THE SEARCH FOR HIGH-MASS PROTOSTARS

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Introduction

In spite of the importance of massive stars for the morphology and evolution of the Galaxy, and galaxies in general, the detailed study of the star formation process has mostly been concentrated on low-mass stars (M $\lesssim$ 1 $M_\odot$). The reasons for this are evident: they are more abundant than high-mass stars, and the clouds in which they form are closer by, allowing a more detailed investigation. The study of high-mass (M $\gtrsim$ 10 $M_\odot$) stars in their early evolutionary stages is furthermore complicated by the fact that they reach the ZAMS while still accreting material (and hence still suffering very high visual extinction), after which they rapidly destroy their natal environment. In recent years however, ever growing efforts have been devoted to the study of the formation of high-mass stars, i.e. early type (O–B) stars with mass in excess of $\sim$ 10 $M_\odot$. In particular, attention has gradually shifted from the study of HII regions to that of ultracompact (UC) HII regions, to that of the molecular clumps in which UC HII regions are embedded. Going from large, low-density structures to compact dense cores, corresponds to approaching the very earliest stages of the evolution of a massive star. Indeed, one of the goals of this type of research is to identify a massive stellar object in an evolutionary phase prior to the arrival on the main sequence, when most of its luminosity is derived from the release of gravitational energy. Such an object is defined a "protostar", and would observationally be recognized as an object of Class 0 (see André et al. 1994).

Many attempts have been made to identify a high mass protostar, but no clear result has been obtained yet. Because stars form in high-density regions with huge visual extinction, one can penetrate the otherwise optically thick cores only by means of radio, (sub-) mm, or FIR observations. The selection of targets must take into account such constraints, and hence one must choose objects visible in high-density molecular tracers (line or continuum), and selected on the basis of their established association with regions of high-mass star formation. For example, some authors (Olmi et al. 1993, 1996; Cesaroni et al. 1994) have observed the molecular environment in the close vicinity of UC HII regions, with the aim to find a protostar in the same cluster of the early type stars exciting the UC HII region. Others (e.g. Cesaroni at al. 1997, 1999; Codella et al. 1997) have selected their targets among water masers *without* free-free continuum emission, under the hypothesis that the association with H_2O masers is synonymous to association with high-mass stars, while the lack of radio continuum emission should identify the youngest stellar objects. One of the most important results to emerge from these studies is the detection of small (~ 0.1 pc), dense ($\sim 10^7$ cm^{-3}), hot ($\gtrsim 100$ K), and luminous (L $\gtrsim 10^4$ L$_\odot$) molecular condensations, which very likely host high-mass objects still too young to have developed an HII region. It is generally thought that these "Hot Cores" represent the natal environment of OB stars (see e.g. Kurtz et al. 2000). However, there are indications that the embedded objects are already main sequence stars, and not true protostars. The next step would be to look for the latter objects, the high-mass equivalent of a Class 0 object. These are most likely not to be found near UC HII regions, because an HII region rapidly alters (or even disrupts) the molecular cloud in which it forms. To find the initial conditions of star formation, one should therefore be looking for the *precursors* of UC HII regions.

Finding candidate protostars

This requires a different approach, which has been illustrated in a series of papers (Palla et al. 1991, 1993; Molinari et al. 1996, 1998a). A sample of 260 objects was selected from the IPSC, based on their FIR emission properties (for details see Palla et al. 1991). In particular, the IRAS colour criteria by Richards et al. (1987) were applied, which identify compact molecular clouds, while all known HII regions were not selected. This sample was then split into two sub-samples, based on their colour indices. The 125 sources with $[25-12] \geq 0.57$ and $[60-12] \geq 1.3$ comply with the Wood & Churchwell (1989) criteria for identifying UC HII regions, and are called "*High*"; the remaining 135 sources are called "*Low*".

