INFRARED SOURCES IN DENSE MOLECULAR CLOUDS

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I. A Short History of Molecular Clouds

The study of infrared sources in molecular clouds necessarily places the practitioner at the interface between two rapidly evolving fields of study. In such a situation, yesterday's heresy often becomes today's dogma. Since it is hard enough to keep up with even one field of study, I thought it might be helpful to recount a bit of history regarding molecular clouds. The objective is to put various notions about molecular clouds into proper context.

In the beginning (around 1969), only a few interstellar molecules were known to exist and those only in a few sources. Interstellar molecules were still a mere curiosity and could be safely ignored by theoreticians of the interstellar medium, among whom the two-phase model still held sway. Beginning in the early 70's, radio telescopes began to operate at wavelengths of 2-4 mm, where many new molecules were discovered, most importantly carbon monoxide (CO). Maps of CO emission showed the existence of large clouds of primarily molecular material. These large clouds (envelopes) often contained cores which were hot and dense, and which often coincided with infrared sources and H II regions. Others, mostly nearby dark clouds, showed no such hot core.

The situation around 1974 was summarized by Zuckerman and Palmer (1974). The typical molecular cloud had an envelope which was 10 pc in size, and a smaller core 0.5 pc in size. The total mass of the cloud was 10^5 $M_\odot$. The prevailing theoretical view was that clouds were collapsing freely (Goldreich and Kwan 1974; Scoville and Solomon 1974), although a minority viewpoint (Zuckerman and Evans 1974) asserted that most clouds could not be in free fall collapse. Zuckerman and Palmer (1974) pointed out that if all such clouds were collapsing freely to make stars, the inferred star formation rate would be more than 10 times the observed one. Zuckerman and Evans (1974) suggested that the suprathermal line widths in molecular clouds were

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more likely to arise from turbulence, that the clouds were quite irregular, and that star formation was likely to occur near a surface of the cloud.

The next major synthesis occurred around 1978, largely based on the results of CO surveys of the galactic plane (Burton and Gordon 1978; Solomon, Sanders, and Scoville 1979). The discovery of extensive CO emission was interpreted by Solomon, Sanders, and Scoville (1979) to imply that at a galactic radius of 5 kpc, 90% of the mass of the interstellar medium resided in Giant Molecular Clouds or GMC's. These GMC's were also located near essentially all OB associations (Blitz 1980; Sargent 1977, 1979). A typical GMC is elongated, with a greatest linear extent of 90 pc and a mass of 10^5 $M_\odot$.

Because of the enormous amount of mass residing in the GMC component, even the former proponents of cloud collapse were now converted and some (Solomon, Sanders, and Scoville 1979, Scoville and Hersh 1979, Kwan 1979) derived cloud lifetimes, $\tau_{c\ell} > 2 \times 10^9$ years, from considerations of GMC formation. Such a long life-time implies that a GMC would survive several passages through the spiral arms and support for the long lifetimes was found in the apparent failure of the CO to manifest spiral structure. A minority viewpoint was expressed by Bash and Peters (1976) and by Bash, Green, and Peters (1977), based on their model of molecular cloud formation in the spiral density wave shock. They found a best match to the CO surveys if $\tau_{c\ell} = 3 \times 10^7$ years (later revised to 4×10^7 years, Bash 1979), in agreement with the age at which CO emission disappears from young clusters.

In the last year, Cohen et al. (1980) completed their fully sampled CO maps of the first and third galactic quadrants, in which they claim to see clear evidence of spiral structure, implying lifetimes in accord with those suggested by Bash, Green, and Peters (1977). The mass fraction of the interstellar medium in molecular form would then be a more seemly 50% or less. Stark (1979) finds that CO emission in M31 is strongly concentrated in the spiral arms, but this does not seem to be the case in M51 (Rickard, private communication). Detailed studies of individual clouds have indicated a wide range in molecular cloud properties such as size, mass, peak temperature, peak density, and chemical composition (see Evans 1980 for a review of cloud properties). Large amounts of atomic hydrogen have been found in and around molecular clouds (cf. Sato and Fukui 1978). In addition, considerable structure is seen within molecular clouds, on various size scales. Turbulence is now the favored dynamical description, as self-absorbed and complex profiles have been seen in many clouds (cf. Langer et al. 1978). The observed linewidths are correlated with size and mass in a way expected for turbulence (Larson 1980).

