HOT MOLECULAR CORES AND THE EARLIEST PHASES OF HIGH-MASS STAR FORMATION

STAN KURTZ
Universidad Nacional Autónoma de México, Mexico

RICCARDO CESARONI
Osservatorio Astrofisico di Arcetri, Firenze, Italy

ED CHURCHWELL
Washburn Observatory, University of Wisconsin-Madison, U.S.A.

PETER HOFNER
University of Puerto Rico, Puerto Rico and Arecibo Observatory, NAIC

and

MALCOLM WALMSLEY
Osservatorio Astrofisico di Arcetri, Firenze, Italy

We review recent observational results in the field of high-mass star formation. Special attention is given to the earliest evolutionary stages of massive stars through the study of hot, dense molecular cores and ultracompact HII regions. The characteristics of these two classes of objects are illustrated in some detail, emphasizing the role of hot cores as sites of massive star formation. Finally, a possible scenario for an evolutionary sequence from hot cores to ultracompact HII regions is proposed.

I. INTRODUCTION

High-mass stars ($\gtrsim 10\ M_{\odot}$) have gained steadily increasing attention in star formation research. As our understanding of low-mass star formation improves, and as observational power increases, we are better equipped to approach the study of massive star formation. More distant, more heavily obscured, more rapid in their evolution, and more strongly interacting with their environment, high-mass star formation is often considered to present a greater challenge than low-mass star formation. Yet the topic demands our attention. The profound effects that massive stars have on the interstellar medium — from cradle to crypt — and their contribution to the galactic environment and evolution, attest to their important place in astronomical studies.

In this review we present an overview of the results obtained with radio continuum and line observations of OB star forming regions. Our discussion is confined to the dense, hot environment in the inner parts of molecular clouds where massive star formation is proceeding. Historically, ultracompact (UC) HII regions have been the primary means to investigate the earliest phases of OB star evolution. Recent studies suggest that "hot cores" represent an even earlier stage in the star formation process. These two classes of objects form the heart of massive star formation. We place special emphasis on them in this review and ultimately propose an evolutionary scenario leading from one to the other. We neglect many important topics such as theory, bimodal star formation, comparison with low-mass star formation, and the important contributions of recent infrared observations, to name only a few. The reader is directed to a number of very relevant chapters elsewhere in this volume, which include the theory of intermediate and high mass star formation (Stahler, Palla and Ho) and various observational aspects of low mass star formation (Andre, Barsony and Ward-Thompson; Myers, Evans and Ohashi; Mundy, Welch and Looney). We first discuss some of the strategies used to locate massive star forming regions (Sec. II); we then discuss some of the results and implications of these searches, first for the ionized gas component, i.e., UC HII regions (Sec. III) and then for the molecular gas component, i.e., Hot Cores (Sec. IV). We examine the evolutionary link between them in Sec. V.

II. THE SEARCH FOR HIGH-MASS (PROTO)STARS

The evolution of massive stars is characterized by shorter time scales than for low-mass objects. The precise duration of each evolutionary phase is unclear, but a lower limit to the time-scale for the formation of a massive protostar through collapse is the free-fall time. This is $\gtrsim 10^4$ yrs, which implies a non-negligible probability of finding a protostar in a typical high-mass star-forming cloud. Observational investigation is hence feasible.

Typically, the role of observations is twofold: surveys are important for statistical purposes and to determine the time spent in each phase, while detailed physical and chemical studies of individual objects are needed to clarify the mechanisms of star formation. In view of these goals, a proper observational approach to the study of young massive stars must rely on two basic choices: a suitable tracer and a sensible sample of targets.

A massive star forms from the contraction of at least 10 $M_\odot$ concentrated in a region comparable to the mean star separation observed in clusters, i.e., $\lesssim 0.05$ pc (McCaughrean & Stauffer 1994; Hillenbrand

1997; Testi et al. 1997). The consequent release of gravitational energy in such a small region must increase the gas and dust temperature. As a consequence, observations of molecular transitions excited at high densities and temperatures, $\gtrsim 10^7$cm^{-3}and $\gtrsim 100$ K, (Blake et al. 1996; Cesaroni et al. 1991; Churchwell et al. 1990; Hofner et al. 1998; Wyrowski 1997) or of the (sub)millimeter continuum (Jenness et al. 1995; Olmi et al. 1996b; Wyrowski et al. 1997; Shepherd et al. 1997; Carral et al. 1997; Hunter et al. 1998) are appropriate to investigate the dusty molecular envelopes around forming stars.

While the choice of the tracer is relatively easy, the selection of a sample of young and luminous (i.e., massive) targets is non-trivial. It is commonly accepted that phenomena such as maser emission, IRAS point sources, UC HII regions, and molecular outflows are signposts of high-mass star formation (see e.g., Wright et al. 1996 and references therein for Orion). However, apart from UC HII regions, a *physical* connection between such phenomena and the birth of massive stars is far from established. Nevertheless, these signposts are useful criteria for selecting candidate massive star formation regions and a number of such searches have been made. We classify them in three distinct types depending on the selection criteria, and discuss them below.

