MOLECULAR CLOUDS

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1. INTRODUCTION

To attempt to understand star formation without knowing the physical state of the dense interstellar molecular gas from which stars are made is an almost impossible task. Star formation has developed late as a branch of astrophysics largely for lack of observational data, and in particular, has lagged badly behind the study of the atomic and ionized components of the interstellar gas because spectroscopic techniques which work well at low density have an unfortunate tendency to fail when the density is high. Optical spectroscopy, which has been applied to the interstellar medium for over 70 years, has made little progress in regions of high density because of obscuration, and the same is true *a fortiori* of spacecraft spectroscopy in the UV; radio 21-cm and recombination line observations, although unhampered by obscuration, are unsatisfactory because the dense condensations are almost entirely molecular in composition.

Recently, however, the discovery of radio lines from the trace constituents of the molecular gas has led to spectacular progress in overcoming this stubborn obstacle, and much of this Symposium will touch on the subject of molecular clouds. To avoid overlap with Kerr's introductory report on star formation and the galaxy, I will not consider the molecular surveys that have been made of the galactic plane or the galactic center, and where possible I will avoid discussing molecular clouds associated with compact objects, so as not to cover the same ground as Mezger, Strom, or Wynn-Williams. The main subjects to be discussed are how molecular observations provide data on the physical state of the dense interstellar gas, and the molecular observations of H II regions, stellar associations, and dark nebulae. There are recent reviews by Zuckerman and Palmer (1974) and Penzias (1975) which cover some of these topics.

2. MOLECULAR CLOUDS ARE CO CLOUDS

Of the more than three dozen molecules so far discovered in the

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interstellar gas with radio telescopes, CO is by far the best as a general purpose tool for studying star formation, and the terms molecular cloud and CO cloud are from a practical standpoint almost synonymous. Many interstellar molecules are not easy to detect, and have only been observed in a small number of sources, but the radio astronomer can observe CO in almost every molecular condensation where the total (H_2) density exceeds a certain value. CO is several orders of magnitude more abundant than any other molecule observed in the radio region, and can be found virtually at will in dark nebulae, in the vicinity of H II regions, and along the galactic plane.

The easiest CO radio line to observe, and the most extensively studied, is the lowest rotational transition at 2.6 mm wavelength, but several higher rotational and isotopic lines have also been observed (Table 1), and others undoubtedly await discovery in the far IR. Since the observed CO lines respond somewhat differently to temperature and density, and cover a wide range of optical depth, they constitute partially independent channels of information, and CO is therefore a very powerful probe of physical conditions -- capable, clearly, of providing much more data than an atom like HI. The high frequency of the CO rotational spectrum is also an important asset, since it allows high angular resolution to be achieved with existing large antennas, and useful survey work to be done with small ones. At the CO 2.6 mm line the largest antenna now operating, the NRAO 36-foot telescope, has a beam width of only 1 arc min, which is an order of magnitude smaller than the beam of the largest steerable telescopes operating at 21-cm; useful CO survey work, comparable in resolution to the best 21-cm surveys, has been done with a 4-foot telescope.

Table 1. Astronomically observed rotational transitions of carbon monoxide

Transition	Isotopic Species C	 O	Frequency (GHz)	References
J = 1 → 0	12	16	115.2	Penzias et al. 1971
	13	16	110.2	" "
	12	18	109.7	" "
	12	17	112.3	Encrenaz et al. 1973
	13	18	104.7	Wannier et al. 1976
J = 2 → 1	12	16	230.5	Phillips et al. 1973
	13	16	220.4	" "
	12	18	219.5	Phillips and Huggins 1976
J = 3 → 2	12	16	345.7	Phillips 1976

Besides being easily observed, a good tracer for the molecular gas should correlate well with the invisible H_2, and the best tracer is obviously one whose density relative to H_2 is constant. CO is the only interstellar molecule with this important property, or at any rate the only one for which there is much theoretical or observational evidence. It is such a simple and stable compound that under astronomical conditions it tends to bottle up a large fraction of the C or O atoms wherever molecules are formed. Calculations have been done for interstellar molecular clouds (Watson and Salpeter 1972; Herbst and Klemperer 1973; Langer 1976), and for cool stellar atmospheres (Tsuji 1964); in either case it is found that the CO/H_2 ratio is fairly constant under a wide range of physical conditions.