One should note that the currently favored lifetime for clouds still exceeds the free-fall time significantly. Rotation (Field 1978), magnetic fields (Mouschovias 1978), and turbulence (Zuckerman and

Evans 1974) have been suggested to provide support against gravity. In the case of turbulence, it has been argued that supersonic turbulence should decay too rapidly to significantly increase $\tau_{c\ell}$ Goldreich and Kwan 1974). This argument is now being questioned on general grounds (Scalo, private communication); also, in the presence of a magnetic field, dissipation may also be decreased via Alfven waves (Zuckerman and Evans 1974; Bash, Hausman, and Papaloizou 1980). Finally, the turbulence may be regenerated by collisions with smaller clouds (Bash, Hausman, and Papaloizou 1980), by stellar winds from T Tauri stars (Norman and Silk 1979), or by nearby H II regions and supernova remnants (Wheeler, Mazurek, and Sivaramakrishnan 1980).

II. Classification of Molecular Clouds

One question which is often raised is which kinds of molecular clouds form stars? The question presupposes the existence of a classification system for molecular clouds; in fact, no satisfactory classification system has ever been developed. Most of the terms used to define cloud types are left-overs from the pre-molecular era. Thus, people refer to dark clouds, dust clouds, diffuse clouds, etc. I have discussed elsewhere why I think this terminology is unnecessarily confusing (Evans 1978). Fortunately, the term "molecular cloud" has come into increasing use as a generic identifier for objects in which molecules are common. The most common sub-division of the genus molecular cloud, is into giant molecular clouds (GMC's) and "dark clouds". Since the latter term merely represents a selection effect (i.e., the cloud is close enough to show up as visual obscuration), nearby GMC's are also dark clouds (e.g., the Orion molecular cloud complex). Therefore, a more useful subdivision may be into "big clouds" and "little clouds", using some arbitrary length scale as the discriminant. Even here, one encounters difficulties because big clouds usually have complicated sub-structure and may equally well be referred to as "cloud complexes". Also the size must be defined consistently; maps of different molecular lines will have different sizes.

Despite this unfortunate confusion, it does appear that big clouds form massive (O and B) stars while little clouds may or may not. It may be that an isolated globule can collapse to form a single massive star, but no example of this presently occurring is known. Rather one finds young clusters of O and B stars near big molecular clouds, with an average size of 90 pc (Blitz 1980). Lower mass stars seem less discriminating in their choice of parent cloud, being found near molecular clouds of all sizes. Even these statements are not entirely secure because selection effects are potentially severe.

Another classification which is sometimes useful is based on the peak gas temperature (T_K) as measured by CO (Evans 1978; Rowan-Robinson 1979). Group A clouds (T_K < 20K throughout) may be explained without invoking local heat sources. Group B clouds (T_K > 20K) require additional heat sources; most Group B clouds have evidence of recent star formation as manifested by compact H II regions, infrared sources, or masers. Thus the question asked to begin this section can be answered in a modified form: Group B clouds are likely to be currently engaged in the formation of massive stars; Group A clouds are not. This answer is not very useful, unless one is looking for star formation regions, because the elevated temperature is a symptom, not a cause of star formation.

Deciding in advance which molecular clouds will form massive stars is at present beyond our capabilities. Much more detailed study of an unbiased sample of molecular clouds is a prerequisite in dealing with this question.

III. Location of Star Formation in Molecular Clouds

Can we specify where, in a given molecular cloud, star formation is occurring? A naive analysis would suggest that stars would form near the center of mass of the molecular cloud, as gravity pulled the outer parts inward in a collapse. This analysis may be correct for a small, isolated, spherical cloud. Indeed, some analysis of globules suggests just such a centrally condensed structure (see Villere and Black 1980). The naive analysis is probably incorrect for larger clouds for two reasons: big clouds are generally very non-uniform and they contain many Jeans masses. In this case, gravitational collapse of randomly located dense regions would tend to produce a more random pattern of star formation, with several different centers of activity, perhaps in different stages of evolution. Such a picture is very commonly seen. In this case, many centers of star formation will lie near the outside of the molecular cloud (Zuckerman and Evans 1974). Even for a uniform density sphere 50 percent of the mass lies in the outer 20 percent of the radius. Elongated and irregular molecular clouds have much larger surface to volume ratios, so that star formation is very likely to occur near some surface region of the cloud. Once formed, the stars are often able to dissipate the remaining layer of molecular material, breaking out to a much lower density medium (cf. Whitworth 1979, Mazurek 1980).