Searches for Protostars towards UC HII *Regions.* The tendency of OB stars to form in clusters and associations is well known. Moreover, the presence of a range of stellar ages and even continuing star formation within a pre-existing association has been established (Blaauw 1991 and references therein). Although debate persists over their lifetimes, UC HII regions probably represent a relatively young stage of stellar development. Clustering is evident even at this early stage, with DR21, W3, W49, W51, NGC6334 and NGC7538 being some of the better known examples. Given the relatively short timescales characteristic of massive star formation, and the observational evidence cited above, it seems clear that some (nearly) coeval massive star formation must occur. As such, the sites of young massive stars, as traced by UC HII regions, are likely candidates in the search for massive (proto)stars in earlier evolutionary states. Indeed, many of the known hot cores were first identified by Churchwell et al. (1990) using a sample of UC HII regions as their targets.

Searches for Protostars towards IRAS Point Sources. Since the advent of the IRAS era, the IRAS Point Source Catalog has been used to identify samples of objects on the basis of their far-infrared (FIR) colors. The most successful applications of this method to massive star formation have probably been the searches for H_2O masers (Braz and Epchtein 1987; Scalise et al. 1989; Palla et al. 1991, 1993) and UC HII regions (Wood and Churchwell, 1989a; Kurtz et al. 1994; Miralles et al. 1994; Kurtz and Churchwell 1999). In both cases, the high detection rates achieved demonstrate the efficacy of the method. The method is clearly empirical, however, and the physical connection between the FIR emission and the radio objects remains uncertain. This is reflected in the variety of color and flux density criteria that have been proposed. This caveat notwithstanding, selection criteria based on the FIR emission are plausible because very young massive stars must be better seen at $\sim$100 μm, where their continuum emission is expected to peak. Some contamination is likely, because a variety of objects may present an infrared appearance similar to that of massive star formation regions. Nevertheless, one can expect that a worthwhile fraction of IRAS selected objects represent bona-fide massive (proto)stars, particularly if the IRAS criteria are combined with other massive star formation indicators.

Searches for Protostars towards H_2O Masers. Various evidence indicates that most water masers are associated with the formation of massive stars. Extensive surveys in the 22 GHz masing line of H_2O (Comoretto et al. 1990; Brand et al. 1994; Matthews et al. 1985) indicate that nearly all ($\gtrsim$90%) H_2O masers in star forming regions have IRAS counterparts with luminosities above 10^4 $L_\odot$ (see Fig. 10b of Palagi et al. 1993), indicating zero-age main-sequence stars earlier than B1. Water masers are also associated with molecular outflows (Felli et al. 1992; Xiang and Turner 1995) and possibly with disks (Torrelles et al. 1996, 1997, 1998; Fiebig et al. 1996). The high temperatures (several 100 K) and densities (10^8–10^{10} cm^{-3}) required to excite the maser line suggest that H_2O masers arise in the hot, dense surroundings of an embedded young star. These characteristics make H_2O masers excellent targets in the search for luminous embedded young stellar objects (YSOs).

III. THE IONIZED COMPONENT: UC HII REGIONS

In this section we discuss some of the results obtained from searches for young massive stars, focusing in particular on the ionized component: UC HII regions. These nebulae represent one of the earliest manifestations of OB stars.

A. UC HII Regions and the Lifetime Problem

UC HII regions have received increased observational and theoretical attention in recent years, particularly stemming from the seminal works of Wood and Churchwell (1989a; 1989b). The interest in these objects is partly because they are unambiguous indicators of young early type stars. The "compactness" (i.e., the small diameter) of the HII region is *presumed* to be proof of its youthfulness. However, any plausible definition of "UC HII region" must also require large electron densities or, equivalently, emission measures, to distinguish HII regions ionized by O or early B stars from those caused by other processes (e.g., shocks associated with mass loss). In the following we somewhat arbitrarily define UC HII regions to be ionized by stars of spectral type B0 or earlier and characterized by diameters $\lesssim 0.1$ pc and electron densities $\gtrsim 10^4$ cm^{-3}. From an observational point of view, such a definition implies that at a wavelength of 1.3 cm and a distance of 5 kpc, an optically thin UC HII region would present a continuum flux density ~100 mJy and a diameter of $\sim 4''$. Such a region would be detectable (at a 1 mJy limit) anywhere in the Galaxy (see Fig. 3 of Churchwell 1991). The spectral type B0 is chosen because the Lyman continuum flux begins to fall rapidly with decreasing effective temperature at this point (Panagia 1973). We caution, however, that if the cut-off were placed somewhat lower (at B2 or B3) the number of UC HII regions might increase significantly.

Much of the research on UC HII regions has touched in some way on the "lifetime problem" (Wood and Churchwell 1989a). One expects the HII region surrounding an O star to be over-pressurized relative to its surroundings due to its high temperature ($\sim 10^4$K). It should thus expand at roughly the sound speed of the ionized material (c_{II} ~10 km s^{-1}), giving a "lifetime" of order r/c_{II} for an HII region of radius r. This lifetime is of order 10^4yr. Many more UC HII regions are seen than this naive view predicts, hence their lifetimes must be longer than anticipated. It is worthwhile to assess the state of this issue, to see if it still constitutes a "problem."

B. Radio Continuum Surveys of UC HII Regions

The Wood and Churchwell (1989a; 1989b) studies proposed color criteria that identified over 1600 IRAS-selected UC HII candidates. Many follow-up studies searched for radio continuum counterparts to these IRAS sources, and, in some cases, suggested that the color criteria had significantly over-estimated the number of UC HII regions and hence of young, early-type stars. These surveys were made in both "biased" (towards selected targets) and "unbiased" modes. Among the former are the Kurtz et al. (1994) and Kurtz and Churchwell (1999) surveys; examples of the latter are the galactic plane VLA surveys of Zoonematkermani et al. (1990) and Helfand et al. (1992) at 1.4 GHz and by Becker et al. (1994) at 5 GHz. Although low frequencies are not optimal to detect UC HII regions, the unbiased nature of the latter surveys allows a valuable check of the color criteria.