A search for H_2O maser emission towards the 260 sources resulted in a detection rate of 26% for the *High*, and 9% for the *Low* sources. As masers are preferentially associated with luminous sources, this might lead one to think that the *Low* sources are less luminous and, by consequence, less massive. However, the distribution in the colour-colour diagram of T Tauri and Herbig Ae/Be stars (with masses between 1 and 10 M$_\odot$) is very different. On the other hand, both the distribution and the H_2O maser detection rate of known HII regions are very similar to those of our sample of 260 *High* and *Low* sources. A possible explanation for the steep decrease of the maser detection rate for the *Low* sources could be, that the two classes of sources are in a different evolutionary stage, with the *Low* sources being the youngest (Palla et al. 1991). We have then performed a series of observations with a twofold goal: to confirm that the *High* sources are indeed UC HII regions, and – most importantly – to clarify the nature of the *Low* sources. This was accomplished by observations in many different tracers: H_2O masers (Medicina telescope), NH_3(1,1) and (2,2) lines (Effelsberg), continuum maps in the IR (ISO satellite), at centimeter (VLA), and (sub-) millimeter wavelengths (JCMT) (for a flowchart illustrating this process, see Molinari et al. 1999, fig. 1).

The main results of these observations can be summarized as follows:

- *High* and *Low* sources have luminosities typical of high-mass stars, with the latter being only slightly less luminous than the former;
- H_2O masers are much more common towards *High* than *Low* sources (detection rates 26% and 9%, respectively);

• NH_3 emission is detected towards both samples (with a detection rate of 45% for *Low* and 80% for *High* sources), although the temperatures derived from the ratio of the (1,1) and (2,2) lines indicate that *Low* sources are slightly colder than *High*. The linewidths also indicate that the *Low* sources have less turbulent envelopes;

• Free-free emission is detected towards 43% of the *High*, but only 24% of the *Low* sources observed with high angular resolution with the VLA (at 2 and 6 cm);

• For 17 out of 30 (57%) of the *Low* sources mapped with the JCMT, the (sub-) millimeter emission arises from a compact ($\sim 30''$) region around the IRAS source; total core masses are typically 10−200 $M_\odot$;

• The continuum spectra of the *Low* sources between 0.35 and 2 mm indicate temperatures of ∼30 K, significantly lower than those, measured towards "Hot Cores", which probably contain early type stars already on the main sequence;

The main conclusions one can draw are that *High* sources are UC HII regions, and that *Low* sources are associated with massive stars (as suggested by their luminosities), but do *not* show any of the tracers typical of the molecular cores hiding a *main sequence* early type star (such as free-free emission, high kinetic temperature).

We thus believe that the *Low* sample contains likely candidates of high-mass protostars (note however that Molinari et al. 1996 found that the *Low* group also contains a fraction of evolved objects, older than *High* sources). A selection of *Low* sources is presently being studied in more detail, which so far has led to the discovery of an excellent candidate for a massive Class 0 object (Mol 160 = IRAS23385+6053; Molinari et al. 1998b).

Mol 160: a massive Class 0 object?

Selected observations of Mol 160 are shown in Figure 1. The left-hand panel shows the contours of the integrated HCO^+(1–0) emission (OVRO), superimposed on the ISOCAM 15 μm image. An enlargement of the central region is shown on the right, with the (OVRO) 3.4 mm continuum contours. The 3.4 mm core is compact, with slight elongations to the SE and N; the deconvolved size is $4\farcs5\times3\farcs6$, corresponding to an average radius of $r_{core} \sim 0.048$ pc, at the (kinematic) distance of 4.9 kpc. The IRAS source almost coincides with this nucleus. Figure 2 shows the spectral energy distribution of Mol 160. Molinari et al. (1998b) have shown that the IRAS 12 and 25 μm flux densities are compatible with the ISOCAM 6.75 and 15 μm fluxes, integrated over all the bright emission visible on the CAM image, while the mm core is the only source that contributes significantly at 60 and 100 μm. The dotted line in Fig. 2 is a model fit to the data, from which we derive a source bolometric luminosity $L_{bol} \approx 1.6\times10^4$ $L_\odot$, a total core mass M $\sim$ 370 $M_\odot$ (for a gas-to-dust ratio of 100 by mass), and a mean H_2 column density $N(H_2) \sim 2 \times 10^{24}$ cm^{-2}, corresponding to a visual extinction $A_V \sim 2000$ mag. The dust temperature is $\sim$ 30 K (Molinari et al. 1999); from recent observations of CH_3C_2H(6–5) with the IRAM 30-m (Brand et al. 2000) we derive a gas temperature of $\sim$ 44 K. The source is also associated with a compact outflow in HCO^+ and SiO(v=0, 2–1), with dimensions $\ll r_{core}$, a dynamical timescale $\lesssim 7\times10^3$ yr, and a mass-loss rate $\gtrsim 10^{-3}$ $M_\odot$ yr^{-1}. Furthermore, the ratio $L_{submm}/L_{bol} \sim 3 \times 10^{-3}$, and $M_{env}/M_* \gg 1$. All these parameters are characteristic of a Class 0 object, and these observations therefore favour the interpretation that Mol 160 is a high-mass protostar.

