RevMexAA (Serie de Conferencias), **1**, 137-148 (1995)

DENSE CORES IN MOLECULAR CLOUDS

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RESUMEN

Se presenta un resumen de lo que se conoce sobre la evolución y estructura de los núcleos moleculares densos. Se discuten estudios realizados recientemente sobre núcleos densos en nubes moleculares cercanas, presentando una breve discusión sobre la manera de estimar en ellos tanto los parámetros físicos como la estructura. Se tratan las características de los núcleos moleculares densos en regiones de formación de estrellas masivas, resumiendo las evidencias que existen de que los núcleos calientes que se observan frecuentemente en las proximidades de regiones HII son precursores de cúmulos galácticos densos.

ABSTRACT

A summary is given of our present knowledge of the evolution and structure of dense cores. Recent core surveys in nearby molecular clouds are discussed and there is a brief discussion of current estimates of core physical parameters and structure. I consider in some detail the characteristics of dense molecular cores in high mass star-forming regions and summarize the evidence that the "hot cores" often observed in the neighbourhood of HII regions are forerunners of dense galactic clusters.

Key words: **ISM: MOLECULES — ISM: HII REGIONS — STARS: FORMATION**

1. INTRODUCTION

Molecular clouds are highly inhomogeneous entities with density contrasts of several orders of magnitude. The highest density structures within them are commonly referred to as "cores" or "dense cores" and they are often associated with young extremely red pre-main-sequence stars. In a somewhat more restricted sense, we use the term "core" in this review to mean structures of between stellar and cluster masses (1-1000 $M_\odot$) which are ""virialised" in the sense that the sum of turbulent kinetic energy and thermal energy of the core is in rough balance with gravitational energy. Cores can thus be reasonably interpreted as "pre-protostars" or structures which are likely sites of future star formation.

From an observational viewpoint, cores have been discovered in surveys of molecular lines whose critical density (the density required in order that collisional excitation is competitive with transitions induced by the cosmic background) is of order 10^4 cm^{-3} or more. This is roughly two orders of magnitude higher than the mean density in giant molecular clouds (GMC's) and thus observing such transitions effectively selects the higher density condensations within such clouds. Typical transitions used to survey cores have been $NH_3(1,1)$ (e.g. Benson & Myers 1989, Harju et al. 1993) and CS(1-0) (Tatematsu et al. 1993). One finds in general that roughly ten percent of the mass of a typical GMC is in the form of such cores.

Useful reviews of core characteristics have been given by Myers (1987) and by Fuller & Myers (1987). A recent discussion is that of Myers (1994). Walmsley (1987) and Cernicharo (1991) have discussed the determination of the physical characteristics of cores while Wilson & Walmsley (1989) consider small scale molecular cloud structure in general. Many of the contributions to the volume "Clouds, Cores, and Low Mass Stars" (Edited by D. P. Clemens and R. Barvainis, ASP Conf. Ser., 65) are relevant to the discussion given here. In particular, the reviews by Fuller(1994) and Mundy(1994) discuss the structures and mass distributions inferred from the observations.

Most of the above studies concentrate on "low mass cores" such as those found in the Taurus complex where stars of order a solar mass or less are currently forming. The evolution of cores in regions such as Orion where higher mass stars are forming may differ radically (see Caselli & Myers 1995) and has received rather less recent attention. This is partly due to the greater distance of the nearest regions of high mass star formation and partly due to the fact that massive stars appear in general to form in clusters and associations rather than as single (or double) stars. Nevertheless, the increasing sensitivity of interferometers such as the VLA and the new generation of millimeter interferometers have made high resolution studies of high mass star formation regions increasingly interesting. In particular, it has been possible to study O-B star evolution by virtue of the compact ionized regions (UCHII regions or Ultra Compact HII regions) which can be observed surrounding massive stars in the early phases of their evolution. A general discussion of this topic is given by Churchwell (1991) and some more recent work is summarized by Gaume (1994). Such UCHII regions are often associated with compact sources of molecular line emission which appear to have temperatures (100 K or more) much larger than in the surrounding dense neutral material. These hot compact regions are known as "hot cores" and their characteristics have been discussed by Walmsley & Schilke (1992).

In section 2 of this review, I summarize briefly the results of recent dense core surveys. I confine the discussion here to surveys of clumps where the density is thought to be at least 10^4 cm^{-3} and thus neglect for example mention of the many interesting ^{13}CO studies. In section 3, work on the magnetic fields and degree of ionization in low mass cores is considered and in section 4, I discuss current ideas on core evolution. Section 5 is devoted to cores in regions of high mass star formation and I discuss evidence for infall and outflow. This is illustrated by some examples of recent studies of individual objects. Evidence is given that hot molecular cores may be forerunners of UCHII regions which in turn evolve into galactic O-B star clusters. In section 6, I consider briefly the possibility that there are dense *cold* clumps immersed in some HII region-Molecular Cloud complexes.