The main result of the galactic plane surveys is the identification of ~470 probable UC HII regions between 350° and 40° longitude. The galactic latitude distribution of these regions is much narrower (FWHM$\simeq$0$^\circ\!\!.$25 or 35 pc at a distance of 8 kpc) than that of sources defined solely by the IRAS color criteria (1°). White et al. (1991) interpret this as meaning that these radio surveys detect sources with larger Lyman continuum luminosities (i.e., O stars), while about 1/3 of the Wood and Churchwell (1989b) sample would contain nearby late B stars. Ramesh and Sridharan (1997) correlate single-dish radio continuum surveys with the IRAS UC HII candidates and conclude that only about 1/4 of the Wood and Churchwell sample are UC HII regions.

A weakness of the continuum surveys is that they lack distance estimates for the sources. This problem has been partly resolved by Codella et al. (1994), and Bronfman et al. (1996) who report spectral line velocities. Codella et al. (1994) studied a sample of IRAS sources detected in radio recombination lines, most of which satisfy the UC HII color criteria. They develop a 60 μm flux density cut-off (of 100 Jy) below which the probability of association with an HII region drops considerably. Forty-four percent of the Wood and Churchwell candidates fall below this cut-off. Bronfman et al. (1996) searched for CS emission toward ~1430 of the Wood and Churchwell sources — 90% of the total — and had detections in about 60% of these, suggesting that at least 40% of the candidates are not massive embedded stars.

From these studies, one can reasonably conclude that from 25% to 75% of the IRAS sources satisfying the Wood and Churchwell (1989b) criteria are not associated with early-type stars. A correction by a factor ~4 of the number of embedded massive stars in the galaxy, and hence on the lifetime of the UC phase of HII regions, is not negligible. However, several further considerations are in order.

First, multiple UC sources are frequently found in a single IRAS field. The number of embedded stars may be nearly double the number of IRAS-identified candidates for this reason. Also, the expected number of UC HII regions can vary by factors of two or three depending on the assumptions made for the number of ionizing photons available as well as the details of the expansion of the HII region.

Another consideration is that several surveys suggest that IRAS criteria actually *under*-estimate the number of galactic UC HII regions. Ellingsen et al. (1996; see also Caswell 1996) find that only half of the roughly 50 CH_3OH masers they detected can be identified with IRAS sources with UC HII region colors. They suggest that the Wood and Churchwell (1989b) criteria under-estimate the number of UC HII regions by a factor of two. The galactic plane surveys mentioned above suggest that about one third of the Wood and Churchwell sample is contaminated by lower mass stars. Yet these same surveys detect a significant number of UC HII regions without any IRAS counterpart: Becker et al. (1994) conclude that about 1/3 of existing UC HII regions are missing from the IRAS catalogue. Part of the problem may be incompleteness of the Point Source Catalog in areas of high confusion; it would be useful to study MSX and IRAS HIRES data.

In conclusion, it seems likely that the actual number of galactic UC HII regions differs by a factor of 2 or 3 from the estimate of Wood and Churchwell (1989b). It seems unlikely, however, that they overcounted by the factor of 10–20 that is required to resolve the lifetime problem. Therefore the disparity seems real, and at least six proposals have been made to resolve it. They fall into two general categories: those which question the underlying assumptions of the argument, and those which propose physical mechanisms to extend the life of these regions beyond that predicted by classical expansion. We consider these in turn, beginning with the latter category.

C. Solutions to the Lifetime Problem

1. Mechanisms to Extend the Lifetime. Wood and Churchwell (1989a) noted that the ram pressure of infalling matter and/or bowshocks might extend the time in the UC phase. Since then, other theories have been developed, including photo-evaporating circumstellar disks (Hollenbach et al. 1994; Yorke and Welz 1996, Richling and Yorke 1997, Hollenbach, Yorke and Johnstone, this volume) and mass-loaded flows (Dyson, Williams and Redman 1995; Lizano et al. 1996). The photo-evaporating disk model makes the reasonable assumption that a recently formed massive star will have a remnant accretion disk. The combined effect of a stellar wind and the ionizing photon flux causes photo-evaporation of the disk. In this model, the ionized gas is not *confined* on timescales of 10^5 yr, but rather is *replenished* by the evaporating disk material. Similarly, mass-loaded flows act to replenish, rather than confine, the ionized gas. In this case, clumps of neutral gas, embedded within the HII region and reasonably supposed to exist within a clumpy cloud, are the source of the replenishing gas. Through a combination of photoionization and hydrodynamic ablation, this clump material is injected into the HII component.

Observational tests of these models will be challenging. For disk photoevaporation, the so-called weak wind case generally applies to unresolved sources and strong observational confirmation is unlikely. The strong wind case, applicable to resolved sources, does make specific predictions for the spectral index of the emission. High quality, high angular resolution images will be required to test these predictions, and, practically speaking, the results are likely to be somewhat ambiguous. The detection of the so-called PIGs which may give rise to mass-loaded flows is perhaps even more challenging. These neutral globules might be seen in various molecular tracers. But to detect such emission, in the midst of a UC HII region and possibly confused with the surrounding molecular material, would be extremely challenging. The externally ionized nature of the PIGs might be confirmed by measurement of their spectral index (Pastor, Cantó, and Rodríguez 1991), but again, such observations would be difficult.

