence X_i. This technique has been widely applied to H_2CO (Wootten et al. 1978; Loren, Evans, and Knapp 1979; Snell 1979). The results have shown a strong anti-correlation of $X(H_2CO)$ and n.

If the cloud model derived from H_2CO is assumed in models of the excitation of other molecules, then measurement of a single line of species i is sufficient to determine X_i provided that collision rates are available for species i. Wootten et al. (1978) found that X_i also declines with increasing n for the species HCN, HNC, HCO^+, and ^{13}CO, based on a sample of 13 regions. The results for these other species are more uncertain since the lines could arise in rather different portions of the cloud.

While $X(HCO^+)$ or X(CO) is more directly related to chemical theories, the additional uncertainties make it safer to use $X(H_2CO)$ to study these effects further. Using the data from Wootten et al. (1978), Loren et al. (1979), and Snell (1979), the best fit power law is $X(H_2CO) = 3.34 \times 10^4\ n^{-1.26}$. This fit has a correlation coefficient r of 0.94 and is based on 73 positions in 30 clouds. Loren et al. (1979) determined n and $X(H_2CO)$ for eight positions in the Corona Austrina cloud: $X(H_2CO)$ has the same dependence on n, even within a single cloud.

The relation between $X(H_2CO)$ and n expected on the basis of theory is undetermined since the chemistry of H_2CO is poorly known. However, $X(HCO^+) \sim n^{-0.5}$ is predicted by simple steady state chemical models with constant CO abundances, and most molecules formed from HCO^+ would follow a similar law. Time dependent calculations suggest that abundances would decline more slowly or even increase as n increases. Wootten et al. suggested several possible explanations for the more rapid decline which they observe: one suggestion is that higher abundances may exist in lower density clouds because they are much older, and thus more evolved chemically. This explanation now appears unlikely since the anti-correlation exists even for a single cloud. Thus it seems that the best explanation is that the molecules are depleted by sticking to dust grains, a process that operates faster at higher n.

The probability that dust grains in dense molecular clouds have substantial mantles of organic molecules is also suggested by infrared work. The 3.1 μm "ice" band is much stronger relative to the 9.7 μm silicate band in molecular clouds than in the general interstellar medium (Merrill, Russell, and Soifer, 1976). Further, the newly discovered 6.0 and 6.8 μm bands appear only in sources behind substantial molecular material. These bands are consistent with being caused by vibrations of C-H and C-O bonds in organic molecules deposited on the grains (cf. Soifer et al. 1979).

Measurement of suitable chemical abundances may also be used to derive X(e), the electron abundance. The most notable technique here is the study of $X(DCO^+)/X(HCO^+)$ (Guelin et al. 1977) which can be related through the theory of HCO^+ formation and deuteration to X(e) (Watson

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1977). Results indicate $X(e) \sim 10^{-8}$ in cool molecular clouds. Wootten, Snell, and Glassgold (1979) have recently devised a method to measure X(e) in warmer clouds and find $X(e) \sim 10^{-7} - 10^{-8}$. For clouds with both kinds of X(e) measures, an upper limit to ζ, the cosmic ray ionization rate is obtained. The resulting limits on ζ of 10^{-18} s^{-1} are consistent with ionization by the high energy portion of the cosmic ray spectrum.

4. ENERGETICS

The gas in molecular clouds cools primarily through line emission by trace elements, emission from H_2 being negligible at the usual cloud temperatures. Goldsmith and Langer (1978) have calculated the cooling due to a number of species under a variety of conditions. They confirm earlier results (Scoville and Solomon 1974) that the dominant coolant is CO, with H_2O becoming important at high T_K and n. Most of the cooling comes from CO transitions with large J, and has not been directly measured. While this is always an uncomfortable situation, our models of CO excitation are probably good enough to predict it correctly, given accurate measures of T_K and n.

The integrated gas cooling rate is $C_g = \int \Lambda g\, dv$. Studies of several clouds with substantial hot spots have shown that C_g is very modest ($5 - 50\ L_\odot$) compared to available energy sources such as embedded and nearby stars (Evans, Blair, and Beckwith 1977; Blair et al. 1978). The difficulty in heating the gas is in coupling radiant energy into kinetic energy of the molecules. The standard mechanism in clouds with hot spots was suggested to be collisions with warmer dust grains (Goldreich and Kwan 1974) which are themselves quite good absorbers of the radiant energy. For this heat source, Γ_{d-g}, to balance Λ_g, T_D must exceed T_K, and n must be rather large ($10^4 - 10^5$ cm^{-3}). These conditions seem to be fulfilled in many dense, hot spots surrounding infrared sources, but the frequent occurrence of extended plateaus at $T_K \sim 15 - 20$ K may be difficult to explain on this basis.