A schematic summary of observational determinations of the interstellar CO/H_2 ratio is given in Figure 1. At the bottom of the Figure are UV spectroscopic data from the *Copernicus* orbiting observatory -- the only instances where both the CO and H_2 column densities are directly measured (Spitzer, et al. 1974; Jenkins and Shaya 1977). These low extinction clouds studied by *Copernicus* in the direction of early-type stars are not molecular clouds according to our

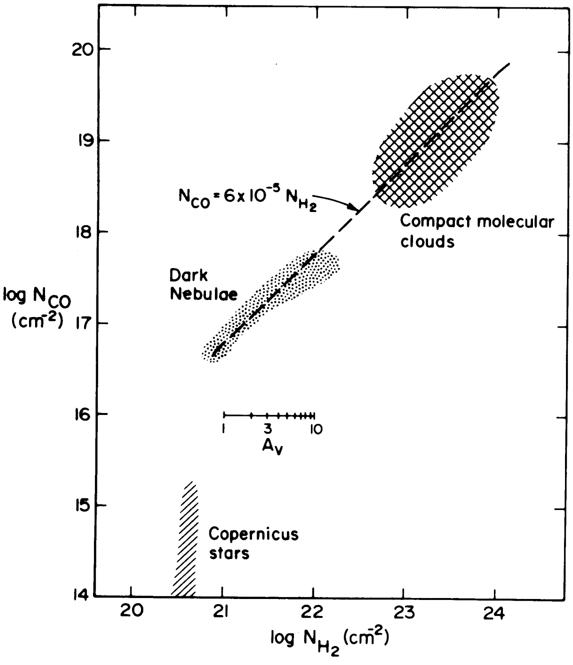

Figure 1. The CO/H_2 ratio in molecular clouds, and in the direction of stars observed by the *Copernicus* orbiting observatory.

informal definition, since there is too little CO for radio detection. In the middle of the Figure are data from visible dark nebulae; these are *bone fide* molecular clouds, too opaque for study in the UV, but easily seen in radio CO. Here N_{CO} is determined directly from CO radio observations, and N_{H_2} is inferred indirectly from star counts, on the assumption that the total hydrogen-to-visual extinction (N_{H_2}/A_V) is constant (Encrenaz et al. 1975; Dickman 1976). The principal shortcoming of this method is that it covers a rather small range of visual extinction or density (when $A_V \lesssim 1$ mag the CO emission is too weak to detect, and when $A_V \gtrsim 6$ mag there are few stars left to count. To extend the density range, it might be useful to count stars in the image-tube IR, where dark nebulae are less opaque). Finally, at the top of the Figure are data from the compact (typically invisible) molecular sources associated with H II regions and infrared sources. Although CO emission is usually much more intense here than in dark nebulae, N_{CO} is generally less well determined, because the compact sources are generally complex. For N_{H_2} , indirect estimates are again necessary,* and these are highly uncertain. One way N_{H_2} has been estimated is from observations of the rotational excitation of H_2CO and other molecules that yield the H_2 number density (Evans et al. 1975; Kutner et al. 1976); another is from observations of thermal emission from the dust grains in the far IR (Westbrook et al. 1976).

In spite of the various uncertainties, the data on dark nebulae and compact molecular clouds considered as a whole confirm rather well our theoretical expectation that the CO/H_2 ratio should be extremely stable. CO is apparently not only an excellent qualitative tracer for the molecular gas over a considerable range of density -- some three orders of magnitude -- but a fairly good quantitative one as well. A representative value for the CO/H_2 ratio is

$$N_{CO}/N_{H_2} = 6 \times 10^{-5}, \tag{1}$$

which, as Figure 1 suggests, is uncertain to about a fraction of three. This ratio implies that from 3 to 30% of the total carbon is in the form of carbon monoxide, which is not an unreasonable amount.

At low densities, however, the *Copernicus* observations show that CO fails as a "faithful" tracer of the molecular gas. Apparently there is a threshold in density ($N_{H_2} \simeq 5 \times 10^{20}$ cm^{-2}) or visual extinction $A_V \approx 0.5$ mag), or both, which must be crossed before an appreciable amount of CO can form and survive. Just what fraction of the molecular gas in the Galaxy lies to the left of this threshold in Figure 1, and is therefore CO free and unobservable by radio techniques, is a difficult question to answer; a local estimate from *Copernicus* data should be possible.

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*H_2 vibration-rotation lines have recently been detected, however, in the Kleinmann-Low Nebula, a typical compact molecular cloud (Gautier et al. 1976).

Although CO is by far the best available general purpose probe for the interstellar molecular gas, and much of the data which can be extracted from observations of other molecules can be obtained faster and better from CO, there is still a great deal of information relevant to star formation to be obtained from other molecules. Paramagnetic molecules like OH and SO are obviously best for Zeeman effect determinations of the magnetic field, and some important information comes from unexpected sources -- the recently discovered DCO^+ ion for example turns out to be an extremely sensitive probe of ionization. To appreciate just how varied and versatile a set of tools the molecules are, and to obtain some notion of how these tools are used, as good a way as any is to go down the list of physical parameters that can be extracted from the observational data. Starting with the most accurately determined, and proceeding to the least, these are the following.