In view of these facts, it is hardly surprising that many young stars are seen near the surface of clouds. Many H II regions can be interpreted in terms of a blister model (Zuckerman 1973, Israel 1978) and such phenomena as Herbig-Haro objects suggest a similar situation for less massive stars. These phenomena in themselves cannot be used to argue that external triggers are needed to induce stellar birth.

On somewhat larger scales, regularities are seen which do suggest the presence of external forces. OB associations are commonly, though not always, arranged in a linear sequence of sub-groups which increase in age with increasing distance from an elongated molecular cloud (cf. Blaauw 1964, Blitz 1980). Elmegreen and Lada (1977) have argued that the expanding H II region from the initial sub-group drives a shock into the molecular cloud, triggering the formation of the next sub-group by compressing a layer of the molecular cloud adjacent to the H II region. This "sequential star formation" finds considerable support in the morphology of many OB associations and the molecular clouds that have produced them. Other external triggers which have been proposed for particular situations are supernovae (Herbst and Assousa 1977), cloud-cloud collisions (Loren 1976), and the spiral density wave (Woodward 1976).

It is difficult to study the location of star formation within a molecular cloud by studying the location of well-developed H II regions and optically visible objects like OB associations and Herbig-Haro objects. If a star has produced a well-developed H II region, then it has probably disrupted a sizeable portion of the molecular cloud. The location of optically visible objects will be selectively near the front edge of the cloud. Thus infrared observations offer two advantages: objects which are more deeply embedded can be detected; and the location of massive stars can be studied before they have altered too drastically the surrounding terrain. Unfortunately, complete surveys of molecular clouds are extremely tedious and hence rare, especially at the longer wavelengths where identification of young objects is more clear-cut. Nadeau (unpublished) has covered large areas in several molecular clouds at 10μm; generally speaking, no sources were found outside already known centers of activity, as marked by CO hot spots or compact H II regions. Unfortunately, a significant number of very cool sources have now been found (Beichman, Becklin, and Wynn-Williams 1979) which would not be detected at 10μm. Complete surveys at longer wavelengths will probably await the success of IRAS.

Meanwhile,the most useful work has been done by Beichman (1979) who surveyed 19 hot spots in Group B molecular clouds at 20μm. About half the clouds were found to contain embedded infrared objects. If the hot spot was also known to be dense, the detection probability was near unity. While hardly free of selection effects, this study does support the view that stars are forming in the hottest, densest parts of molecular clouds. Even within the region searched at 20μm, Beichman found that the sources were tightly concentrated in a single center of activity. The projected separation of the infrared sources from the edge of the cloud is larger than the thickness of the shocked layer, where one would expect to see the sources if their formation were induced by the nearby H II region. Thus, these observations do not support the detailed predictions of the sequential star formation scenario, and Beichman (1979) argues that the apparent tendency for stars to form near the surface of a cloud is based on selection effects caused by the short wavelengths previously used to find the young stars.

Beichman (1979) also found that multiple infrared sources were often found within a single hot spot (see also Wynn-Williams et al. 1980). The mean separation between sources is 0.17 pc, very similar to that found in compact clusters of O and B stars, like the Trapezium, and not much greater than the mean separation of wide visual binaries. He argues that fragmentation during gravitational collapse provides the best explanation, both of wide binaries and of compact clusters, while bifurcation of a rotating fragment leads to close visual binaries, as also suggested by the work of Abt and Levy (1978).

On a larger scale, Elmegreen (1980) has used I band photography to study a 2° x 3° field including W3 and most of W4. About 135 stars were found which were brighter at I than at R; Elmegreen suggests that most are young stars embedded in the cloud. They tend to cluster near regions of peak CO, optical, or far-infrared activity. This technique may prove useful for studying the fainter, but less obscured members of a nascent open cluster.