An alternative possibility is, that this object is a heavily obscured B0 ZAMS star. In this case, the lack of radio-continuum emission requires the HII region, if present, to be optically thick and very compact ($r_{HII} \lesssim 100$ AU); however, a modest amount of residual accretion could quench the HII region. In both of these extreme scenarios we are dealing with a very young and massive object.

Future work

If definite proof of the evolutionary state of an object is at all possible, it certainly cannot be delivered by a single observation. Rather, it will be the combination of many observations, both at higher and lower angular resolution, and at various frequencies, that in the end will provide enough "circumstantial" evidence to enable one to make a reasonably secure statement as to the evolutionary status of any object.

For example, we have started a mapping survey with the NRAO 12-m at Kitt Peak, which will help in establishing an evolutionary sequence for our objects. Two phenomena often associated with protostars (of all masses) are H_2O masers and molecular outflows. The association of CO outflows with UC HII regions has been well established by Shepherd & Churchwell (1996). However, surveys show that H_2O masers can appear slightly *before* the development of a detectable HII region (Codella et al. 1996, 1997), and that they are also closely associated with CO outflows (Felli et al. 1992; see also Wouterloot et al. 1995, for a statistical analysis of the correlations between FIR, H_2O, and CO emission). From maps of the outflows, one can determine the dynamical timescale, which provides a lower limit to the protostellar age. Combining the presence or absence of H_2O maser- and radio continuum emission should provide a sensitive measure of the age of the source. Some preliminary results of this survey are shown in Figure 3.

Interferometric (mm-continuum, and -lines) are needed to study the envelopes and (eventual) disks of the embedded objects. Single-dish observations are important to study the physical and kinematical properties of the molecular cores, in which the candidate protostellar objects are embedded. A study of the kinematic properties is especially important: protostars derive the major part of their luminosity from accretion, and one therefore expects to see signatures of infall towards these sources (see e.g. Myers et al. 2000, and references therein). We therefore continue to observe the objects on our list of candidate high-mass protostars, with the aim to narrow the range of possible alternative explanations.

Collaborators

The people involved in this project from the start, apart from the author, are S. Molinari (Bologna/IPAC), R. Cesaroni and F. Palla (Arcetri). In the follow-up projects we collaborate with L. Testi (Caltech/Arcetri), Q. Zhang, T.R. Hunter, and T.K. Shridharan (SAO-Harvard CfA), and L. Olmi (FCRAO).

References

André P., 1994, In: The Cold Universe, Proc. XIIIth Moriond Astrophysics Meetings, eds. T. Montmerle, C.J. Lada, I.F. Mirabel, J. Trân Thanh Vân, p. 179

Brand J., Cesaroni R., Palla F., Molinari S., 2000, A&A *in preparation*

Cesaroni R., Churchwell E., Hofner P., Walmsley C.M.,Kurtz S., 1994, A&A 288, 903