The requirement that $T_D > T_K$ leads in turn to predictions of substantial dust cooling rates, Λ_D and $C_D = \int \Lambda_D dv$. In the clouds with hot spots, the predicted C_D may be $10^4 - 10^5\ L_\odot$, and thus the dust would clearly dominate the cloud energetics. Observations of these regions have detected the large far-infrared fluxes predicted from the immediate vicinity of the hot spot (Harvey et al. 1978; Rouan et al. 1977). Only recently has very extended emission been detected by de Muizon et al. (1979). The results indicate that $T_D > T_K$ quite far out in the S140 cloud. Nonetheless, estimates of $\langle n \rangle$ in the outer regions suggest that Γ_{d-g} is insufficient to balance Λ_g. The role of other possible heating sources such as collapse and magnetic ion-slip is hard to determine because of our lack of knowledge about the dynamical state and magnetic field strengths in clouds.

In clouds without hot spots $T_K \sim 10$ K, and Λ_g is low enough that heating by cosmic rays appears to be sufficient (Nachman 1979). Recent calculations (Clavel et al. 1978) suggest that chemical heating may be able to raise T_K to $\sim$15 K and that near the outside of a cloud T_K should rise rapidly, in agreement with Snell's (1979) results. Leung (1975) and Clavel et al. (1978) have calculated T_D in a cloud heated only by the interstellar ultraviolet radiation, and predict $T_D \sim 5 - 10$ K, in agreement with the only available observation of such a cloud (Keene et al. 1978). The rough agreement of T_D and T_K in such clouds appears to be coincidental since coupling between gas and dust will be weak until $n > 10^4$ cm^{-3}.

5. MAGNETIC FIELDS

The magnetic field in molecular clouds can potentially play a critical role in energetics and dynamics. The latter area is especially important, since magnetic fields may largely control the collapse, fragmentation, and angular momentum of molecular clouds (Mouschovias 1978). The problem is that magnetic fields have proven essentially impossible to measure in molecular clouds. Zeeman studies of H I clouds have indicated that B increases steadily with increasing n. If this increase is represented by $B \sim n^{\kappa}$, the exponent, κ, would be 2/3 for isotropic collapse and flux freezing. The data may be better fit if $\kappa = 1/3$ (Mouschovias 1978), a value which agrees better with theoretical calculations. In molecular clouds, Zeeman splitting in OH (Chaisson and Vrba 1978) and SO (Clark et al. 1978) has been searched for but never found outside maser regions. Limits as low as 50 μG have been set in two dark clouds (Crutcher et al. 1975) with $n \sim 10^3$ cm^{-3}. Using $B_o = 3$ μG at $n_o = 1$ cm^{-3} as initial values (Mouschovias 1978), we predict B = 30 μG if $\kappa = 1/3$ and 300 μG if $\kappa = 2/3$. κ larger than $\sim$1/2 would conflict with the limits, but κ may vary with position in the cloud, complicating the interpretation.

Zeeman effects are widely suspected of being involved in the polarization of OH masers, but clear patterns seldom emerge from the data. A few promising cases have been interpreted as evidence for $B \sim 10^3$ μG. The density in such regions is poorly known, making the implications of these results unclear.

Studies of polarization in dark clouds do suggest the importance of magnetic fields in the evolution of such clouds. While estimates of field strength based on polarization depend on many poorly known parameters, the alignment of magnetic field direction with some cloud structures suggests that the magnetic field has played a major role (Vrba et al. 1976). Recent evidence suggests that this role may extend to the dense star-forming cores. Dyck and Lonsdale (1979) have compared the direction of infrared polarization of 31 protostars and compact H II regions with the average direction of the surrounding interstellar polarization. For 65% of the sample, the two directions agree to within 30°. The authors conclude that the magnetic field has strongly affected the cloud evolution even down to the very compact scales that determine the infrared polarization.

Thus the role of magnetic fields remains tantalizing. Our ignorance of their strength in molecular clouds may represent one of our most serious unknowns.