IV. Properties of Infrared Sources

A. Size

Determining the size of infrared sources, one encounters problems similar to those which make it hard to determine the size of molecular clouds. The size clearly depends on the wavelength. At millimeter and sub-millimeter wavelengths the emission may be coextensive with the molecular cloud. At such long wavelengths the emission is close to Rayleigh-Jeans and even the low temperature envelopes of clouds may emit. Such extensive emission may be very hard to detect unless large beams and very large chopper throws are employed. In this regime, the dust emission is optically thin and studies of dust-to-gas ratios, and molecular depletion may be pursued by comparing the optical depth, τ_λ, to N_{13}, the ^{13}CO column density. Moving to shorter wavelengths, the source shrinks, as only the relatively warm dust grains emit substantially. Somewhere around 10μm the typical infrared source becomes smaller than can be resolved normally (ignoring extended H II regions). Here occultations and Michelson or speckle interferometry must be used to supply a size. The data are difficult to obtain and only exist for a few sources.

In some cases, the infrared source is resolved into a double source (W3IRS5 Low 1980; Mon R2IRS3 Beckwith et al. 1976). In other cases, (GL2591, the Becklin-Neugebauer object, S255, and S140) the source remains single and is resolved (Low 1980; Foy et al. 1979; Neugebauer, private communication). Generally speaking, the available sizes are consistent with observed luminosities and inferred dust temperatures. The size is a crucial input into the question of evolutionary state since massive stars will eventually produce an H II region which expands into an extended infrared source, even in the near-infrared. Thus the size and structure of extremely compact sources should be related roughly to an evolutionary sequence.

Studies of the shape of compact infrared sources are also of interest, since deviations from spherical symmetry are suggested by the presence of infrared reflection nebulae (Werner et al. 1979). Other studies have also invoked aspherical geometries (Harvey, Campbell, and Hoffman 1977; Beichman, Becklin, and Wynn-Williams 1979) and these are also expected on theoretical grounds if rotation plays a role in the collapse.

B. Energy Distribution and Luminosity

The difficulties in establishing sizes spill over into the effort to determine the energy distribution, especially in the presence of multiple sources. Typically several near infrared sources are embedded within a region of extended far-infrared and even more extended sub-millimeter emission. With no a priori way to apportion the far-infrared energy to the various near-infrared sources, one can only define the energy distribution and luminosity of the source complex. Thus the search for the elusive simple, solitary source is a worthwhile, if frustrating, one.

In this situation, only a few generalities are possible. The most well established is that the bulk of the energy from molecular clouds does appear in the far-infrared. Typical energy distributions are shown by Werner, Becklin, and Neugebauer (1977). The shape of the energy distribution shortward of about 50μm shows considerable variation from source to source. The spectra of some sources drop very steeply with decreasing wavelength. Others show a nearly power law energy distribution through the near-infrared (cf. Beckwith et al. 1976). As shown by Kwan and Scoville (1976) the latter behavior can be understood if the emission arises from dust at a wide range of temperatures. This situation is often present in well-evolved compact H II regions embedded in molecular clouds. Here the dust in the H II region reaches temperatures of several hundred kelvins and is extended sufficiently to contribute substantially to the energy distribution.

In contrast, the sources with steep energy distributions in the near-infrared are often radio-quiet or have only a very compact H II region. It is tempting to assign these sources to an earlier evolutionary state, but caution must be exercised. Heavy overlying extinction can redden the energy distribution substantially. In general, it is very hard to distinguish an energy distribution which is intrinsically steep from one which has been selectively extinguished. This can be illustrated with the spectra of Type II OH masers which can have extremely steep energy distributions and deep silicate features even though they are not embedded in molecular clouds (Evans and Beckwith 1977). By the same token, some compact H II regions have quite steep spectra, suggesting heavy extinction. In this case, specific spectral lines such as Brα and Brγ can be used to estimate the extinction and hence allow de-reddening of the energy distribution. For sources without such lines, the intrinsic spectrum cannot be disentangled from the overlying extinction. Indeed, there may be no real distinction between them in the very early evolutionary stages, before dust shells and H II regions form.