Cesaroni R., Felli M., Testi L., Olmi L., Walmsley C.M., 1997, A&A 325, 725

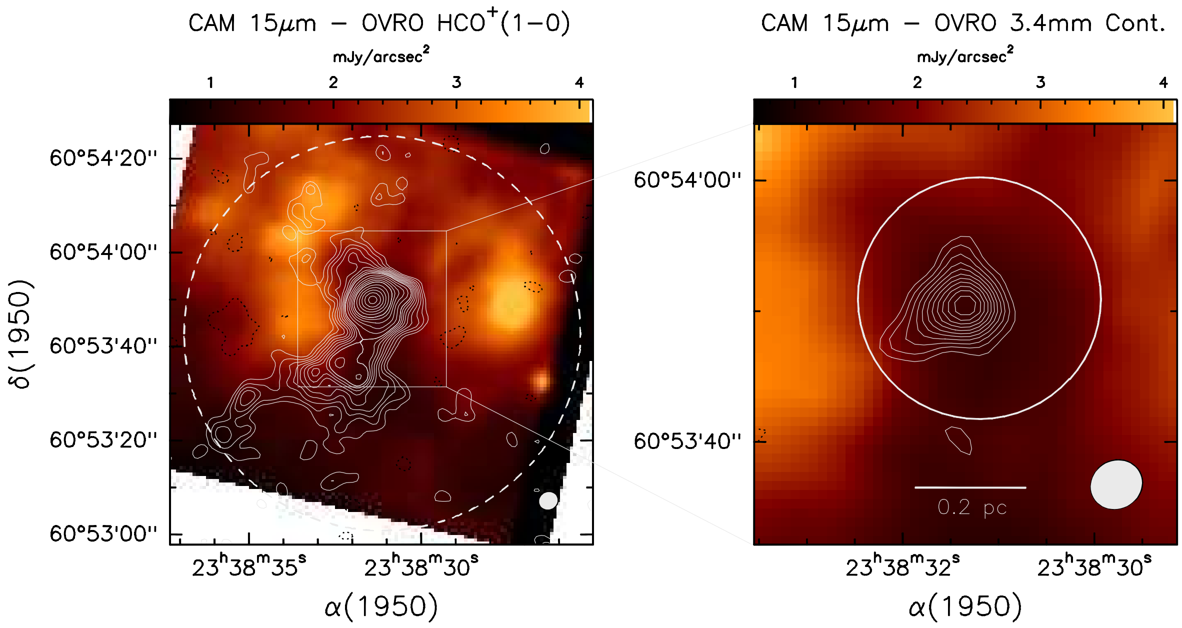

Figure 1: Molinari 160 (IRAS23385+6053; taken from Molinari et al. 1998b)
a (*Left*) Colour-scale: emission at 15 μm (ISOCAM); contours: $\int$HCO$^+$(1–0)dv. The dashed circle indicates the OVRO main beam.
b (*Right*) Enlargement of the central part of the left panel. Colour-scale: emission at 15 μm (ISOCAM); contours: 3.4 mm continuum emission. The circle indicates the beam of the JCMT observations at 1.1 mm (19″); in both panels the white ellipse is the OVRO synthesized beam FWHP.

Cesaroni R., Felli M., Walmsley C.M., 1999, A&AS 136, 333
Codella C., Felli M., Natale V., 1996, A&A 311, 971
Codella C., Testi L., Cesaroni R., 1997, A&A 325, 282
Felli M., Palagi F., Tofani G., 1992, A&A 255, 293
Kurtz S., Cesaroni R., Churchwell E., Hofner P., Walmsley C.M., 2000, In: Protostars and Planets IV, eds. V. Mannings, A.P. Boss, S.S. Russell (Tucson: Univ. of Arizona Press), *in press*
Molinari S., Brand J., Cesaroni R., Palla F., 1996, A&A 308, 573
Molinari S., Brand J., Cesaroni R., Palla F., Palumbo G.G.C. 1998a, A&A 336, 339
Molinari S., Testi L., Brand J., Cesaroni R., Palla F., 1998b, ApJL 505, L39
Molinari S., Brand J., Cesaroni R., Palla F., 1999, A&A *submitted*
Myers P.C., Evans N.J. II, Ohashi N., 2000, In: Protostars and Planets IV, eds. V. Mannings, A.P. Boss, S.S. Russell (Tucson: Univ. of Arizona Press), *in press*
Olmi L., Cesaroni R., Walmsley C.M., 1993, A&A 276, 489
Olmi L., Cesaroni R., Neri R., Walmsley C.M., 1996, A&A 315, 565
Palla F., Brand J., Cesaroni R., Comoretto G., 1991, A&A 246, 249
Palla F., Cesaroni R., Brand J., Comoretto G., Felli M., 1993, A&A 280, 599
Richards P.J., Little L.T., Toriseva M., Heaton B.D., 1987, MNRAS 228, 43
Shepherd D.S., Churchwell E., 1996, ApJ 457, 267
Wood D.O.S., Churchwell E., 1989, ApJ 340, 265
Wouterloot J.G.A., Fiegle K., Brand J., Winnewisser G., 1995, A&A 301, 236