2. CORE SURVEYS

Core surveys have in general had the aim of determining the fraction of molecular cloud mass which is at high densities (above 10^4 cm^{-3}) and therefore implicitly on small size scales (0.1 pc.). Since one cannot observe molecular hydrogen directly, one uses a tracer whose abundance (or emissivity) is supposed proportional to the H_2 density. This allows a conversion from the observed intensity of tracer X to the hydrogen mass. Much of the discussion concerning the precision of core mass determinations is related to the correctness of this assumption. Where molecular lines are concerned, this involves the uncertainties of interstellar chemistry. One conclusion is that it is useful to use *more than one* tracer to study core properties and determine masses. If different molecular species lead to the same conclusions, one can have more confidence in the results. Conversely, if they do not, it does not imply necessarily that one tracer is better than another. It is quite likely that the abundances of both are varying as a function of density and position. Understanding such variations will require understanding of both the excitation and the chemical processes involved.

The main core surveys have been carried out in $C^{18}O$, CS, or NH_3. Of these, $C^{18}O$(1-0) fails the criterion mentioned above that the transition critical density should be above 10^4 cm^{-3}. When one uses $C^{18}O$(1-0) in order to study cores, one is therefore assuming implicitly that cores stand out from their background not only because their density is higher than in the surroundings but also because their column density is higher. This appears to be true albeit rather marginally. Figure 1 taken from Myers et al. (1991b) shows half–power contours in $C^{18}O$, CS, and NH_3 toward a number of nearby cores. One sees that the same basic features are seen in all three tracers although NH_3 tends to mark the more compact structure. An implication of this is that the cores must have column densities rather larger than the background. Put into other words, the column density invariance discussed by Larson (1981) is not valid for the cores of figure 1.

In any event, there are now available some relatively large scale surveys in $C^{18}O$(1-0) and (2-1) which aim at determining masses and sizes of cores (Fukui et al. 1994, Dutrey et al. 1993). These authors have also carried out companion CS(2-1) observations which show similar structures to those found in $C^{18}O$ but with greater contrast. Fukui et al. find for example using the Nagoya 4-m telescope that CS and $C^{18}O$ are in reasonable agreement in the northern part of the L1641 cloud around (but not toward) Orion-KL but that the distributions differ (there is relatively little CS except toward embedded infrared sources) in the southern part where star formation is less intense. Fukui et al. (1994) attribute these differences to varying CS abundances and conclude that "CS is not a good tracer of dense gas". An alternative interpretation (given that the CS(2-1) transition requires considerably higher densities to be excited than $C^{18}O$(1-0)) may be that on the contrary CS is only seen toward the density peaks and that there is much less high density gas in the southern part of the L1641 cloud. In this context, it is worth noting that Lada et al. (1991 a) have carried out a large scale CS survey

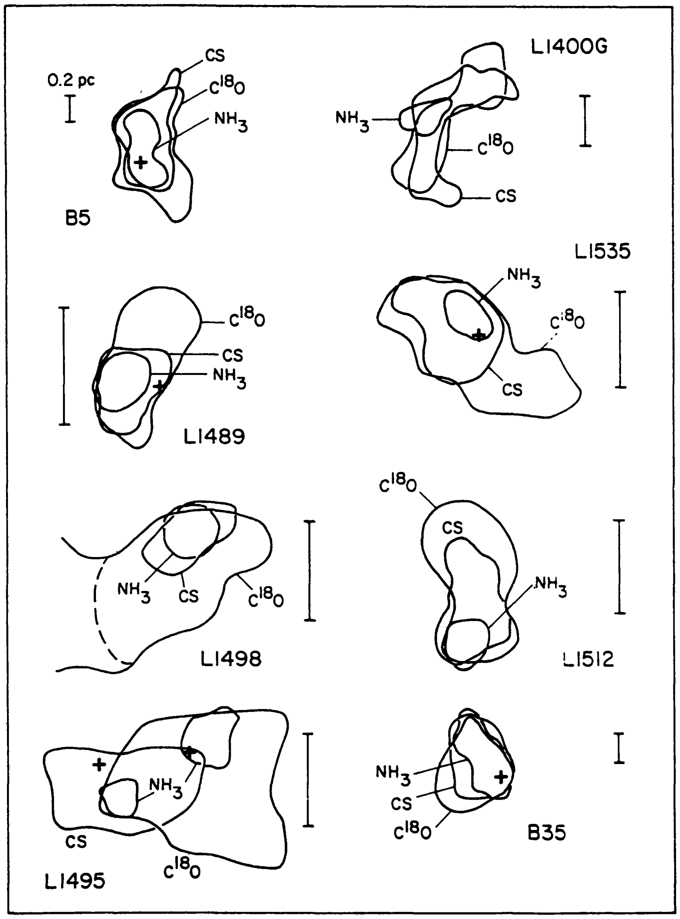

Fig. 1.— A comparison of the half-maximum contours of $C^{18}O$(1-0), CS(2-1), and NH_3(1,1) taken from Myers et al. (1991b). For each map, North is up and east to the left. The vertical markers denote a linear scale of 0.2 parsec.

of the L1630 cloud. In this case, there is no companion $C^{18}O$ study but one finds relatively good agreement between CS emission peaks and groups of 2 micron sources which are thought to be pre main-sequence objects (Lada et al. 1991b).