Finally, another type of energy distribution can be identified: the far-infrared emission dominates as usual, but the source is reasonably strong in the near-infrared. The energy distribution may be fairly flat in the near-infrared, and in some cases a star is even visible optically. The striking feature of these sources is that emission in the middle-infrared (5-30μm) is weak. Thus, these sources must have little dust at temperatures from 100-500 K. Since this is hard to explain with a continuous distribution of dust, it is likely that inhomogeneities play a role. The extreme of this class occurs when a normal main-sequence star exists near a molecular cloud, but does not have significant dust in a shell around it. These sources are often marked by reflection nebulae, and a nice example is NGC 2023 (Harvey, Thronson, and Gatley 1980). Because powerful optical spectroscopy techniques can be brought to bear on these objects, they promise to be very useful sources for separating processes which are entangled in embedded sources.

C. Spectral Features

The difficulty of separating the intrinsic spectrum from effects of overlying extinction increases the importance of specific spectral features. The most directly useful are recombination lines and molecular bands. If the source has produced a significant volume of ionized gas, recombination lines such as Brα and Brγ may be detectable, even when the H II region is too compact to show radio continuum emission. If more than one line can be detected, recombination theory can be invoked to predict the relative strength of the lines, and the observed lines can then be used to determine both the extinction and the flux of ionizing photons (cf. Thompson and Tokunaga 1979). Measurement of the total luminosity could then allow us to begin to place young stars on a modified HR diagram (see Thompson review). Molecular bands have been less widely used, owing to the weakness of most sources at relevant wavelengths. The 2.3μm CO overtone band has been used to distinguish post-main-sequence objects from young ones, while studies of the 4.7μm CO fundamental band with sufficient resolution and sensitivity can indicate the amount of molecular gas in front of the object. Such studies have also revealed large mass motions around the Becklin-Neugebauer object (Hall et al. 1978) and can help to distinguish collapse from expansion. The remarkable phenomena of the H_2 emission in vibration-rotation lines (see Beckwith review) and emission from CO rotational lines as high as J=22→21 (Watson et al. 1980) are precursors of the exciting discoveries awaiting extension of spectroscopy throughout the infrared. Much of this work will use the infrared source as a convenient background lamp for doing absorption spectroscopy of the intervening molecular cloud, but studies have also shown that phenomena such as expanding shells and shocks associated with activity of the source itself are able to heat some of the gas enough to produce emission in the infrared.

Another category of spectral features are the broad band features, presumably associated with broad-band resonances in the dust grains. While these are primarily diagnostic of the dust material (see review by Aitken), they have also been used to obtain information on the source itself. For example, the 9.7μm absorption feature, generally attributed to silicates, has been used to estimate extinction, as calibrated by studies of stars whose intrinsic spectrum is known or can be deduced. Values of $A_V/\tau_{9.7}$ range from 8 (Becklin et al. 1978) to 13 (Gillett et al. 1975) and 23 (Rieke 1974). Direct application to sources deeply embedded in molecular clouds is suspect because the dust immediately surrounding the ultimate energy source may produce the feature either in emission or in absorption as illustrated by the radiative transport of Kwan and Scoville (1976). Nonetheless, the depth of the 9.7μm feature is useful as a qualitative indicator, at least, of how deeply buried an object must be. Other spectral features (e.g., the 3.1μm "ice" feature and the 6.0 and 6.8μm un-identified features) seem to be particularly diagnostic of extinction by cold molecular cloud material and may be useful measures of extinction, if they can be calibrated.

D. Evolutionary State

It is tempting to arrange the various types of energy distributions discussed above into an evolutionary sequence, but differences in stellar mass, geometry and initial conditions may complicate matters greatly (cf. Habing and Israel 1979). To begin with the most general view, one would want to consider pre-main-sequence, main-sequence, and post-main-sequence stars as possible infrared sources in molecular clouds. Post-main-sequence stars have generally been discounted, although the presence of an SiO maser in the Orion infrared cluster has been used to raise the possibility that a post-main-sequence object is present. The energy distribution alone cannot always be used to rule out post-main-sequence objects. Type II OH masers are post-main-sequence objects with energy distributions which can be disturbingly similar to those seen in molecular clouds (Evans and Beckwith 1977). As isolated objects, they are relatively weak in the far-infrared (Werner et al. 1980) but this would not necessarily be true if one were embedded in a molecular cloud.