Much of the theoretical work on UC HII regions has avoided the issue of the observed morphologies. Notable exceptions are the work of Dyson, Williams and Redman (1995) and also that of Kessel et al.

(1998). In the former case, kinematic information would be useful to test their model for the cometary morphology, but it is not clear if the expected velocity gradients can be uniquely distinguished from those predicted by other models.

2. Reassessing the Lifetime Problem Assumptions. The underlying assumptions of the lifetime problem are questioned by De Pree et al. (1995) who point out that recent molecular line data suggest that more realistic values for the density and temperature of the circumstellar molecular gas are 10^7 cm^{-3} and 100 K, increasing the ambient pressure by a factor of 400 over that assumed by Wood and Churchwell (1989a), and resulting in smaller radii, both of the initial Strömgren sphere and of the final expanded region in pressure equilibrium with the ISM. In fact, HII regions would still be classified as UC even when they had reached pressure equilibrium with such a high pressure environment. Akeson and Carlstrom (1996) develop this argument further, both underscoring the denser, warmer cores that we now find and also refining the expansion model beyond that of the strong shock approximation. An even more detailed examination of the expansion phase is given by García-Segura and Franco (1996).

Xie et al. (1996) note that the parameters suggested by De Pree et al. would result in regions with emission measures of order 10^{11} pc cm^{-6}. To date, the highest emission measures found are $\lesssim 10^{10}$ pc cm^{-6}. Such regions would remain optically thick into the millimeter range, however, and existing surveys would probably not detect them. Xie et al. note that turbulent pressure – whether hydrodynamic or hydromagnetic in nature – can provide the high ambient pressures needed to confine the HII region, and because the pressure does not arise from very high densities the prediction of large emission measures is avoided.

IV. THE MOLECULAR ENVIRONMENT: CLUMPS AND CORES

Probably the most significant finding in recent studies of high-mass star-forming regions is the detection of dense gas around high-mass star formation signposts such as those discussed in Sec. II. The most salient features are the extent of these gaseous clumps (almost 1 pc in size) and the existence of embedded denser, hotter molecular cores. The latter are very often positionally coincident with H_2O (and sometimes OH) masers but often do not seem to be physically connected with the nearby UC HII region (if any). Figure 1 shows an example of this: the UC HII region G29.96–0.02 (seen in the 1.3 cm continuum) is embedded in a molecular clump traced by the $C^{34}S$(5–4) line and lies close to a compact core mapped in CH_3CN(6–5).

A single nomenclature to describe the molecular environment in star forming regions has not yet emerged in the literature. We adopt the term "molecular clump" to signify the large ($\sim$1 pc) regions of molecular gas and we use "hot core" to signify the high density, hot condensations within the molecular clumps. In this section we discuss the molecular gas in high-mass star formation regions, with special attention to hot cores and to their role as massive star formation sites. A more extensive review is given by Evans (1999).

A. Molecular Clumps

There is compelling evidence that high-mass star formation is related to the formation of clusters and associations inside molecular clouds. O stars do not form as "single spies" but "in battalions" and hence understanding O-star formation involves understanding cluster formation (e.g., Blaauw 1991; Zinnecker et al. 1993). It is useful to compare the mass distribution in young clusters with that observed in the associated molecular clouds and to determine the gravitational effect of the stars upon the gas and vice-versa.

For the Orion Nebula/Trapezium cluster, Hillenbrand and Hartmann (1998) find evidence that the cluster is elongated north-south, as is the background molecular cloud, suggesting a relation between the two. Within the central 2 pc of the cluster they estimate 1800 $M_\odot$ in the stellar component. The mass of the background cloud has been inferred from molecular emission maps (Goldsmith et al. 1997, Bally et al. 1987, Castets et al. 1990) and is consistent with a surface density of between 1000 and 1600 $M_\odot$ pc^{-2}, which is within a factor of $\sim$2 of the stellar surface density mentioned above. One concludes that gas and stellar masses are similar and that a dynamical effect of one upon the other is probable. It is worth noting that the stellar mass within 0.16 pc of the Trapezium cluster corresponds to a volume density of $n_{\mathrm{H}_2} \simeq 4 \times 10^5$ cm^{-3}, similar to the n_{H_2} of molecular clumps in regions of high-mass star formation.

Molecular aggregates similar to OMC1 can be observed throughout most of the Galaxy in contrast to the stellar component of the Orion Nebula cluster. Thus, using H_2O masers, UC H II regions, or IRAS sources as tracers of high-mass star formation, several studies have been made to search for high-mass ($>$1000 $M_\odot$) compact ($\lesssim$1 pc) clumps and to estimate their parameters. Examples are the works of Churchwell et al. (1992), Cesaroni et al. (1991), Plume et al. (1992; 1997), Hauschildt et al. (1993), Zinchenko et al. (1995), Molinari et al. (1996), and Juvela (1996). Of these, the most extensive studies are those of Plume and collaborators, who observed the CS(2–1), (3–2), (5–4), and (7–6) transitions toward 150 galactic water masers. The critical densities of these transitions range between 4×10^5 cm^{-3} and 2×10^7 cm^{-3} and thus they are well-suited for density estimates of molecular clumps.