2.1 Radial velocity

Although radial velocity can be measured with many molecules, CO and its isotopic species usually provide the fastest and best determinations. Readily observed molecules sometimes competitive with CO are OH, CS, H_2CO, C_2H, HCN, and HCO^+. In dark dust clouds especially, CO linewidths are sometimes as narrow as 1 km sec^{-1}, and radial velocities can be measured to very high accuracy -- sometimes to 0.1 km sec^{-1} or better. For radial velocity determinations, it is usually best to avoid saturated lines; when the normal CO line is saturated (as it is in many dark nebula and most compact sources), an isotopic line can usually be detected which is both optically thin and strong enough for a precise velocity measurement.

2.2 Temperature

The local kinetic temperature can be determined from interstellar molecular observations in several ways. First, as with the 21-cm line, molecular linewidths provide an upper limit to the kinetic temperature, though seldom, a very useful one, since most of the observed line broadening is usually the result of mass motion. Second, the excitation (rotational) temperature can be determined from measurement of the relative intensities of two or more lines, and it is sometimes possible to equate the excitation temperature to the kinetic temperature -- a common procedure in molecular optical and infrared spectroscopy. For this technique to work well, accurate intensity measurements are required, and molecules like NH_3 and CH_3OH, possessing families of transitions close in frequency, but from levels well separated in energy, are generally better than CO. Third, when a line is saturated, and the total density exceeds a certain value, the line brightness temperature approaches the kinetic temperature. These conditions are often well satisfied for the fundamental CO line in space, and this is therefore the most commonly used method for determining the kinetic temperature of molecular clouds. How accurate this technique is in practice is difficult to say; molecular intensity measurements have been notoriously inaccurate in the past, and the spectre of line formation is present; an informal estimate is that at present the best such temperature determinations are not to be trusted to better than 15%.

2.3 Density

Unfortunately, density and hence mass cannot be measured in molecular clouds nearly as well as radial velocity or temperature, and the accuracy attributed to many published density and mass estimates is probably inflated. The most common estimate of the total molecular column density N_{H_2} is simply made by inverting equation (1): the CO column density is measured at 2.6 mm, and the CO/H_2 ratio is assumed to be about 6 x 10^{-5}. Actually, because the normal CO line is usually saturated, it is often the ^{13}CO column density which is measured, but this distinction is not important here; the ratio to H_2 of none of the CO isotopic species is known to much better than a factor 3, and this uncertainty afflicts any density determinations based on this technique. If number rather than column density is desired, an additional assumption must be made as to the thickness of the molecular cloud in the line of sight, and the uncertainty is obviously even larger.

A more sophisticated, but not more accurate, method of determining the H_2 number density is based on measurements of the excitation temperature of molecules like H_2CO not in rotational equilibrium. This method requires knowledge of the quantal response of the molecule in question to H_2 impact (i.e., the excitation cross sections), and knowledge of the kinetic temperature as well; it has so far yielded only order-of-magnitude estimates of the H_2 number density.

Finally, let me mention a fallacy with respect to the determination of density that is often made, and which is discussed briefly by Penzias (1975) in his review. It is frequently stated that a number density threshold of H_2 is required to collisionally excite CO, and that a much higher such threshold is required to excite most of the other interstellar molecules, which are much more polar than CO. The densities usually given are of the order 100 cm^{-3} for CO, and 10^4 cm^{-3} for a strongly polar molecule like HCN. The detection of CO is therefore taken as evidence that n_{H_2} is at least 100 cm^{-3}, and the detection of HCN that n_{H_2} is at least 10^4 cm^{-3}. Although these conclusions may often be approximately correct, the physical reasoning is wrong. A threshold does exist in the kinetic temperature required to excite a given radio line, but there is none in density; CO and HCN at the same location will be collisionally excited at about the same rate, and HCN will then radiate faster than CO; if HCN isn't observed, there simply isn't enough HCN. It is quite plausible that a certain H_2 column density or number density is required for the production of HCN -- as appears from Figure 1 to be the case for CO -- but this is an entirely different matter, a chemical threshold, not a collisional one, and if it exists there is as yet no evidence that it occurs at a higher density than for CO. HCN and other strongly polar molecules are no better than the rare CO isotopes as qualitative tracers for dense regions, and it is necessary to exercise considerable restraint in drawing quantitative conclusions from the mere appearance of molecular lines.

2.4 Ionization

An extremely sensitive way to determine the degree of ionization in cold molecular clouds has recently been found. It is based on the remarkable extent to which deuterium has been discovered to fractionate in the interstellar formyl ion HCO^+ (Hollis et al. 1976; Guélin et al. 1977).

The molecular ion H_3^+ is thought to play a key role in interstellar chemistry. When a hydrogen molecule is ionized by a low energy cosmic ray primary,

$$H_2 + CR \rightarrow H_2^+ + e, \tag{2}$$

H_3^+ is formed almost at once via the fast reaction

$$H_2^+ + H_2 \rightarrow H_3^+ + H. \tag{3}$$

The H_3^+ ion is a stable, fairly long lived molecule, destroyed principally by dissociative recombination,

$$H_3^+ + e \rightarrow H_2 + H, \tag{4}$$

and by proton exchange with trace neutral constituents of the molecular gas, mainly with carbon monoxide,

$$H_3^+ + CO \rightarrow HCO^+ + H_2. \tag{5}$$

The product of this reaction, the formyl ion HCO^+, is one of the most abundant interstellar molecules, and its detection at about the predicted amount is important corroboration that the above reasoning is correct.