6. GLOBAL PROPERTIES

6.1. Cloud Size, Shape, Orientation

Discussions of cloud size often degenerate into disagreements over definitions of "cloud" and "size". One man's cloud is another man's complex of clouds. A given cloud will have a different size as mapped in different molecular lines. One has to decide also on the limit which defines the cloud's size - the half-power point or some arbitrary limit of antenna temperature are generally chosen.

Typical cloud sizes have been estimated from galactic plane CO surveys to be 5-20 pc (Gordon and Burton 1977) and 10-80 pc (Solomon, Sanders, and Scoville 1977). Mapping of eight individual clouds found in such surveys and lying in the 4-8 kpc molecular ring indicated maximum cloud dimensions of 20-100 pc at the 3 K contour level of CO; the clouds were elongated but showed no tendency to align with the galactic plane (Sanders and Solomon 1977). The group at Goddard Institute have mapped a number of molecular cloud complexes near OB associations with $\langle d \rangle \sim 1.4$ kpc, as summarized by Blitz (1979). Using the $T_A^* \Delta V = 1$ K km s^{-1} level of CO to define the size, they find that these complexes are elongated with a mean largest dimension of 90 pc within a range of 60 - 110 pc; the elongation has some tendency to lie along the galactic plane. The more local ($\langle d \rangle = 170$ pc) clouds in Snell's sample have an average diameter of 1.1 pc using the $T_A^* = 1$ K level of ^{13}CO emission. Snell suggests that much more extensive and tenuous envelopes exist and often encompass several apparently separate clouds. Since Blitz (1979) reports that the complexes near OB associations contain 20-50 clouds with sizes of 2 pc and up, it would be useful to determine whether such complexes are more distant versions of nearby "dark cloud" complexes. For such studies, it would be useful to measure higher order structure parameters, such as the size and spacing of regions of enhanced T_K and n.

6.2. Mass

The mass of a cloud may be estimated in several ways. The most common method is to use a column density tracer such as ^{13}CO. Then

$$M = A_i \frac{N_i}{X_i} m_H \mu$$

where A_i is the projected area as mapped in species i, m_H is the hydrogen atom mass, and μ is the mean molecular weight. If N_i varies substantially over the cloud, $A_i N_i$ can be replaced by some suitable integral of N_i over the cloud area. Uncertainties in M so obtained are large. A_i may be poorly defined (cf. Section VIa) and depends on d^2, where d is the distance. If i = ^{13}CO, the variation of $X(^{13}CO)$ from Dickman's value may cause masses to be underestimated, especially in dense cores.

An alternative method is available in dense cores where n has been determined. There,

$$M_c = v_c \, n \, m_H \mu$$

where v_c is the volume of the core. v_c is usually determined from the area by assuming spherical symmetry and also depends on d^3. M_c is obviously extremely uncertain, but often appears to be a significant fraction of the total mass (Snell 1979; Evans et al. 1977; Blair et al. 1978).

Finally, a virial mass can be computed by assuming the cloud is in equilibrium, supported by turbulence, or by assuming free-fall collapse with $V \sim r$. In both cases, some suitable measure of the line width (ΔV) and cloud radius (R) are used to calculate

$$M_{vir} \sim \frac{R \Delta V^2}{G} \; .$$

The masses of the clouds (or complexes) in the molecular ring have been estimated at 10^4 - 5×10^6 $M_\odot$ (Solomon et al. 1977), while the cloud complexes accompanying OB associations have an average mass of 10^5 $M_\odot$ (Blitz 1979). Solomon and Sanders (1979) have estimated a mass distribution function from a survey of clouds in the molecular ring and find that most of the mass is contained in the most massive ($M \sim 10^6$ $M_\odot$) clouds. For the clouds in Snell's sample, the average mass is 70 $M_\odot$ within the $T_A^*(^{13}CO)$ = 1 K contour.

7. DYNAMICAL STATE OF MOLECULAR CLOUDS

This issue has surely provoked more controversy than any other issue in this controversial field. One may begin by noting that, based on the T_K's measured as discussed earlier, the thermal velocity in molecular clouds, V_{th}, is generally much less than the observed line-widths, ΔV. Thus the line-widths must be produced by mass motions. Suggestions for these motions include small-scale turbulence, "macro-turbulence", or the random motion of rather large blobs, and systematic motions, primarily collapse. Rotation can be ruled out as the cause of ΔV, as can expansion, with the exception of a few very small regions. The arguments against turbulence of any kind have been summarized by Penzias (1975), while the case against collapse has been presented by Zuckerman and Evans (1974) and by Zuckerman and Palmer (1974). I will consider only some of the recent developments.