Plume et al. (1997) find a mean density of 8×10^5 cm^{-3} in the clumps, similar to the estimates cited above for Orion. They also derived clump diameters and hence masses for a few sources. For the mass estimates, they used three approaches: the estimated number density and size ($M_{\rm n}$); the estimated CS column density and size ($M_{\rm N}$) with an assumed CS abundance; and the virial theorem ($M_{\rm v}$). They find that on average $M_{\rm n}$ and $M_{\rm N}$ agree, though with considerable dispersion. On the other hand, $M_{\rm v}$ is typically an order of magnitude smaller than $M_{\rm n}$, perhaps due to low volume filling factors.

Although it is debatable, we would argue that due to the filling factor problem, more reliable masses for dense molecular clumps can be derived either from measurements of optically thin CO isotopomers or based on millimeter dust emission. Both of these approaches have difficulties, mainly stemming from the use of a surrogate for molecular hydrogen. For six well-studied objects, in Figure 2 we compare masses derived from submillimeter continuum maps (Hunter, 1997) with masses based on $C^{17}O$ observations (Wyrowski, 1997). Although there is considerable dispersion, the various methods generally agree within an order of magnitude. These differences are at least in part due to temperature gradients on angular scales smaller than the single dish resolutions used for the studies of Figure 2.

The studies cited above demonstrate that molecular clumps of size $\sim$1 pc and mass $\sim 10^4\ M_\odot$ are common in high-mass star forming regions. Their masses are of the same order as the virial mass and hence they are likely to be gravitationally bound though not necessarily stable. How long will such gas clumps survive? Plume et al. (1997) estimate a period of 10^7 yrs for the conversion of the molecular gas into stars. We take this to be a maximum value since ablation by HII regions, supernovae, etc. are not included (cf. Franco, Shore and Tenorio-Tagle, 1994). A minimum lifetime is given by the free-fall time of $\sim 10^4$ yrs.

B. Hot Cores

The molecular gas associated with UC HII regions and H_2O masers often shows strong emission in lines excited at temperatures >100 K and densities $>10^6$ cm^{-3}, even when the observations are carried out with low angular resolution ($\gtrsim 10''$). This suggests that such lines arise from compact, optically thick hot cores, the existence of which is confirmed by high angular resolution ($\lesssim 1''$) observations.

Hot cores (HC) may be defined physically as having diameters $\lesssim 0.1$ pc, densities $\gtrsim 10^7$ cm^{-3}, and temperatures $\gtrsim 100$ K. Observationally, they are characterized by large molecular line optical depths and high line brightness temperatures (when resolved). HC are also rich in rare molecular species.

In Table 1 we list all HCs known to date with their main physical parameters. These parameters have been determined by a variety of means and must be taken with caution: for a given object the temperature estimate can easily vary by a factor of 2 and the mass by an order of magnitude depending on the method used. Furthermore, different sources have often been observed in different tracers, each of which might probe distinct regions of the core, as clearly demonstrated for the Orion HC by Wright et al. (1996; see their Fig. 2). The core luminosity is also a difficult parameter to determine. In many cases it is derived from the FIR flux densities of the associated IRAS source; this very likely overestimates the actual contribution of the core, as the IRAS beam also includes any adjacent UC HII region, diffuse galactic plane IR emission, and possibly other discrete sources unrelated to the region. These caveats notwithstanding, one sees from Table 1 that the core masses and luminosities span more than two orders of magnitude, while diameters and temperatures vary by at most a factor of three. We plot the mass-luminosity of the known hot cores in Fig. 3; the trend toward higher luminosities for heavier cores is clearly evident.

Although single-dish spectral-line surveys furnish important information on the physical status and chemical composition of HCs (Mauersberger et al. 1988; Churchwell et al. 1992; Cesaroni et al. 1992; Olmi et al. 1993; Helmich 1996; Olmi et al. 1996a; Wyrowski 1997; Hunter 1997; Hatchell et al. 1998), the high angular resolution of interferometric observations makes them a more powerful tool for investigating the detailed nature of HCs. The tracers used are low abundance (and therefore low optical depth) molecules or high excitation transitions of more common species, and millimeter continuum emission. Given the small number of HCs with detailed analysis of interferometric data, we will describe the results for the best-studied objects rather than discussing general properties.

The location of the energy source heating the HCs is a question of significant interest. It is premature to make a general statement, but for at least some sources it appears that the heat source is internal. In the G10.47+0.03 complex, for example, three UC HII regions are embedded in a core seen in ammonia and methyl cyanide (Cesaroni et al. 1994a, 1998; Olmi et al. 1996b). Sub-arcsecond maps in the $NH_3(4,4)$ line show that the kinetic temperature increases towards the center of the core where the two most compact HII regions are located. This suggests that the embedded high-mass stars are heating the molecular gas. Two other HCs (G29.96–0.02 and G31.41+0.31) were mapped by Cesaroni et al. (1998) at $\sim 0\farcs4$ angular resolution, and in both cases the temperature increases towards the center. This argues in favor of *internal* core heating. Existing observations of the W51 region (Ho and Young 1996; Zhang and Ho 1997; Zhang et al. 1998a) lack the angular resolution to detect a temperature gradient. They do find that the gas *density* increases toward the center, as expected if star formation is occurring close to the core centers. Theoretical models of Kaufman et al. (1998) examine both internal and external heating, and, for the Orion

HC, are supportive of the former. Finally, we urge caution in the use of "internal" versus "external" to describe HC heating. In particular, an "external" heat source and the clump it heats may have arisen from collapse within a *single* core. In this sense, "external" would not mean "unrelated genetically."