In contrast to the work on $C^{18}O$ and CS, ammonia core surveys have been "selective" in the sense that one has searched for (mainly) NH_3(1,1) emission in regions thought likely to give positive results. For example, Benson & Myers (1989) used the Haystack telescope to search regions with high visual extinction while Wouterloot et al. (1988) have used the Bonn telescope to search the environs of IRAS sources. The "bias" which this induces is difficult to quantify and it would certainly be useful to carry out a large scale ammonia survey in the same manner as the CS studies mentioned above. For the moment, the most useful comparison seems to be that of the Nobeyama CS(1-0) data (Tatematsu et al. 1993) and the Bonn NH_3(1,1) data (Cesaroni & Wilson 1994). A general conclusion from this seems to be that ammonia (see also Fig. 1) traces essentially the same structures as seen in CS although the NH_3 half-power diameters are in general smaller. This latter characteristic has given rise to some controversy. It appears to be correlated with narrower linewidths seen in ammonia which suggests that the $[NH_3]/[CS]$ abundance ratio increases with density (but see also the discussion of Zhou et al. 1989).

An interesting result that comes from the ammonia surveys is that there appear to be differences between the characteristics of cores found in different types of giant molecular cloud (GMC). Harju et al. (1992) mapped the ammonia cores in the Orion and Cepheus regions detected in the Wouterloot et al. survey. They found in these GMC's an almost complete absence of the narrow line cores found in Taurus and other nearby cloud complexes. By narrow line cores, one means here cores in which the contribution of thermal line broadening to the observed linewidth becomes appreciable (see discussions of Fuller & Myers 1987 and Myers et al. 1991 a,b). In such regions, thermal pressure must be playing an important role in stabilising the core against collapse. The absence of such narrow line cores in the Orion GMC suggests that some "non-thermal" pressure is the dominant force supporting cores in giant clouds (see Caselli & Myers 1995). The pressure seems to grow with the cloud mass. A recent study by Ladd et al. (1994) shows that in the Perseus cloud complex, cores have intermediate properties between those found in Orion and the Taurus cores.

An alternative to using molecular probes as a tracer for cores is to observe dust emission at millimeter and sub–millimeter wavelengths. This is becoming a very powerful approach due to the development of bolometer array receivers. Even without an array, it has been possible to show that within certain regions of high mass star formation, one can find high density clumps or cores of relatively cold gas (Mezger et al. 1988). In low mass star forming regions, progress has been more difficult. Nevertheless, recent studies (Mezger et al. 1992, Ward–Thompson et al. 1994, André & Montmerle 1994) have shown that both recently formed pre-main-sequence objects and pre-stellar cores are detectable and can be studied using their dust emission. The weak point in this approach is our present ignorance of the dust emissivity at millimeter wavelengths and indeed also our ignorance of dust grain size and constitution in such high density cores. Probably the most powerful technique is to combine the molecular line and the millimeter continuum data.

3. CORE CHARACTERISTICS IN LOW MASS STAR FORMATION REGIONS

I briefly summarize in this section our knowledge of core physical parameters in nearby star formation regions such as Taurus. These are the regions where (because of their proximity) one might hope to be able reliably to determine the parameters of potential star forming regions. The dense cores found in ammonia surveys of Taurus and other similar regions of low mass star formation have linear sizes in the range 0.05-0.2 parsec, densities of order $3\,10^4$ cm^{-3}, and masses in the range 0.3-100 $M_\odot$(Myers 1987). They have temperatures very close to 10 K and, as mentioned earlier, line profiles for which the width is determined both by thermal broadening and "non-thermal" turbulence. It is worth noting however that for most such low mass dense cores, the turbulence in question is sonic or at most mildly supersonic. Hence the problem of maintaining the turbulence is of a different order than for the larger scale cloud.

The prevailing view is that the source of the non-thermal broadening in some way reflects magnetic support for the core (Myers & Goodman 1988a,b). Unfortunately, there are rather few objects for which direct magnetic field estimates are available. However, Myers & Goodman (1988a) have shown that in cases where Zeeman measurements are available, the data are consistent with equipartition between gravitational energy, turbulent kinetic energy (inferred from the line width), and magnetic energy. In other words, the Alfvén speed is comparable to the observed line width suggesting that Alfvén waves (or more generally magnetic turbulence) are the cause of the observed non-thermal motions.

If this analysis is correct, it is clear that ridding the dense core gas of magnetic field may be a pre–condition for star formation. One process which would naturally account for this is ambipolar diffusion. There has consequently been a considerable number of theoretical studies aimed at studying the evolution of cores evolving from states where the magnetic flux suffices to halt collapse to states which are gravitationally unstable (see Shu et al. 1987, Lizano & Shu 1989, Fiedler & Mouschovias 1993). Observational checks on such models are difficult basically because the magnetic field and the ionization degree in cores are extremely difficult to determine.

A recent OH Zeeman study by Crutcher et al. (1993) gives a detailed discussion of the observational problems involved in magnetic field determinations. These authors used the Greenbank 43-m telescope and detected a magnetic field in one source (B1 with a line of sight component of 19 microgauss) out of twelve. The angular resolution of the telescope at the frequency of the OH lines is however poor (18′) relative to dense core sizes and so one must be careful in interpreting these results. One might think that a solution is to go to higher frequencies where angular resolutions are in general better but unfortunately Zeeman splittings (relative to line widths) are worse. Fiebig (1990) has used the Bonn telescope with an angular resolution of 1′ to observe CCS toward 3 cores and derives upper limits of roughly 70 microgauss.