Given the density of giants of all types of 6×10^{-4} pc^{-3}, the average GMC could contain over 20 giant stars purely by accident. Thus, the possibility that a given infrared source in a GMC is a post-main-sequence object cannot be discounted. The chance that a giant star accidently lies in a molecular cloud core or in a nearby small cloud (both with typical diameters of 1 pc) is much less: $\sim 3 \times 10^{-4}$.

Another possibility is that a star might exhaust its main sequence life without leaving its parent cloud. If the age of a molecular cloud is 4 x 10^7 years, the mass of such a star would have to be greater than $\sim$ 10 $M_\odot$. If the star had a random velocity component of 1 km s^{-1}, it would travel 40 pc in its lifetime, probably escaping the cloud. To be confined within the 1 pc diameter of the dense core the star would have to live < 10^6 years, implying a mass > 40 $M_\odot$. Such a massive star would surely disrupt the cloud core during its lifetime. Thus it appears safe to conclude that infrared sources in dense cloud cores are not post-main-sequence objects, but that sources found more generally in molecular cloud envelopes could be.

The more difficult question is then to separate main-sequence stars from pre-main-sequence stars or protostars. Since the terminology can be confusing, let us concentrate on the question of whether ionizing photons are being produced yet. If the star in question is massive enough, this question can be answered in principle by observations in the radio continuum or by observation of infrared recombination lines. If no evidence of ionizing photons can be found, at a level below that expected for a main-sequence star of the same luminosity, the term "protostar" has often been applied. (Recently more modest descriptions, such as "extreme youth" have been favored.) Note that application of this criterion depends on having sufficient sensitivity to detect radio or recombination line fluxes expected from main-sequence stars. Further, the luminosity, usually concentrated in the far-infrared, must be assumed to arise from a single object (or somehow be apportioned among a number) in order to predict the flux of ionizing photons from a main-sequence star. Finally, note that stars which have only recently begun to produce ionizing photons may have H II regions so compact as to be optically thick at radio frequencies and hence weaker than expected, as well as heavy dust shells which attenuate substantially even the infrared recombination lines. The upshot is that conclusive proof that an object is not yet producing ionizing photons is very difficult to obtain. A candidate "protostar" is always susceptible to the ravages of time and improved sensitivity. Thus the Becklin-Neugebauer object, long considered the prototype of this group, fell from grace with the discovery of Brα emission (Grasdalen 1976).

The other question involved in separating protostars from main-sequence stars is whether material is still accreting. High spectral resolution studies have been able to identify outflow around some objects, and continued work in this area may locate sources with infalling material.

V. Energetics

It was suggested earlier that one useful classification system for molecular clouds was to ask whether they contain a hot spot (T_K > 20 K). Those with hot spots usually are engaged in active star formation. It seems natural then to suggest that young or forming stars supply the energy for the hot spot. Goldreich and Kwan (1974) suggested a specific mechanism: the dust in the molecular cloud absorbs photons emitted by the star or by the H II region, if present, and is warmed to $T_D \sim 20 - 100$ K; collisions of gas molecules with these warm grains leads to an equipartition of energy and the gas molecules leave with 3/2 k T_D translational energy. Thus, as long as $T_D > T_K$, the gas will be heated by these collisions. A consequence of this picture is that copious far-infrared emission should be produced by the warm dust grains.