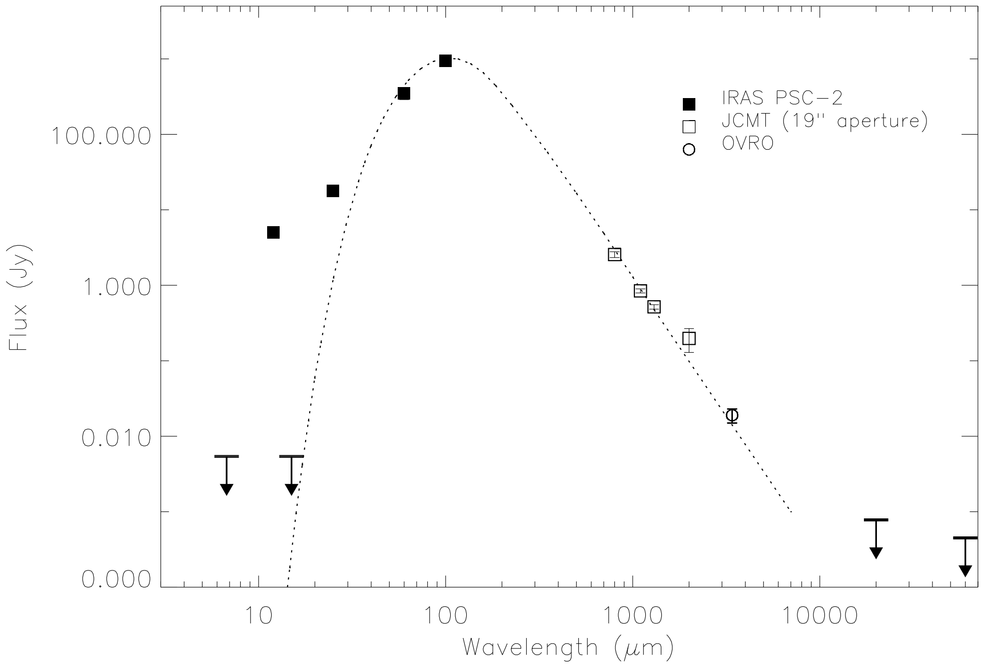

Figure 2: Spectral energy distribution of the Mol 160 core. Upper limits at 7 and 15 μm are from ISOCAM, those at 2 and 6 cm are from the VLA. The dotted line is a model fit (from Molinari et al. 1998b).

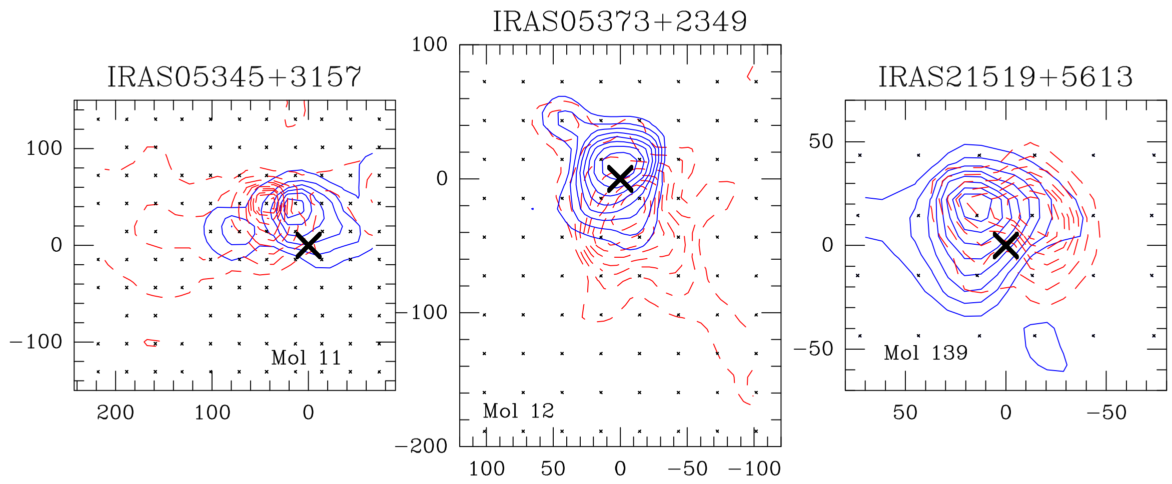

Figure 3: Examples of outflows associated with *Low* (Mol 11 and 12) and *High* (Mol 139) sources; CO(2–1) data obtained with the NRAO 12-m at Kitt Peak. Coordinates are α, δ offsets in arcsec with respect to the IRAS position (big cross). Observed positions are indicated by the small crosses. Drawn and dashed contours trace blue and red wing emission, respectively.