While great efforts have been made to determine the magnetic field in cores, rather less time has been devoted to obtaining the degree of ionization $N_e/N(H_2)$. However a useful summary of the early work in this field is given by Langer (1985). He discusses the limits which can be put upon the electron density based on measurements of HCO^+ , CO, and their isotopically substituted forms. An open question at that time was the rate for dissociative recombination of H_3^+. The most recent laboratory data suggests that this reaction is rapid (Rowe 1992 and references therein) and hence presumably that limits on the electron density based upon deuterium fractionation can be usefully derived. Some very recent observational work is discussed by Helmich et al. in poster A45 at this conference. They have observed a variety of molecular ions toward NGC2264 and W3 IRS5 and determine the ionization degree to be in the range $2\,10^{-9}$ to 10^{-8}.

4. CORE STRUCTURE AND EVOLUTION

Various authors have proposed (see Shu et al. 1987, Zhou 1992) that a natural initial condition for protostellar collapse is an isothermal sphere in hydrostatic equilibrium. This implies a spherically symmetric structure with a $1/r^2$ density distribution and there have been several recent attempts to find such a structure. In doing this, one is faced with the problem that it is difficult to find a reliable tracer and it is difficult to find a spherically symmetric core. Nevertheless, it is interesting that both Zhou et al. (1994) who observed $C^{18}O(2\text{-}1)$ using the CSO and Ward-Thompson et al. (1994) who observed sub-mm dust emission using the JCMT find difficulty in obtaining a fit to a $1/r^2$ distribution. The two studies vary both in terms of the tracer used as well as in the sense that Ward-Thompson et al. concentrated on "starless cores" (ammonia cores lacking an associated embedded infrared (IRAS) source) whereas Zhou et al. observed a mixture of cores with and without emedded IRAS objects. Both studies find that their observations are consistent with density distributions flatter than predicted by the simplest form of model of collapse of an isothermal sphere. In both cases, this may be due to "contamination" by surrounding interstellar cores associated with but not part of the hypothesised isothermal sphere. An alternative explanation for the "starless cores" is that these are objects which are still supported by their magnetic field and whose structure reflects this fact. Since the non–thermal line broadening observed in such sources is also associated with magnetic field, it would follow that such an explanation of the flat density profiles cannot apply to the cores with line-widths dominated by thermal broadening.

In fact, as pointed out by Zhou (1992), one can plot observed sizes and linewidths of cores in order to obtain an "evolutionary track". Figure 2 based on the Zhou et al. (1994) study illustrates what is meant. In this scenario, cores are thought to commence their development at high linewidth (thought to be a proxy for magnetic field) and diameter. Over a timescale of perhaps 10^6 years, cores lose field due to ambpolar diffusion and evolve slowly toward lower linewidth and size. Indeed they evolve along the linewidth-size relationship (roughly Δv proportional to $r^{0.5}$) discussed by many authors. At some point, thermal pressure and thermal broadening dominate and the density distribution (according to theory) should approach $1/r^2$. However at this point, the core should start to collapse and within a relatively short time, an infrared source should become observable. The consequence of this is the roughly vertical track shown in figure 2. Sources in this part of the diagram should be associated with infrared sources and indeed (due to the collapse) have larger linewidths. A complication here is that such young objects are in practise always found to be losing mass at large rates and this mass loss also makes itself apparent in the form of increased linewidths.

The above discussion suggests that in this case the most interesting sources are then those with the narrowest line widths. Perhaps for this reason there have been several attempts to obtain high angular resolution maps of sources such as L1498 (the data point with the lowest linewidth on fig.2). Lemme et al. (1995) have mapped $C^{18}O$ and CS using the IRAM 30-m whereas Velusamy et al. (poster at this meeting) have obtained OVRO CS observations. These maps show considerable sub-structure and it is difficult to identify the centroid of the hypothesised isothermal sphere. It is intriguing however that Lemme et al. find "self-absorbed" CS profiles of the type expected in collapsing clouds (see Zhou et al. 1993). Is this due to the effects of absorption by cold foreground material unrelated to the core or does it mean that infall at one or more positions has started? I don't think we have presently got satisfactory answers to these questions.

5. CORES IN REGIONS OF HIGH MASS STAR FORMATION

The discussion of the previous section suggests that with increasing core mass, "something different" happens and indeed that that something different is associated with formation of stars having approximately 10 $L_\odot$(Myers et al. 1991a). One reasonable expectation is that for core masses (or densities) above a certain limit, the formation of clusters similar to the Trapezium cluster becomes favored. The characteristics of the Trapezium cluster have been defined with increasing precision recently (see O'Dell 1995 in these Proceedings, McCaughrean & Stauffer 1994) leading to an estimate for the stellar density of $4.7\,10^4$ stars per cubic parsec in a region of diameter 0.1 parsec . Within the central 0.5 pc., one can estimate that there are of order 200 solar masses in the form of stars taking a typical stellar mass to be 1 $M_\odot$. This corresponds to a hydrogen number density of roughly 10^6 cm^{-3} which is not greatly different than the estimates for the OMC1 cloud. It is