One of the strongest arguments against small-scale turbulence has been the absence of self-reversed profiles (cf. Liszt et al. 1974). With the advent of higher sensitivity and spectral resolving power, such profiles have begun to show up rather commonly in nearby dark clouds (Langer et al. 1978), though in high excitation molecules rather than in CO. Thus the dense cores which produce these lines may be largely turbulent. The more distant sources may not show such self-reversals because of superposition of several such cores (a kind of macroturbulence). Further evidence along these lines comes from studies of the $J=2\rightarrow 1$ and $1\rightarrow 0$ CS lines (Linke and Goldsmith 1980), which find a constant ratio of these two lines across the profile. This conflicts with collapse models wherein each part of the line would represent a different part of the cloud, and hence different densities.

On the other side of the fence, Myers et al. (1978) have found a strong correlation between the spatial extent of emission of a molecular line and the linewidth, as predicted by collapse models with $V_c \sim r^{\alpha}$; $\alpha > 0$. Snell (1979) has found a similar effect and fits his data well with $V_c \sim r^{0.5}$, a retarded collapse. Such a velocity law might join smoothly to a turbulent core. This result suggests a possible resolution of the dilemma. If a substantial fraction of the gravitational potential energy released by contraction of a cloud can be coupled into turbulence, perhaps mediated by the magnetic field, then free fall collapse could be slowed, creating a turbulent core and a contraction velocity $V_c \sim r^{0.5}$ in the outer regions.

The dynamical effect of newly formed stars on molecular clouds is only beginning to be explored. Such stars often have strong stellar winds which may compress, accelerate, or push holes in the molecular cloud. Such effects are suggested by the phenomena of Herbig-Haro objects and high velocity H_2O masers. In addition, expanding H II regions and eventual supernova explosions may have severe effects on molecular clouds. All of these phenomena will result in a shock propagating through the molecular cloud. Observations of H_2 emission (Gautier et al. 1976; Beckwith et al. 1978) have spurred a number of calculations of shocks in molecular clouds. Such shocks may play major roles in initiating further star formation (Elmegreen and Lada 1977), in disrupting the cloud (Wheeler, Mazurek, and Sivaramakrishnan 1979) and in increasing the general kinetic energy content of the cloud.

8. SUMMARY

The discovery of interstellar molecules led to the recognition of molecular clouds as an important new galactic structure. As our understanding of molecular excitation and line formation has improved, we have begun to use observations of the molecular lines to probe the conditions in molecular clouds. Techniques now exist for determining most of the parameters that are needed to characterize the clouds. While discrepancies among different methods and uncertainties in line formation still are serious problems, a consensus on techniques appears to be emerging for at least some parameters. Indeed, the worst problem in trying to characterize clouds from a survey of the literature is the unsystematic nature of many investigations, the failure to publish a standard set of parameters determined in a standard way, and the lack of overlap in the clouds studied by different techniques. Because of this problem, I have relied heavily on a few studies and used them as examples of the techniques. With a few exceptions, the appropriate data do not yet exist to define average values or distributions of parameters.

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DISCUSSION FOLLOWING EVANS

Crutcher: A recent OH experiment by Crutcher, Heiles, and Troland gave 3σ limits to the magnetic field of $\sim$25 μG toward dust clouds with $n_H \sim 10^3 cm^{-3}$. A possible detection of OH Zeeman splitting in Taurus gave $B=12\pm4$ μG.

Evans: These new results are beginning to put pressure on the theory.

Biermann: Would it not seem, taking into account the very low relative electron abundances you mentioned, that the coupling between mass motions and magnetic fields becomes so small that no substantial increase of the magnetic field strength by compression is expected?

Evans: The very low electron abundances really apply only to the dense cores of the clouds, so that the magnetic field may still play a major role in most of the volume of the cloud. One might expect that the magnetic field is no longer important in the dense cores for the reason you suggest, but the results of Dyck and Lonsdale give one pause.

Ho: The derivation of X_i depends on dV/dr. What happens if dV/dr varies with radius? Observations indicate that line widths vary between the centers and edges of clouds. In fact "cores" or "condensations" towards the centers of clouds may be very quiescent, in which case dV/dr may be very small. Would X_i then be larger than has been deduced?

Evans: In most cases we have used dV/dr as deduced from H_2CO itself; thus our velocity gradients do apply to the dense core. A calculation of dV/dr for ^{13}CO actually indicated a lower dV/dr on the average, although the difference was very small (Wootten et al. 1978).