Because the isotopic species H_2D^+ is a slightly more stable molecule than H_3^+, the exchange reaction

$$H_3^+ + HD \rightleftarrows H_2D^+ + H_2 + \Delta E \quad (\Delta E/k \approx 200K) \tag{6}$$

will proceed strongly towards H_2D^+ in cold molecular clouds, and the H_2D^+/H_3^+ ratio may be many orders of magnitude higher than the HD/H_2 ratio. Dissociative recombination of H_2D^+, however, sets a ceiling to this enhancement of deuterium, which depends directly on the density of free electrons. It is readily shown that

$$\frac{n_e}{n_{H_2}} < \frac{n_{HD}}{n_{H_2}} \frac{r_e}{r_d} \frac{n_{H_3^+}}{n_{H_2D^+}} \tag{7}$$

The first factor in equation (7) is known from *Copernicus* observations to be about 4 x 10^{-5}, and the second factor, the ratio of the rate of hydrogen exchange -- equation (6) -- to the rate of dissociative recombination, is know from laboratory studies to be about 1 x 10^{-3}, so equation (7) becomes simply

$$\frac{n_e}{n_{H_2}} < 4 \times 10^{-8} \; \frac{n_{H_3{}^+}}{n_{H_2D^+}} \; . \qquad (8)$$

Although $H_3{}^+$ and H_2D^+ are not observed interstellar molecules, surprisingly enough this is not a serious difficulty. It can be shown that there is a strong tendency for the deuterium enhancement in $H_3{}^+$ to be passed on to HCO^+ formed by reaction (5), so one expects that

$$\frac{n_{H_3{}^+}}{n_{H_2D^+}} \sim \frac{n_{HCO^+}}{n_{DCO^+}} \; . \qquad (9)$$

A striking deuterium enhancement in the formyl ion has recently in fact been observed. In the cold molecular cloud L134, Hollis et al. (1976) find that the lowest rotational line of DCO^+ is about as intense as that of HCO^+. By equations (8) and (9), this then implies that the fractional ionization must be less than roughly 10^{-8}-10^{-7}. Since charge equality sets a lower limit on the ionization (the number of electrons must be greater than the observed number of formyl ions), a fairly well defined value of the ionization results,

$$10^{-9} \lesssim n_e/n_{H_2} \lesssim 10^{-8}\text{-}10^{-7}. \qquad (10)$$

This is of course a remarkably low level of ionization, with important implications for the hydromagnetics of the molecular matter, and a systematic study of DCO^+ in molecular clouds is eagerly awaited.

2.5 Magnetic field

Although no definite measurement of the Zeeman effect in a molecular cloud has yet been made, knowledge of the magnetic field is so important to understanding how stars form that brief mention of the work that has been done is desirable. Following Verschuur's first measurement of an interstellar 21-cm Zeeman effect eight years ago, there were attempts to apply his technique to self-absorbed 21-cm features in dark nebulae; an account of these investigations is given in two recent reviews (Verschuur 1974; Heiles 1976). No positive Zeeman effect was observed, but several very low upper limits on the magnetic field strength were obtained. An important unanswered question is, does the cold hydrogen observed in 21-cm self absorption fill the molecular cloud? If instead it merely constitutes a low density mantle to the cloud, a high magnetic field in the interior might easily escape detection. To measure the magnetic field in a molecular cloud, clearly the best procedure is to use the Zeeman effect of a molecule.

Of the seven known interstellar paramagnetic molecules, the best for measuring the Zeeman effect are probably OH and SO -- OH for diffuse dark nebulae where SO is hard to find, SO for compact molecular sources where OH is hard to resolve, and where OH may possess maser polarization and velocity structure easily confused with the Zeeman effect. Careful studies of OH in dark nebulae have yielded upper limits to the magnetic field strength in the range 50-130 microgauss (Turner and Verschuur 1970; Crutcher et al. 1975).

The magnetic field in compact sources is a more controversial subject; in the Kleinmann-Low nebula, for example, possible Zeeman-effects in both SO (Clark and Johnson 1974) and OH (Chaisson and Beichman 1975) have recently been suggested, but disputed (Zuckerman and Palmer 1975) -- in part because the fields obtained from these two different molecules differ by a large factor. It seems clear that better observations, and probably an advance in observational technique, are required before field measurements in molecular clouds gain general acceptance. Circular polarization in the lowest rotational SO line at 13 GHz is one of the most sensitive probes for magnetic field in compact molecular sources, and I believe that apparatus to search for this is being developed at NRAO, and at Bonn.