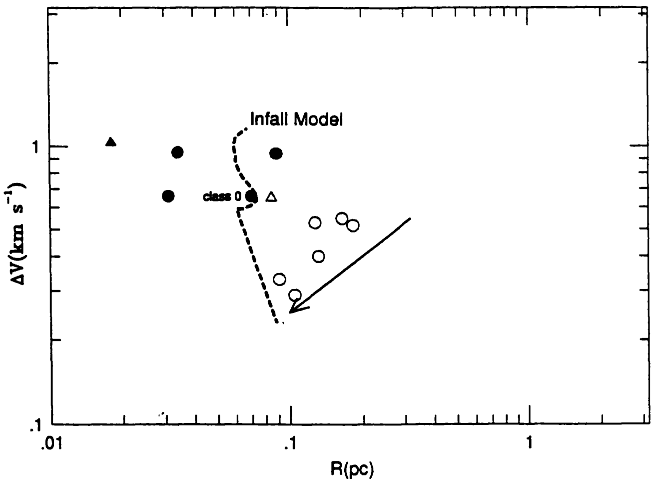

Fig. 2.— Plot of line width against size from the study of Zhou et al. (1994). Filled circles show cores associated with embedded IRAS sources whereas empty circles denote cores without associated IRAS sources. The triangles refer to the cores in L1489. The dashed (roughly) vertical line shows the expected evolution for a core which collapses according to the predictions of an inside-out collapse model. The arrow shows the direction in which contracting cores losing magnetic field due to ambipolar diffusion might evolve

thus plausible that the high density molecular cores such as OMC1 which are found associated with HII regions evolve eventually into something similar to the Trapezium cluster. This may in fact be the dominant form of star formation (Lada 1992, Larson 1994) and it appears likely to be locally to be very efficient (i.e ratio of mass in stars to mass in gas within the high density clumps of order unity) even if inefficient on the size scale of a GMC (few percent of mass of a GMC in young newly formed stars).

The best marker on a galactic scale for the early phases in the evolution of O-B clusters are the UCHII or ultra–compact HII regions. While there is discussion about the age of UCHII's (see e.g. Gaume 1994 and references therein), they clearly mark the early phases of evolution (10^5 years or less) of stars in the spectral type range O5-B0. However, in association with many UCHII's, one finds hot clumps of molecular gas with densities of order 10^7 cm^{-3} and of temperature 100 K or more. These are the "hot cores" of which the best known example is the Orion hot core (see Genzel & Stutzki 1989) .Understanding their role in the evolutionary scheme and their relationship to UCHII's is a problem of considerable current interest . One possibility is that such "hot cores" are forerunners of UCHII's which are accreting mass at a rate sufficient to "choke off" an incipient HII region.

The mass accretion rate implied by such a statement is considerable but not unreasonable. Assuming matter collapsing onto a star of mass M_* at a velocity $(GM_*/r)^{.5}$ where r is the radius , one obtains a "critical accretion rate" $dM/dt(crit)$ given by :

$$dM/dt(crit) = (4\pi\, L(LyC)\, G\, M_*\, m_H^2 \beta^{-1})^{0.5} \tag{1}$$

In the above equation, $L(LyC)$ is the Lyman Continuum photon luminosity and β is the hydrogenic recombination (n>1) coefficient. If one takes the Lyman continuum luminosity from Panagia(1973) , one finds $dM/dt(crit)$ to be 10^{-4} $M_\odot$ yr^{-1} for a 60 $M_\odot$O5 star (bolometric luminosity 8 10^5 $L_\odot$). This decreases to 4 10^{-6} $M_\odot$ yr^{-1} for a 17 $M_\odot$ B0 star (bolometric luminosity 5 10^4 $L_\odot$). If one considers the values given above for the Trapezium cluster (200 $M_\odot$) however, one realises that for a free fall time corresponding to a density of 10^6 cm^{-3} , accretion rates of order 10^{-2} $M_\odot$ yr^{-1} are indicated. Thus it is plausible that for timescales of a few thousand years, one might have accretion at rates sufficient to reduce the HII region to a small volume close to the stellar surface.

Is there good evidence for infall? Welch et al.(1988) reported inverse P-Cygni (red shifted absorption and blue shifted emission) HCO$^+$ profiles toward the UCHII's associated with W49. They estimated an accretion rate of 0.07 $M_\odot$yr^{-1} onto a parsec sized disk. A more detailed analysis has recently been carried out by Dickel & Auer (1994) who conclude that a collapse model with density varying as $r^{-1.5}$ fits the HCO$^+$(1-0) and 3-2 data. Similar phenomena have been seen toward several other sources (see Welch 1994 and references therein) including G10.6 for which quite sophisticated models have been developed (Keto et al. 1987, 1988). However, one should note that many of the regions under discussion are distant (typically more than 5 kpc) and the velocity fields are complex. A very recent study by Willner et al. (poster A38 at this conference) using the BIMA interferometer to observe HCN(1-0) and HCO^+(1-0) shows evidence for blue-shifted as well as red-shifted absorption toward several UCHII's. Red-shifted absorption appears to be more common in this sample but the statistics are not good enough to conclude (for example) that infall toward the exciting star of the UCHII is the dominant dynamical process.