Another question is the form of the initial mass function (IMF) in these objects. High-mass stars very likely exist inside the cores, as proved by the core luminosity and, in some cases (see Table 1), by embedded UC HII regions. If the stellar content of the cores were described by a Miller and Scalo (1979) IMF, the presence of massive stars would imply a *total* stellar mass at least an order of magnitude greater than the mass of the core itself. If this were true, then the hot core virial mass would be substantially greater than its mass determined by dust observations. Inspection of Fig. 2 shows that this is not the case. This demonstrates that the number of low-mass stars within HCs is much smaller than predicted by the standard IMF. The idea that HCs form "mainly" high-mass stars thus seems reasonable. We caution, however, that lower mass stars belonging to an OB association would not necessarily be contained within the hot core, and hence would not necessarily contribute to the warm dust emission. That the virial masses are in rough agreement with the masses derived from dust observations is suggestive of a truncated IMF, but it is not a proof of it.

HCs are likely sites of star formation. The main evidence for this is: (i) they are hot and internally heated, as shown by the observed temperature gradients; (ii) they are centrally dense, as expected for collapse; (iii) embedded stellar sources are seen from their FIR- or radio-continuum emission; (iv) maser emission (mostly H_2O) is detected in the core, possibly tracing an outflow or a disk.

C. Kinematics of Hot Cores

The kinematics of HCs should provide important information regarding the physical processes occurring during the star formation process, including both the necessary collapse of molecular material and the possibility of outflows.

Strong observational evidence indicates that powerful molecular outflows exist in high-mass star forming regions (e.g., Shepherd and Churchwell 1996a, 1996b) and may have properties similar to those from low-mass stars, the main difference being the mass involved, which is an order of magnitude larger (see Table 1 of Churchwell 1997b). A discussion of the nature of outflows associated with massive star formation may be found in Churchwell (1997a; 1997b); see also Richer et al. this volume.

It is clear that regardless of the details of contraction, conservation of angular momentum will force the gas to form rotating structures around the center of collapse. The detection of such "disks" in HCs would support the existence of embedded newly-born stars. In recent years increasing evidence for rotation and/or collapse in massive objects has been found, so it is not unreasonable to believe that circumstellar disks may form around higher-mass stars as well as their lower-mass counterparts (see Natta et al., this volume). Although the resolution presently attainable with interferometers is not sufficient to resolve these disks, observations in high density/temperature tracers such as NH_3(4,4) and CH_3CN have shown that the inner part of HCs is slightly elongated; moreover, a systematic velocity shift of the line peak is found across the major axis of these structures. Evidence for Keplerian rotation is seen in IRAS 20126+4104 (Zhang et al. 1998b) which strongly suggests the presence of a disk. In cases where a molecular outflow or jet is present, the axis of the flow is perpendicular to the direction of the velocity gradient in the core, lending strong support to the disk hypothesis (see Fig. 4). Examples of these studies are Ho et al. (1994), Cesaroni et al. (1994b; 1997), Olmi et al. (1996b), Akeson and Carlstrom (1996), Wyrowski et al. (1997), and Zhang and Ho (1997).

There is also evidence for collapse in HCs, mostly from inverse P-Cygni profiles in single dish spectra. Interferometric observations show red-shifted absorption against the continuum of an embedded UC HII region. This has been found in at least four objects (see Keto et al. 1988 for G10.62–0.38; Wink et al. 1994 for W3(OH); Zhang and Ho 1997, Zhang et al. 1998a for W51; and Hofner et al. 1998 for G45.47). The interpretation is not always clearcut. In the case of W3(OH), for example, the collapse suggested by absorption profiles is not supported by maser proper motions (Bloemhof et al. 1992).

In conclusion, rotation and collapse seem to be quite common in HCs, supporting the idea of star formation at the center while we are seeing the remnants of collapse.

D. Chemistry in Hot Cores

It was recognized at quite an early date (e.g., Sweitzer 1978; Genzel et al. 1982) that the Orion HC had unusually high abundances of ammonia and other saturated species. This led to the suggestion that one was observing (albeit in some processed form) the contents of grain ice mantles which had recently ($\sim 10^4$ yrs) been evaporated and released into the gas phase. Reviews on the gas and solid phase composition of HCs have been given by Van Dishoeck et al. (1993), Millar (1997), Ohishi (1997), van Dishoeck and Blake (1998), and Langer et al., this volume.

In this section, we highlight some new developments. The most important of these is probably the information on the composition in both solid and gas phases obtained from the ISO satellite. This has led to an improved knowledge of the main species in interstellar ices (Whittet et al. 1996) and to the detection of gas phase water at high

(>200 K) temperatures in absorption towards young massive embedded stars (Helmich et al. 1996; van Dishoeck and Helmich 1996). This suggests a gas phase abundance ratio $[H_2O]/[H_2] \simeq 3 \times 10^{-5}$, a factor of two smaller than that estimated for solid water (van Dishoeck et al. 1993; cf. Gensheimer et al. 1996) but we doubt that this difference is significant. Thus the thesis that HC material has recently been liberated from grain surfaces seems confirmed. Nevertheless, it is clear that some of the species observed are "daughter species" produced by gas phase processes subsequent to evaporation. Distinguishing between "daughters" and "parents" could be worthwhile, because suitable models (e.g., Charnley 1997) relate the daughter/parent abundance ratios to the age of the hot molecular gas. We note, however, that care must be taken with age arguments of hot cores based on chemical reactions because rates may have been significantly enhanced by the greater thermal energies.