Because saturation is common, line formation is an important problem in molecular radio astronomy. I cannot review the recent literature in the space available; an up-to-date list of references can be found in recent papers by Baker (1976) and Leung and Liszt (1976). The extraction of physical data from saturated lines is so difficult, and the product often so unreliable, that one is sometimes tempted to ask whether the effort is worthwhile. If the aim is to study star formation, why not simply avoid the issue -- regard saturation as a defect of a particular probe of the molecular gas, and work instead with easily analyzed optically thin lines? The answer, of course, is that *in principle* saturated lines convey more information than optically thin ones. They are usually intense, and so provide a good deal of information in the technical sense that they can be observed with high signal-to-noise, and saturated lines may contain information absent in optically thin lines -- for example, the relative position along the line of sight of the material observed. There is general agreement that mass motion is required to account for the width and shape of most saturated lines, but it has proven difficult to determine the nature and scale of such motion -- whether, in particular, it represents large scale rotation, expansion, or collapse, or instead small scale turbulence. This is an area clearly of considerable interest to theories of star formation, where a great deal remains to be done.

3. SOME RECENT OBSERVATIONS

I would now like to consider briefly some of the observations that have been made of molecular clouds. Much of the observational work is tentative or incomplete, and not particularly suitable for review, and space is limited. I will therefore simply give a selection of recent work, with emphasis on papers that have been submitted to me by those attenting the Symposium.

3.1 H II regions and stellar associations

The first surveys of CO in H II regions, like previous surveys of OH and H_2CO, were generally done in the direction of strong thermal radio sources (Penzias et al. 1971; Liszt 1973; Wilson et al. 1974; Linke and Wannier 1974). By virtue of the high angular resolution and sensitivity provided by CO, and because CO is superior to OH and H_2CO as a tracer of the total molecular mass, a much better understanding was quickly obtained of the relationship of molecular clouds to H II regions. Molecular clouds, it became clear, are normally found in the vicinity of the more compact H II regions, and their mass is almost always substantial -- usually as large or greater than the mass of everything else in the region.

Recent molecular work on H II regions and related objects has had several aims. One has been simply to extend the survey work to smaller emission knots, and early type stars associated with nebulosity, in the hope that in these comparatively simple regions it will be easier to examine the process of star formation. Blair (1976) has undertaken a CO survey of visible H II regions and Hα emission knots; in a survey of 60 regions, most from the Sharpless catalog, he finds CO in 30, and evidence for high density cores in 6 of these. Similar CO observations have been undertaken by Kislyakov and Turner (1976). Although usually surrounded by H II regions too small to detect, the Herbig Be and Ae stars show distinct evidence of interaction with the interstellar gas and it has recently been shown that essentially all are CO sources; when the CO radio line is intense, other molecules as well can usually be detected (Loren, Vanden Bout, and Davis 1973; Loren 1975).

The molecular clouds in the vicinity of well known H II regions and stellar associations are complex and often extremely large; nearby ones may cover an area as large as 20 square degrees, and until recently none had been adequately mapped. There now exist, however, reasonably complete CO surveys of Orion (Chin 1977, Kutner et al.1977), M17 (Lada 1976; Elmegreen and Lada 1976), Cygnus X (Cong 1977), and the vicinity of the Ceph OB3 association (Sargent 1976), and comparable surveys of W3 (Cong et al. 1977), the Rosette Nebula (Blitz 1976), Perseus OB2 (Baran 1976), and NGC 2264 (Blitz 1976) are underway. During the discussion this afternoon we will learn further details of the M17 and Ceph OB3 surveys.