A better guide than HCO^+(1-0) might be thought to be absorption seen in some tracer of the hot dense gas close to the UCHII. Olmi et al. (1993) have considered high excitation ammonia lines toward UCHII's and conclude (but on the basis of 5 sources) that red-shifted and blue-shifted absorption lines (relative to the emission line velocity) were equally likely. Olmi et al. also considered the statistics of velocity differences between the ionized and the molecular gas and found no trend in this case either.

Part of the complexity in the observed velocity patterns is likely to be due to outflows in the regions concerned. The outflow which appears to be associated with Orion-IRC2 has been estimated to have a mass loss rate of 10^{-3} $M_\odot yr^{-1}$ (Genzel & Stutzki 1989). Towards W3OH, there is evidence that there is an outflow associated with the water maser core whose outflow rate may be as large as 0.005 solar masses per year (Wink et al. 1994). Other examples have been studied by Shepherd & Churchwell (poster A26 at this meeting). How can this be reconciled with the *infall* that one requires to form compact O-B clusters. Shu et al. (1991) show that models of bipolar outflows powered by infall via a disk are a possibility. While these ideas have been developed for low mass star forming regions, there seems to be no obvious reason why they should not apply also to much more massive objects. In this case, one expects mass outflow rates to be *of the same order* as the accretion rates and thus to zero order the measured outflow rate gives a measure of the (more difficult to measure) inflow. Hence, the outflows seen in Orion and W3(OH) suggest that accretion may be occuring with rates of order 0.01 $M_\odot yr^{-1}$.

In the following discussion, we give some examples of massive clumps or cores which we suspect are in a phase prior to the formation of an O-B cluster.

5.1. The Hot Core Associated with G31.41+0.31

One of the most remarkable hot cores is that associated with the UCHII region G31.41+0.31. This object attracted attention in the NH_3(4,4) survey of Cesaroni et al. (1992) as having both an extremely large ammonia column density and a high temperature. The column density was sufficiently high that the hyperfine satellites of the (4,4) line were detected (their intrinsic intensity is only 1.8 percent of the main (4,4) component). Further investigation using the VLA showed that much of the ammonia (4,4) emission (Cesaroni et al. 1994a) was coming from a region 0.1 parsec in diameter with a temperature of order 120 K. The results suggested that millimeter interforemetry would be profitable and 110 GHz observations centred on the methyl cyanide 6-5 transitions were consequently carried out with the IRAM Plateau de Bure array (Cesaroni et al. 1994b).

The results of this latter study were surprising for at least two reasons. One was that a 2.7 mm (110 GHz) continuum source was found that did not seem to have a 1.3 cm counterpart. There is good reason to believe that this source is due to dust emission but the mass implied on this hypothesis is extremely large (of order 1000 $M_\odot$). This is a lot within a region 0.1 parsec in size ! The other surprise was an apparent velocity shift across the region mapped in methyl cyanide. The interpretation of this is debatable but one possibility is rotation and in this case, the inferred mass is also of order 1000 $M_\odot$. However, the angular resolution only just suffices to resolve the methyl cyanide clump and thus the above conclusions are very tentative.

5.2. The Molecular Cores within W3

The high density core associated with the W3 HII region complex have been the subject of several recent studies. Richardson et al. (1989) using the JCMT showed that the infrared sources IRS4 and IRS5 are both associated with massive molecular cores (of order 1000 $M_\odot$) of sizes less than 0.5 parsec. Embedded in the IRS5 core, Claussen et al. (1994) have found 7 weak radio continuum sources with fluxes suggesting ionization by early B stars. There is thus direct evidence that a young cluster is forming in a region roughly 0.03 parsec in extent.

The IRS5 core is hot (100 K according to Helmich et al. 1994) but not as hot as the gas surrounding the water maser complex associated with W3OH (150-200 K). Wink et al. (1994) haved used the Plateau de Bure interferometer to map this region in $C^{18}O$ and CH_3CN. They find a 60 $M_\odot$ core 0.05 parsec in size surrounding the water masers . It also surrounds a curious non-thermal radio continuum source which has recently been studied by Reid et al. (1995). Rather surprisingly, Wink et al. find that there is much less molecular gas associated with the well known UCHII region 0.1 parsec to the west.

Helmich et al. (1994) have attempted to use their submillimeter line data toward the cores in W3 to rank the various cores in the region in order of evolution. They conclude for example that the star formation associated with IRS4 took place around 10^5 years ago and this has given time for the chemical abundances in the molecular core to reach the "standard" Orion ridge values as observed. The core around the W3(OH) water masers by contrast shows a "hot core" abundance distribution and Helmich et al. suggest that it is younger by a factor of 3 or so. IRS5 may be still younger based on the fact that the temperature is lower and abundances of species such as methanol are low suggesting that they are still depleted onto grain surfaces. However the CO outflow associated with this source has an estimated dynamical age of $2\,10^4$ yr (Mitchell et al. 1992) and hence the age difference is unlikely to be large. Moreover Tieftrunk et al. (1995) suggest that the IRS4 core (which they find on the basis of their $C^{18}O$ measurements is the more massive of the two) is the younger precisely because it shows fewer indications of star formation. This is a controversy which may be with us for some time.