Making use of such models requires both a vast spectral coverage and high angular resolution. For Orion there has been a set of "classical" single dish studies which, when completed, will have covered the entire submillimeter range available to ground based telescopes (Ziurys and McGonagle 1993; Serabyn and Weisstein 1995; Schilke et al. 1997, 1998). Other sources for which less detailed studies are available are SgrB2 (Nummelin 1996), W3 (Helmich and van Dishoeck 1997), G34.26+0.15 (Macdonald et al. 1996) and a selection of 14 UC HII regions (Hatchell et al. 1998). Interferometrically, Blake et al. (1996) observed Orion-KL covering 4 GHz with roughly 2″ and 1 MHz resolution. They found excitation gradients on scales of 1000 AU and suggest that source I in the IRc2 complex is the main energy source. High angular resolution is of greater importance for HCs more distant than Orion, such as W3(H_2O), which in many ways is similar to the Orion HC (Helmich and van Dishoeck 1997; Helmich et al. 1994). Wyrowski et al. (1997) found that W3(H_2O) contains both an "oxygen-rich" peak similar to the Orion "compact ridge" (where methanol, methyl formate, and dimethyl ether are abundant) and a "nitrogen-rich" peak (with species such as ethyl and vinyl cyanide) similar to the Orion HC (see Caselli et al. 1993 for a possible explanation).

Are there differences between the abundances found in HCs of differing physical characteristics? A first cautious answer to this question appears to be "no". The molecular species and abundances in G10.47+0.03 and G31.41+0.31 (see Wyrowski 1997) are approximately the same as those in Orion, Sgr B2(N), and G34.26+0.15 (see also Mehringer and Snyder 1996; Miao and Snyder 1997). Moreover, the abundances do not seem to have a strong dependence on temperature. Light HCs such as Orion do not have chemical properties that distinguish them greatly from heavy HCs such as SgrB2-N and G10.47+0.03.

Our tentative conclusion is that the abundance pattern is strikingly similar in objects whose mass, luminosity, and location in the Galaxy vary widely. We suggest that this means that dust ice mantle composition does not vary enormously between the inner galaxy and the solar neighborhood. Moreover, we suspect that we are mainly observing parent rather than daughter species. This implies that most of the sources are younger than 10^5 yr, since the ion-molecule chemistry (driven by cosmic rays) requires a timescale of this order to break down the parent species.

E. Masers, UC HIIs, and Hot Cores

A fruitful line of research in recent years has been the study of molecular masers found in the environs of UC HII regions and HCs. Especially important are studies of H_2O, OH, and CH_3OH masers. Large single dish databases of H_2O masers have been compiled (Cesaroni et al. 1988; Comoretto et al. 1990; Brand et al. 1994) that are useful in statistical studies of the correlation of masers with UC HII regions and HCs. Ultimately, however, interferometric observations are essential to study the detailed physical relationship between the masers and the star-forming core. Relatively few workers have begun to examine the detailed physical connection between masers and other star formation signposts; Codella et al. (1997) are one exception. Their ammonia observations toward water masers suggest that the maser emission arises from HCs rather than UC HII regions. The possibility that masers arise in circumstellar disks has long been discussed; recent observations of NGC7538 (Minier et al. 1998), among others, are supportive of this view.

Methanol masers were discovered much more recently than H_2O and OH masers, and as a result their place(s) in the star formation process is not as well understood. Southern hemisphere observations are extensive, but lack the supporting observations that are more plentiful in the north. Conversely, many well-observed northern regions have received less attention in CH_3OH maser studies; high resolution (interferometric) data are particularly lacking. Among the more extensive surveys are those of Bachiller et al. (1990), Menten (1991), Kalenskii et al. (1993), Norris et al. (1993), Slysh et al. (1994), Caswell et al. (1995), van der Walt et al. (1996), Caswell (1996), and Ellingsen et al. (1996). The latter two are noteworthy because they are sensitivity limited surveys of galactic plane regions. Further work is needed to clarify the nature of the masers they detected, but it seems clear that CH_3OH masers are a significant feature of massive star-forming regions and will be an important observational probe in future studies of UC HII regions and HCs.

V. FROM HOT CORES TO UC HII REGIONS

If HCs represent the natal environment of massive stars, then an interesting question is the evolutionary sequence connecting them with UC HII regions. The latter should follow the former in direct succession, but the precise details of the transition, and regions observed to be undergoing such a transition are lacking, although a few candidates have been found.

A region presenting massive YSOs in different evolutionary stages is G9.62+0.19. This region, shown in Fig. 5, has a chain of UC HII regions of different sizes (and possibly of different ages) associated with a hot core traced by the NH_3(4,4) emission, probably corresponding to an earlier phase, and possibly near the point of becoming a UC HII region.

Another candidate for a HC on the verge of developing an UC HII region is IRAS 20126+4104 (Cesaroni et al. 1997; see Fig. 4), which is associated with a molecular outflow and probably a rotating disk. The bottom panel of Fig. 4 shows a 1.3 mm image (R. Cesaroni, personal communication, $0.7''$ resolution) in the J=12-11, K=8 transition of CH_3CN (526 K above ground). An offset of $0.4''$ (0.0033 pc) is seen between the blue and redshifted CH_3CN emission, perpendicular to the HCO^+(1-0) outflow (upper panel). This is consistent with the outflow emanating from the rotating disk seen in CH_3CN. Recent NH_3 observations by Zhang et al. (1998b) support the interpretation of rotation and show that the "disk" is much larger than seen in CH_3CN. The source is weak at centimeter wavelengths where it appears as a double source, possibly in the form of thermal jets (P. Hofner, personal communication).