In order to formulate a more quantitative test of this picture, Evans, Blair, and Beckwith (1977) used CO and ^{13}CO observations of the S255 molecular cloud to predict far-infrared luminosities. They assumed that $T_D = T_K$, a minimum condition, and that the shells of various T_K defined by the CO observations emitted like gray-bodies at T_D with an optical depth τ_{FIR}. From data on a variety of sources, they found that $\tau_{FIR} = 10^{-18}\ N_{13}$ was roughly satisfied. The far-infrared emission from the S255 molecular cloud has been observed (Werner, private communication; Sargent et al. 1980). Blair et al. (1978) applied the same technique to the S140 molecular cloud and Harvey, Campbell, and Hoffman (1978), Rouan et al. (1977), and de Muizon et al. (1980) observed far-infrared emission at about the expected level. Similar results were found in several other clouds [S235 (Evans and Blair 1980; Evans et al. 1980); W3-W4 (Thronson, Campbell, and Hoffman 1980)]. The dust-gas heating scheme appears to be plausible at least in dense, hot cores of molecular clouds.

On the other hand, some discrepancies have also been found. Crutcher, Hartkopf, and Giguere (1978) applied the techniques of Evans, Blair, and Beckwith (1977) to the NGC 2264 molecular cloud and predicted about 10 times the observed (Harvey, Campbell, and Hoffman 1977) far-infrared luminosity. To check this discrepancy, the region should be observed with a large beam in the far-infrared, because Sargent and Van Duinen (paper presented at this conference) have found far-infrared luminosities to be as much as 10 times larger when measured with large beams. Even in the case of S140, Blair et al. noted that the far-infrared emission was predicted correctly only from the regions very close to the middle-infrared source, S140IR. The extended plateau of modest T_K was not seen by Harvey et al. (1978). Subsequent observations by de Muizon et al. (1980) indicate far more extensive far-infrared emission and they conclude that $T_D > T_K$ as far as 20' from S140IR. Still, the densities thought to exist in those regions are insufficient to effectively couple T_D and T_K. The energetics of these extended plateaus of warm gas are still not adequately explained. More striking discrepancies have been found by Lada and Wilking (1980a). The ρ Ophiuchi molecular cloud has regions of quite high T_K (cf. Loren, Evans, and Knapp 1979) which do not show substantial far-infrared emission (Fazio et al. 1976).

A particularly hard limit is available at a position of ^{13}CO self-absorption (Lada and Wilking 1980a) where $N_{13} = 2.5 \times 10^{17}$ cm^{-2} and $T_K \geq 35$ K. Predictions of far-infrared fluxes from dust at $T_D = 35$ K and with τ_{FIR} inferred from molecular lines far exceed the observed upper limit of 10 Jy. In other cases, no stellar or proto-stellar heat sources have been found which are luminous enough to balance dust cooling rates inferred from the molecular data. An example is B35 (Lada and Wilking 1980b). Since some infrared sources have not appeared until wavelengths as long as 20μm were used to search for them, these results should be viewed with caution until corroborating far-infrared observations are made. Nonetheless, it is certainly plausible that other energy sources exist and may produce CO hot spots (cf. Elmegreen, Dickinson, and Lada 1978). Shock waves, magnetic ion-slip, and dissipation of turbulence are all processes which can heat the gas directly, thus avoiding the much greater energy requirements involved in heating the dust.

VI. Future Prospects

I will conclude by reviewing some of the areas in which future work may be of the greatest value.

Our understanding of infrared sources in molecular clouds is impeded by the absence of systematic surveys. These are now becoming available in CO from the Columbia telescope, but surveys in other lines would also be of value, as would surveys from the sourthern hemisphere. A number of surveys exist in the infrared, but none are completely satisfactory. The IRAS survey promises to revolutionize this field. With an unbiased sample in hand, we can hope to develop useful classification schemes, determine the location of star formation in molecular clouds, and determine a luminosity function for infrared sources in molecular clouds.

The size and shape of the dust distributions around newly formed stars should be determined and compared to theoretical models. In the near-infrared and middle-infrared, interferometric techniques will be needed to achieve adequate resolution. Larger telescopes, or separate telescopes, will be needed to provide appropriate baselines. The techniques have been pioneered and suitable telescopes are being planned. In the far-infrared, a large airborne or space telescope is essential for obtaining adequate resolution. The observations must be interpreted with radiative transport models to determine the distribution of dust temperature and optical depth. Comparably high resolution in the radio molecular lines, again with appropriate radiative transfer models, is needed to determine gas temperature and density distributions; with these data in hand, a full understanding of the energetics of both gas and dust will become possible. A more immediately achievable goal is to measure the total luminosity of molecular clouds with large beams and large chopper throws.