5.3. The Cores and UCHII's in G9.62

Another region to which a considerable amount of recent work has been devoted is the complex of cores and compact ionized regions associated with the UCHII region G9.62 . This source appears to be associated with the 3 kpc arm of our galaxy. It is notable both due to its methanol maser emission (Menten 1991, Norris et al. 1993) and because a "unique" maser in the NH_3(5,5) transition has been detected toward G9.62 (Cesaroni et al. 1992, Hofner et al. 1994). Hofner et al. (1994, see also Cesaroni et al. 1994a) found that in addition to the maser in NH_3(5,5), there was a compact source of "thermal" ammonia emission more or less coincident with the water maser spots found in G9.62. The various star formation indicators (hot ammonia clumps, UCHII's, water masers) are all found along a narrow line of roughly 0.5 parsec in extent and less than 0.05 parsec in width. Figure 3, taken from Hofner et al. (1994), illustrates this alignment.

These characteristics again suggested that higher frequency interferometric observations would be interesting. G9.62 (like G31.41) was found to have strong methyl cyanide emission (Olmi et al. 1993). Experience seems to show (see e.g. Wink et al. 1994) that methyl cyanide is an excellent tracer for hot cores. In particular, the higher excitation transitions show little extended emission which (due to lack of short spacing information) confuses many molecular line interferometric maps in more abundant species. With this in mind, Hofner et al. (1995) have recently observed CH_3CN(6-5) and $C^{18}O$(1-0) toward G9.62 using the OVRO interferometer. They find indeed that the hot core methyl cyanide emission is coincident with the hot core ammonia emission. However they also find a millimeter continuum source toward the "hot core" associated with the water masers (i.e toward the northern portion of the "thermal ammonia" clump seen in figure 3) which does not appear to have a VLA counterpart. There is also methyl cyanide emission and a continuum source associated with the NH_3(5,5) maser.

Although again it is debatable, one is tempted to think that one is observing different stages in the evolution of a few hundred solar mass clump into a cluster whose earliest member is late O or early B. In this scenario, the UCHII C is the most advanced object having dispersed its mother molecular clump while the hot ammonia cores represent the earliest evolutionary stages. The core corresponding to the 3 mm continuum source would then be the youngest of these clumps and the regions associated with ionized gas would be older. An alternative interpretation is possibly that the masses of the associated embedded objects differ and that the 3 mm core without free-free emission is powered by a star of late B type. We do not have good estimates of the individual bolometric luminosities of these cores. However, the high temperatures inferred from the molecular line data make it seem probable that a relatively luminous star is embedded in the molecular clump.

5.4. The Core Associated with IRAS 20126

Presumably qualitatively similar to the hot cores discussed above are several luminous IRAS sources associated with water masers but without associated radio continuum emission. An example is the object IRAS 20126+4104 which is a red IRAS source of approximately 10^4 $L_\odot$ associated with a CO outflow (Wilking et al. 1990). The IRAS source is associated with strong H_2O maser emission but VLA observations show no associated continuum source (Felli, priv. comm.).

Recent 30-m observations however (Felli et al. in preparation, Wilking priv. comm.) show that also associated with the IRAS source is a compact core detected in various transitions of CH_3CN and CH_3OH as well as in CS(5-4). A fit to the methyl cyanide data implies a temperature of roughly 90 K. Earlier 3 mm continuum observations by Wilking et al. (1989) suggest a mass of 50 $M_\odot$ for this core. When all this is taken

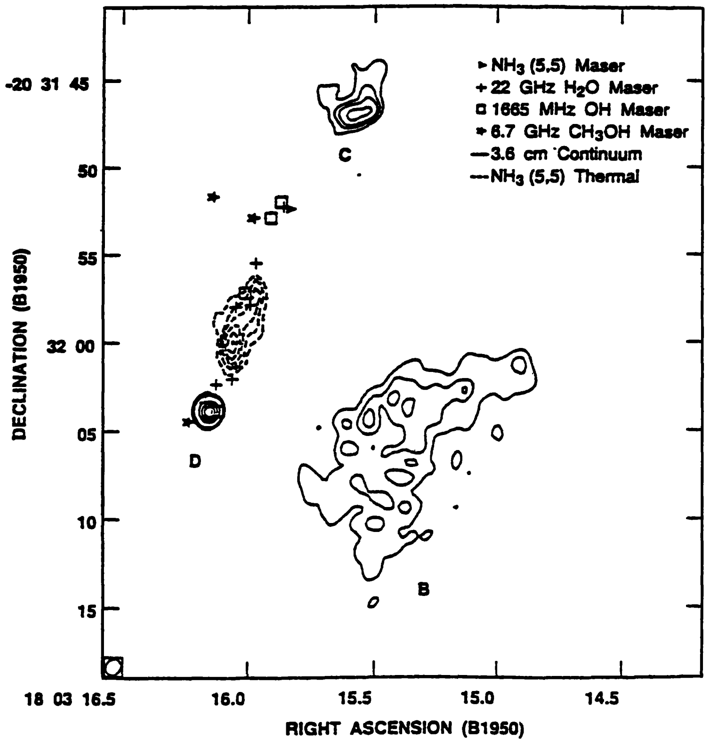

Fig. 3.— Comparison taken from Hofner et al. (1994) of various star formation tracers toward G9.62+0.19. The full contours are the 3.6 cm continuum emission from Kurtz et al. (1993). The dashed contours show the $NH_3(5,5)$ thermal emission and the crosses are water masers (Hofner et al. 1994). Methanol and OH masers are shown as stars and empty squares respectively. The filled triangle shows the position of the $NH_3(5,5)$ maser. The line of star formation tracers referred to in the text stretches from the compact UCHII region D in the east to the somewhat more extended UCHII C in the north.

together, it appears similar to the core without associated ionized gas in G9.62 discussed above. IRAS 20126 is however closer and may be simpler to analyze.