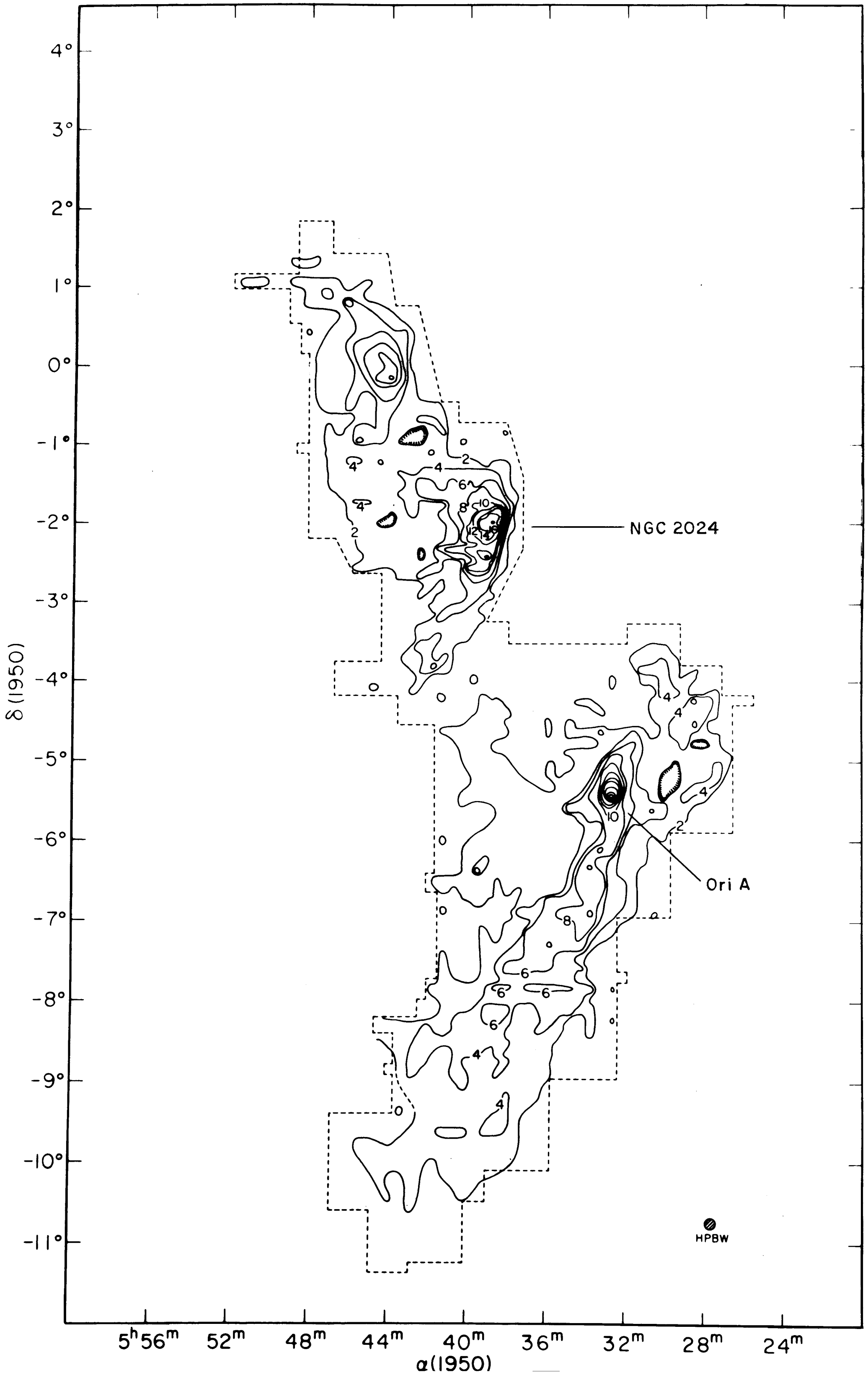
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Figure 2 shows the CO distribution in the interior of Barnard's Loop -- probably the best studied region of star formation in the galaxy, containing the Orion Nebula, NGC 2024 (Ori B), the Orion OB1 association, numerous dark and reflection nebulae, and many other young objects. These CO observations, made by Chin (1977) at an angular resolution of 8', show that essentially all the very young objects in Orion are embedded in two large molecular complexes, a northern one extending about 4° up from NGC 2024 and the Horsehead Nebula to the reflection nebulae NGC 2068 and NGC 2071, and a southern one extending about 6° southeast from the Orion Nebula in a direction parallel to the galactic plane. For reasons already discussed, it is difficult to give a precise value for the density and mass of these large molecular complexes, but the mass of the northern one is probably about 6×10^4 $M_\odot$, and the mass of the southern one is probably about 1×10^5 $M_\odot$. In either case, the molecular mass is comparable to or even exceeds that of all the other material -- stars, atomic gas, and ionized gas -- within Barnard's Loop, and it is clear that previous observations gave a seriously incomplete picture of this important region.

The southern molecular complex in Orion has a distinct velocity gradient along its long axis of about 0.1 km sec^{-1} pc^{-1}. Whether this gradient results from rotation, shear, expansion, or collapse is unknown, but if rotation is the cause, the period is about 4×10^7 years, and the sense of rotation is contrary to that of the Galaxy. A similar velocity gradient exists in the 21-cm line in this direction, and has been attributed to the expansion of Gould's belt.

Figure 2 provides an excellent example of the general finding that CO emission is almost always enhanced in regions of suspected star formation. In the northern complex of molecular clouds, the most intense CO line is in the direction of the strong H II region NGC 2024, but it can be seen that there is a definite spur to the south. This is the reflection nebula NGC 2023, an intense far IR source (Emerson et al. 1975), possessing several signs of recent star formation (Milman et al. 1975; Knapp et al. 1975; Strom et al. 1975). The broad secondary maximum in the CO emission at the top of the northern complex surrounds the reflection nebulae NGC 2068 and NGC 2071, the location apparently of a highly obscured young cluster (Strom et al. 1975). In the southern complex, the long ridge of CO emission extending to the southeast of the Orion Nebula contains a wealth of young objects, including the reflection nebula NGC 1999, and numerous Herbig-Haro objects and T Tauri stars. In each case, it is probably the heat released by stars or protostars rather than a rise in molecular density which is responsible for the enhancement of CO emission; some analysis, and usually observation of both ^{13}CO and CO, are required to trace the molecular gas, but to trace star formation, CO alone often suffices.