A third area where important advances are likely is in spectroscopy. With improved resolution and sensitivity, the velocity, temperature, and density structure of molecular clouds can be probed on a very fine spatial scale, using the infrared source as a background lamp. High excitation lines may also be used to study the role of shocks in molecular clouds. Finally, the long-standing question of the nature of the dust grains may be answered by higher resolution studies of some of the new, unidentified features.

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DISCUSSION FOLLOWING PAPER DELIVERED BY N. J. EVANS

SARGENT: You have referred to Beichman's assertion that he finds protostars to be too deeply embedded in molecular clouds for the mechanism formalized by Elmegreen and Lada to be valid. Beichman used the present positions of visible H II regions to derive his result. Certainly in the case of the Cepheus OB3 association, if the positions of the stars are projected backwards in time to their birthsites the scales determined by Elmegreen and Lada hold well.

RICKARD: Two comments about the interpretation of galactic plane CO surveys: First, Liszt and Burton (1980, preprint) have shown that, because of blending, the GMC interpretation of the first quadrant data (i.e., domination by >50 pc clouds) is not self-consistent. Intercomparisons of models and data suggest that most of the molecular gas is in smaller (~20 pc) clouds. Second, it may be fair to say that the CO surveys show as much spiral structure as the H I surveys. But, as Burton has shown, the apparent patterns are purely kinematical phenomena. There is little evidence for real enhancements in the density of CO clouds within spiral arms. M31 may be different; but even there, the arm-interarm contrast is not large (less than a factor of three).

EVANS: The question of the sizes of molecular clouds is a real problem because their structure is so complicated. You can equally well describe something as a complex of clouds or as a group of unrelated, overlapping clouds.

T. L. WILSON: The CO cloud sizes are biased, perhaps, to lower density gas. In cloud mass and lifetime calculations the gas densities in the cores of these clouds should be considered.

EVANS: It is true that the CO can mislead us because it is so extended compared to everything else, but the dense cores are much more confined, typically 1 pc in size.

SCOVILLE: In my opinion much of the confusion on the question of molecular clouds in spiral arms or out of them has resulted merely from imprecise definition of the question and what constitutes a regular spiral pattern. Thus, although the CO data in both our survey (Sanders, Solomon, and Scoville 1980) and that done at Columbia (Cohen, Dane, and Thaddeus 1980) show regular arms in the outer galaxy (e.g., the Perseus arm), the two groups do disagree on the interpretation in the interior of the galaxy. If one is willing to take liberty with the definition and the required regularity for the "spiral" arms, then it is of course possible to connect up most of the CO features in the inner galaxy into a pattern. In our opinion such a procedure does not fairly test the coherence of the pattern since the observations themselves have been used in a circular fashion to define the pattern. For example, the "arm" traced out at lowest longitude (ℓ = 30°) in the ℓ/V picture of Cohen *et al*. does not really have a reasonable spatial/kinematic behavior to be a density wave spiral arm. The most clearcut test of whether the clouds exist in both arms and interarms occurs for the emission at the terminal velocity of each longitude. The observed continuity near the terminal velocity out to ℓ = 50° is inconsistent with what one would expect from clouds confined to just one or two arms here. This is not to say that there are not large structures (~300 pc long) in the cloud distribution. It is simply that the pattern is irregular, perhaps like that in an Sc galaxy.

EVANS: I think that the question is still open, and depends on whether you emphasize the fact that there is some contrast which indicates spiral arms, or whether you emphasize the fact that you sometimes see CO in places there are not supposed to be any spiral arms.

RICKARD: Scoville's comment that CO spiral arms may only be well-defined outside the solar circle has a parallel in the Westerbork H I map of M51, in which the arms are not seen in strong contrast until outside the bright optical disk of the galaxy.

HABING: You commented that IRAS was needed to make an unbiased survey for regions of star formation. I suggest that masers are also ideal for this purpose since, as Downes and Genzel have shown, they are easy to map out throughout the Galaxy.

EVANS: This is clearly a useful technique, but I have questions as to whether the lifetime of the maser phenomenon is long enough to ensure that you find all the star formation regions.