6. COLD DENSE CORES WITHIN HIGH-MASS STAR FORMING REGIONS

A question which has been ignored in the above discussion is that of whether there is a phase in the evolution of high mass cores where the cores are cold and dense. As pointed out by Mundy (1994), one would expect that there is a stage in the star formation process when "the future star is but a twinkle in the eye of some centrally condensated condensation in the cloud". Moreover in the case of cluster formation, it seems quite likely that the future components of the cluster are present in some form prior to the moment in which an early type O star ionizes their surroundings causing them to be visible. Thus one might expect a high degree of lumpiness in molecular cores whose mass is substantially greater than stellar masses.

When one looks with sufficiently high angular resolution, one does in fact find evidence for such lumpiness. However, it often turns out that the lumps are filamentary in appearance. A striking example is given by the $NH_3(1,1)$ map of Wiseman & Ho (1994) where one sees streamers 0.2-0.5 parsec in length oriented approximately radially relative to the Orion-KL core. These "fingers" are not special to ammonia. Similar structures are seen in maps of HCN (Schilke et al. 1992), and HC_3N (Martín-Pintado et al. 1990). And one finds filamentary like structures elsewhere in the L1641 cloud as evidenced by the HH1-2 map of Torrelles et al. (1994).

Within these streamers or filaments are what one may call clumps. The most detailed determinations of physical parameters have been made for the M17 cloud core (Wang et al. 1993, Stutzki & Güsten 1990). Wang et al. (1993) use their CS data to show that the density is fairly uniform at a value of around $5\,10^5$ cm^{-3} throughout the M17 core. The structure one observes reflects varying beam filling factor but there is no evidence for higher density toward the column density peaks. There is also no evidence for objects which are both colder and denser than average.

Such evidence however might be difficult to obtain. Observational biases (the lines are stronger) cause one to tend to detect hot clumps in particular if the surroundings are hot. Cold dense clumps are hard to distinguish against the background in regions such as M17 and Orion. The problem is made worse due to the fact that cold dense regions are precisely those where accretion onto grain surfaces is most likely. Mezger et al. (1988, see also Mezger 1994) have presented evidence for the existence of cold dust condensations ("isothermal protostars") of mass of order 10 $M_\odot$ associated with the HII region NGC2024. These condensations are observed in the millimeter and sub–millimeter wavelength region by virtue of their dust emission but are not prominent in molecular line emission suggesting depletion of heavy elements into ices. This poses the general question of whether our view of star-forming regions is being greatly biased due to depletion of C,N,O.

The problem has been discussed in the context of NGC2024 by Walmsley & Güsten (1994) who point out that even if (as seems probable) there is a considerable amount of depletion in cores such as NGC2024 FIR3, it nevertheless seems likely that molecules are observable from these regions. The basis for this is that the available calculations show (see e.g Pineau des Forêts et al. 1992) that certain species remain abundant even when (say) 99 percent of the available C,N,O is in solid form. In the Pineau des Forêts et al. (1992) models for example, the ammonia abundance stays roughly constant at a value of about 10^{-8} (factor of 3 variation) as the depletion factor for C.N,O varies between 1 and 1000. Moreover, Gaume et al. (1992) give a qualitative confirmation of this by detecting NH_3 with the VLA toward some of the cold clumps in NGC2024 where depletion is thought to have taken place. The conclusion is thus that one can hope to study highly depleted regions using molecular lines if one chooses the right tracer. This is of some importance in that it means that one can hope to learn something about the kinematical structure of "isothermal protostars".

Notwithstanding the above, it seems probable that sensitive studies of the millimeter and sub-millimeter dust emission from star forming regions is giving us insight into the structure of both high and low-mass star forming regions. This is an area which one can expect to expand considerably in the years to come. The availability of both bolometer arrays (Zylka 1995) and millimeter interferometers (Carlstrom et al. 1995 in these Proceedings; Sargent in her conference talk) should allow us to gain more insight into the importance of cold dense cores in star-forming regions.

7. FUTURE WORK

The future of this topic is difficult to predict in detail but some general points are clear. It has already been pointed out that the advent of bolometer arrays should allow us to obtain high quality information on the structure of nearby cores. Similar arrays of heterodyne receivers will allow us to obtain complementary information on the kinematics. And interferometry both at centimeter and millimeter wavelengths will probe the structure within the structure. Most importantly, interferometry allows us to analyze the embedded stars and clusters of stars which are the root cause of much of the complex dynamical behavior seen in cores associated with star formation. There may often be a symbiotic relationship between young stars and their associated cores (see Franco 1993 for a discussion of such relationships on a rather larger scale). Understanding this will require studies of the structure of the stars as well as of the gas.

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