Figure 2. Molecular clouds in Orion: contours of peak intensity of the CO J = $1 \rightarrow 0$ line at 115 GHz, observed at an angular resolution of 8'. The contour interval is 2K.

Blaauw (1964) some time ago pointed out that stellar associations are often composed of subgroups strung out in order of age along the galactic plane. These subgroups are typically 10-20 pc apart, and differ in age by 2-3 million years, so the mean rate of advance of star formation is about 5-10 km sec^{-1}. The Orion OB1 association is one of the best examples of such a progression; it extends about 6° down from the upper right in Figure 2 more or less along the axis of the southern molecular complex, and joins this complex at the Orion Nebula, whose exciting stars are members of the youngest subgroup. To judge from the CO observations in the vicinity of other associations that have now been made, this progression from old subgroup to young subgroup to molecular cloud is a fairly common one, and the obvious inference is that stellar associations are formed by some kind of disturbance propagating through a molecular cloud at a speed of roughly 5-10 km sec^{-1}.

Elmegreen and Lada (1977), in work to be discussed in greater detail later this afternoon, have proposed a specific model to account for sequential OB star formation of this kind. An ionization front advancing into a molecular cloud will be preceeded by a shock front, and Elmegreen and Lada suggest that eventually a dense, gravitationally-unstable layer of molecular gas will accumulate between the two fronts; a schematic illustration of their model is given in Figure 3. They argue that the temperature and mass of this molecular layer are such that a new OB group is likely to result from its fragmentation and collapse. Since this new subgroup is likely to be detected first as OH and H_2O masers and IR sources, the frequent existence of such objects in molecular clouds just ahead of ionization fronts is readily understood (it is estimated that roughly half a million years are required for the star forming layer to be disrupted, and the new subassociation to emerge as visible OB stars). Elmegreen and Lada claim that several of the important properties of associations can be understood in terms of their model, including the distances between the subgroups, their differences in age, the regularity of the subgroup masses, and the alignment of the subgroups along the Galactic plane.

3.2 Dark nebulae and globules

There have been several recent molecular radio studies of visible dark nebulae and "Bok" globules. Most of the work has been with the 2.6 mm CO line, but there have also been observations of H_2CO, CS, and other molecules (cf. for example, Meyers 1973, 1975; Martin and Barret 1975; Sandqvist and Lindroos 1976).

Dickman (1975) has surveyed CO in a number of Lynds dark clouds shown by Dieter (1973) to exhibit 6-cm formaldehyde absorption. He finds both the normal and the carbon-13 isotopic line in nearly every dark cloud observed; the mean kinetic temperature is about 10 K, and there is surprisingly little variation in kinetic temperature from one cloud to the next. Similar results have been obtained by Milman et al. (1975) in a separate CO survey of dark nebulae.

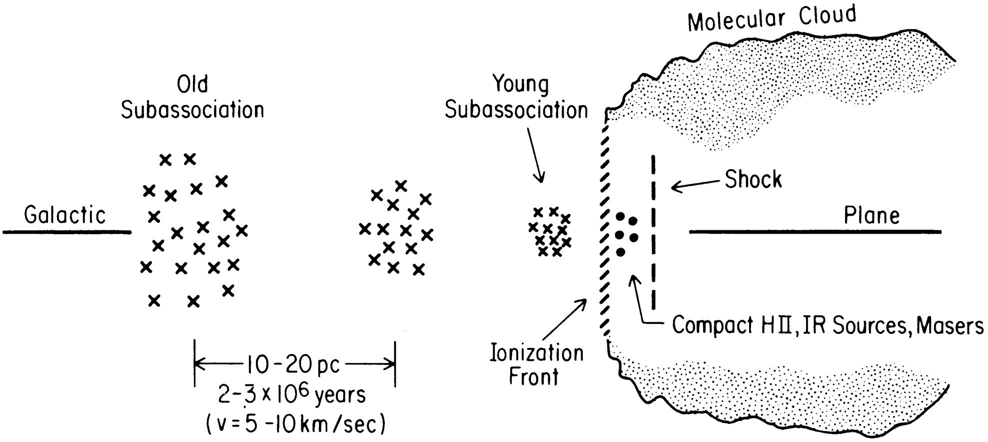

Figure 3. Sequential formation of OB subassociations along a molecular cloud.