G9.62 and IRAS 20126 represent the search for HCs on the verge of becoming UC HII regions. Another approach is to search for the youngest UC HII regions, which have just made the transition from HCs, to see what artifacts of their earlier state may remain. DePree et al. (1998) searched the Sgr B2 Main region in the 7 mm continuum, and detect some 20 extremely small ($\sim 10^{-3}$ pc) very high emission measure ($\sim 10^9$ pc cm^{-6}) HII regions. Such high emission measure objects may be recently born UC HII regions. Other promising sites to search are those UC HII regions still embedded in HCs listed in Table 1, particularly those un-resolved even by sub-arcsecond beams, such as G10.47+0.03 or W51 e8. We note that some HCs, e.g., W3(OH/H_2O), may be powered by B stars of sufficiently late spectral type that they have a negligible Lyman continuum flux. Other HCs (see Table 1) are so luminous that they probably are powered by a (proto) O star. In these latter cases, one might hope to see a transition state from a HC to a UC HII region. With enough such regions detected — either evolved HCs or nascent UC HII regions — one hopes that we can begin to understand the transition between the two.

In fact, the transition phase from HC to UC HII region may be intimately related to their lifetimes, and hence to the number of such objects present at any one time. Similar to the estimates for UC HII regions, one may estimate HC lifetimes based on an assumed massive star formation rate (10^{-2} yr^{-1}) and the number of HCs thought to be present at any one time. Using the number of detected HCs (19; see Table 1) as an extreme lower limit, and the number of candidate high-mass class 0 objects ($\sim$575; see Ramesh and Sridharan 1997) as an upper limit, one estimates the HC lifetime between 1.9×10^3 and 5.7×10^4 yr.

What is the physical mechanism responsible for the transition from HC to UC HII region? Mass accretion rates of 10^{-4}–10^{-5} $M_{\odot}$ yr^{-1} can effectively quench the development of an HII region (Walmsley 1995). As discussed in Sec. IV.C., there is considerable evidence to suggest that such infall is a significant feature of HCs. Assuming free-fall collapse of the molecular gas onto the embedded massive star one finds that the Strömgren radius depends dramatically on the mass accretion rate (see Yorke 1979). One thus speculates that the transition from HC to UC HII region occurs because of some modification in the accretion mechanism, such as a gap in the influx of matter or departure from spherical symmetry, which the previous result relies upon. Formation of disk-like structures on scales $\gtrsim$100 AU might suffice.

VI. CONCLUSIONS

Recent high frequency, high angular resolution studies have allowed us to probe hot, dense molecular cloud cores on scales $\lesssim$1000 AU, where OB stars are forming. We have re-examined the lifetime problem of UC HII regions and conclude that, though the problem is real, probable solutions have been proposed. We have reviewed the most recent observational findings concerning the formation and the earliest evolutionary stages of high-mass stars. The most salient result is the detection of hot, compact, dense cores, rich in rare molecular species and positionally coincident with various masers (especially H_2O). These HCs are often (but not always) associated with nearby or (in some cases) embedded UC HII regions, which suggests a connection between the two. Indeed, there is strong support for the idea that HCs represent the natal environment of high-mass stars. It is tempting to speculate that HCs will eventually evolve into UC HII regions, but a definite answer to this question will come only from more sensitive and higher resolution observations capable of revealing the temperature, density, and velocity structure of the HCs. This goal will be achieved with the forthcoming generation of instruments such as the MMA/LSA/LMSA and FIRST.

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FIGURE CAPTIONS

Figure 1. Top: Comparison of the $C^{34}S(5–4)$ (grey contours), $CH_3CN(6–5)$ (black contours), and 1.3 cm continuum (dotted contours) emission toward the UC HII region G29.96–0.02. Bottom: enlargement of the region where the HC and the UC HII region are located; the triangles indicate the position of the H_2O masers.

Figure 2. Hot core masses as derived by different methods. $M_{\mathrm{C^{17}O}}$ and M_{v} are based upon $C^{17}O$ measurements reported by Wyrowski (1997). M_{dust} is based upon submillimeter continuum measurements by Hunter (1997). The methods generally agree to within one order of magnitude.

Figure 3. The mass-luminosity distribution of hot cores. The data plotted are taken from Table 1. As discussed in the text, there is considerable uncertainty, particularly in the core masses. Nevertheless, a clear trend toward higher luminosities for heavier cores is seen. The two "light cores" (Orion-KL and IRAS 20126) have conspicuously lower masses than the heavier cores.

Figure 4. Top: Overlay of the H_2 2.1 μm line emission (grey scale) and $HCO^+(1–0)$ emission integrated under the blue (full contours) and red (dashed contours) line wings in IRAS 20126+4104 (Cesaroni et al. 1997). Bottom: enlargement of the region where the hot core is located; the grey scale represents the 1.3 mm continuum emission and the full and dashed contours correspond to the $CH_3CN(12–11)$ emission integrated respectively under the blue and red wing of the K=8 line (Cesaroni, personal communication). The triangles indicate the position of the H_2O masers. Note the perpendicularity between the H_2-jet/HCO^+-outflow and the rotating disk seen in CH_3CN.

Figure 5. Maps of the $NH_3(4,4)$ line (dashed contours) and 1.3 cm continuum emission (solid contours) toward G9.62+0.19 (Cesaroni et al. 1994a). The positions of the H_2O (Hofner and Churchwell 1996) and OH (Forster 1993) masers are indicated respectively by the filled triangles and empty squares.

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