Ho: The H_2 densities derived from NH_3 observations seem comparatively low (Table 2) because you have ignored the effects of the clumped distribution of NH_3.

Evans: That explanation works only if NH_3 is more clumpy than the other molecules; otherwise the discrepancy persists. Since NH_3, analyzed with simple assumptions, follows the same trend as ^{13}CO, we may not have to invoke clumpiness after all.

Ho: If different molecules such as NH_3, CS, and H_2CO are really sampling regions of different densities, how do you explain their similar spatial distribution? If $n \propto 1/r$, would a difference in derived n by a factor of 10 imply a difference in spatial extent by a comparable factor? Spatial extents of different molecules should be considered, because a very steep radial decrease of n may be implied.

Evans: We suggested $n \propto r^{-2}$, giving changes of n by factors of 10 for changes of r by factors of 3. More generally, I agree that a completely satisfactory model would also account for the spatial extent of the emission of each line.

Mouschovias: On the important issue of large linewidths in molecular clouds, the theoretical arguments against turbulence are well known, as you said, and one need not repeat them. Have you not also presented in your talk *observational* evidence against turbulence? I am referring, of course, to the results of optical and infrared polarization measurements, which show unambiguously a beautiful ordering of the magnetic field over large length scales. The presence of significant turbulence would have destroyed this ordering, would it not? Incidentally, in 1975 I suggested that linewidths are due to large-scale oscillations at supersonic, but sub-Alfven, speeds of self-gravitating magnetic interstellar clouds about stable equilibrium configurations [(Ph.D. Thesis); see also IAU Symposium No. 75.]

Evans: Your question brings into focus a certain conflict that is just under the surface at this meeting. It seems to me that there is an essential conflict between the evidence for very large scale structure (eg. the paper by Morris et al.) which appears to be ordered by magnetic fields, and the picture of giant molecular clouds growing by collisions of essentially isolated clouds. On the smaller scale of the dense cores, however, there is some observational evidence now for turbulence. I agree that it is difficult to reconcile that with the polarization results.

Kwok: One observational parameter that you did not discuss is the line profile of ^{12}CO. The centrally peaked profiles observed in many molecular clouds place severe constraints on the allowable density and velocity laws. For example, there must be a density gradient, and velocity must vary with radius according to a power law with a positive index. What is needed now is a dynamical justification (eg. collapse calculations) for such density and velocity laws.

Evans: I will venture to say that no one in this room really understands why these lines have the shapes that they do, and I would be delighted to be contradicted.

Clark: Do the observations absolutely rule out rotation? A small near-rigid rotation consistent with Mouschovias' calculations could very nicely reproduce your observed variation in linewidth.

Evans: It is pretty clearly ruled out as the *cause* of the linewidth in the clouds I described. Rotation may still play a role, of course.

Penzias: In your talk you enumerated some of the problems encountered in modelling the intra-cloud flows which manifest themselves as large linewidths. I think it is worth emphasizing that the physical constraints which I set down in my Les Houches review lead to contradictions when one attempts to construct self-consistent slowly dissipative macro-turbulent models. If, on the other hand, one could identify an adequately

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powerful source with which to drive dissipative flows, it seems to me that one could resolve the remaining theoretical difficulties with a judicious combination of ordered motion and macroturbulence.

Evans: I tend to agree that macroturbulent models are probably closest to the actual situation, at least in more distant objects, where the beam could include a number of separate blobs. The suggestions of Silk and Norman for driving the flows with T-Tauri winds can be tested in nearby clouds by infrared searches for the stars. One should also explore non-stellar sources for driving turbulence, including the collapse (or contraction) itself.

Gilmore: You made a comparison between Snell's sample of local dark clouds and more distant cloud complexes associated with HII regions. In no way is either of these sets complete. In fact local clouds have a very diverse nature, ranging from less than 1 pc to several parsecs in size, ranging in opacity, and ranging in degree of association with other clouds. More distant clouds represent an unknown sample, since most of those known are associated with HII regions and star formation. There are local large complexes similar in size to distant ones, yet different in physical characteristics observed via molecular lines at millimeter wavelengths. A most significant indicator of the difference is the presence of star formation. The nature of the clouds being observed, especially with respect to evolutionary state and the presence, for some external or internal reason, of star formation, could strongly bias the nature of the chemistry observed as well as other general deductions one might make concerning any of the parameters you mentioned.

Evans: Your comment supports my call for more systematic studies.