A large scale survey of CO in the Taurus complex, and the dark clouds to the north and west in Perseus, is being undertaken by Baran (1976). With an 8' antenna beam, and observations on a grid 30' or finer on a side, he expects in the next few months to complete a survey of the entire region in the normal isotopic line; selected regions are also being mapped with the carbon-13 species. His preliminary results are of considerable interest. Although as expected the CO emission is generally strongest in areas of high extinction, and usually fills the dark nebulae seen on the Sky Survey prints, it occasionally appears to spill over from one dark cloud to another -- there is in other words detectable CO emission in regions of quite low visible extinction. There are usually pronounced peaks in the CO intensity in the direction of Hα knots, Herbig-Haro objects, reflection nebulae and T Tauri associations. The large hole in the H I intensity in Perseus noted by Heiles and Jenkins (1976) possesses a distinct CO counterpart.

The dust cloud L134 is an unusual dark nebula which many molecular observers have studied. Several molecules usually seen only in compact molecular sources have recently been detected in L134, including CS (Martin and Barrett 1975), HCN, HCO^+, and HNC (Snyder and Hollis 1976); as already described, even the deuterated ion DCO^+ has been observed in this source. L134 provides a good example of the care which must be exercised in deriving density and mass from molecular observations. It has been estimated from the appearance of strongly polar molecules like HCN that the total H_2 density is as high as a few times 10^5 cm^{-3}, which implies that the mass of L134 is in the vicinity of 10^4 $M_\odot$. Star counts give much lower and more reasonable mass estimates: Tucker et al. (1976) show that the visual extinction in L134 implies a mass of 25-60 $M_\odot$, and that such a mass is consistent with the observed CO linewidth and the virial theorem. A comparable mass has also been derived by Mahoney et al. (1976) from CO observations.

Recent work on Barnard 42, the well known dark cloud near Rho Ophiuchi shown schematically in Figure 4, provides a good illustration of how effectively radio and infrared observations complement each other in the investigation of star formation. Radio observations of CO (Encrenaz et al. 1975) and several other molecules, including CS, C_2H, NH_3, H_2CO, and SO, indicate that the Rho Oph nebula is a comparatively dense molecular cloud with internal sources of heat (Encrenaz 1974; Tucker et al. 1974; Myers and Ho 1975; Morris et al. 1973). The nature of these energy sources has been clearly revealed by IR observations. Grasdalen, Strom, and Strom (1973), and Vrba et al. (1975), have mapped Barnard 42 at 2 microns, and found about 70 IR point sources, most without visual counterpart. From IR photometry, they conclude that these are probably the upper main sequence of a young cluster still embedded in the dark cloud material; the IR extinction is low enough for direct observation of the stars at 2 microns,

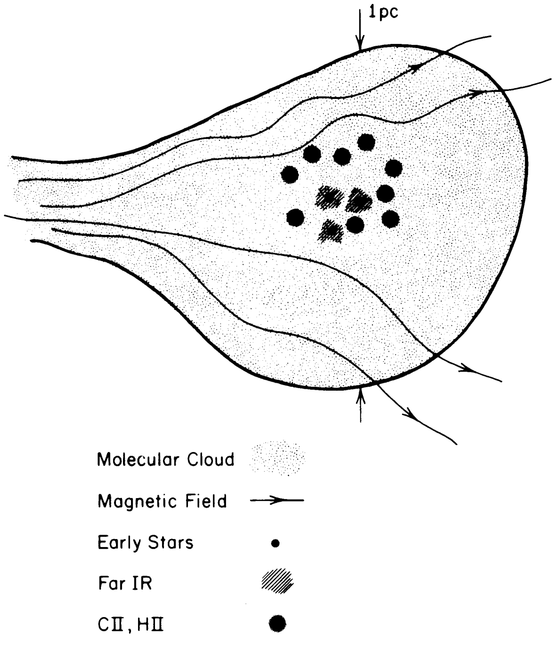

Figure 4. Schematic illustration of Barnard 42 -- the Rho Ophiuchi molecular cloud.

but at shorter wavelengths the extinction is so high (A_V = 5-40 mag) that visual observation of most of the stars is impossible.

It is expected that the absorbed visual energy from such embedded stars will be reradiated in the far IR. Simon et al. (1973) have detected a strong, extended 350 micron source near the peak of CO emission in Barnard 42, and Fazio et al. (1976), from recent far IR observations (40-250 microns) with a large baloon-borne telescope, find three extended source, two of which can be identified with 2-micron sources. The far-IR flux is consistent with radiation from dust heated by early B stars.

Additional evidence for B stars hidden in Barnard 42 comes from radio continuum and recombination line observations. Brown and Zuckerman (1975) have detected several compact H II regions in the cloud, two of which are associated with 2-micron sources. Observations of carbon recombination lines (Brown et al. 1974; Chaisson 1975) also indicate the presence of sources of ionization. There therefore seems very little doubt that the suggestion of Grasdalen, Strom, and Strom is correct, and that a highly obscured young cluster is being observed. Whether star formation is actually continuing at the present time is, however, another matter, for which little evidence exists.

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