HIGH-MASS PROTOSTARS

J. Brand[1], R. Cesaroni[2], F. Palla[2], Q. Zhang[3], M.A. Kramer[4], T.R. Hunter[3], S. Molinari[5], T.K. Shridharan[3]

[1]Istituto di adioastronomia, CNR, Bologna, Italy - [2]Osservatorio Astrofisico di Arcetri, Florence, Italy - [3]Center for Astrophysics, Cambridge MA, USA
[4]Oberlin College, Oberlin OH, USA - [5]IFSI-CNR, Rome, Italy

ABSTRACT and BACKGROUND

We present results of new observations in our continuing effort to clarify the evolutionary status of a set of objects which we consider to be precursors of UC HII regions. Presentation is in graphical form, with the essence described in the captions.

The identification of stellar objects of high- and intermediate mass (M≥8-10M$_\odot$) is much more difficult than that of objects of solar mass or less. This is because massive stars are on average more distant, and because they start H-burning while still accreting mass, thereby altering or destroying their natal environment. We attempt to find massive protostars, i.e. *precursors of UCHII regions*, by selecting and systematically studying a sample of IRAS sources with colours typical of sources embedded in compact molecular clouds.

An original sample of 260 IRAS sources with colours typical of compact molecular clouds was divided approximately evenly into a *High* group, with IR colour indices [25-12] ≥0.57 and [60-12] ≥1.3, and a *Low* group with complementary colours. The similarity in luminosity between the *High* and *Low* sources, the different distribution in the FIR colour-colour diagram, and the lower detection rate in H_2O maser emission of the *Low* sources, led to the hypothesis that the majority of these objects represent an earlier stage in the evolution than the members of the *High* group, which are mostly identifiable with UCHII regions. Subsequent observations, illustrated in FIGURE 1, led to the selection of 12 *Low* sources that have FIR luminosities indicating the presence of B2.5 to O8.5 V_0 stars, are associated with dense gas and dust, have (sub-)mm continuum spectra indicating temperatures of ~30K, and have no detectable radio continuum emission.

We present:

1) IRAM observations of the molecular environment of 11 of these 12 objects, made with the aim to derive the physical parameters of the gas in which they are embedded, and to find further evidence in support of our hypothesis that these sources are the precursors to UCHII regions. We find that the data are consistent with such an interpretation.

Examples of core maps are given in FIGURES 2-4, while FIGURE 5 gives a summary (from Brand et al. 2001).

2) NRAO 12-m (Kitt Peak) $^{12}CO(2-1)$ observations of a search for molecular outflows towards 69 *Low* and *High* sources. Many of the outflow masses and momenta are two orders of magnitude larger than those associated with low-mass star formation, and are most likely driven by high-mass YSOs.

Examples of outflow maps are shown in FIGURES 6, 7, and a summary of the results is presented in FIGURES 8, 9 and the TABLE (from Zhang et al. 2001).

CORES

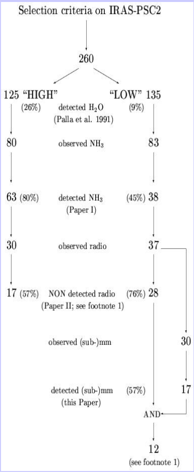

Fig.1 Flow-chart for the selection of intermediate- to high-mass protostellar objects. The final sample consists of 12 objects detected in the (sub-)mm and not associated with radio continuum. (from Molinari e al. 2000)

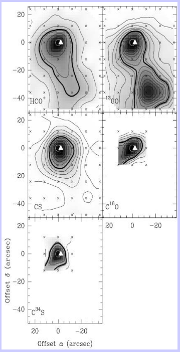

Fig. 2 Maps in various molecular tracers towards IRAS05137+3919. The filled triangle marks the IRAS position; the circle indicates where longer observations were made in $CH_3C_2H(6-5)$ and in CH_3CN. Crosses mark the observed positions. Contours (low(step) high, in Kkms^{-1}) are: 0.5(1)6.5 [HCO^+ (1-0)]; 4.5(4)60.5 [$^{13}CO(2-1)$]; 0.5(1)11 [CS(3-2)]; 1(1)8 [$C^{18}O(2-1)$]; 0.4(0.4)2 [$C^{34}S(3-2)$]

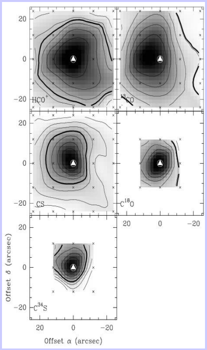

Fig. 3 As Fig.2, for observations towards IRAS18527+0301. Contours (low(step)high) are: 1(0.5)4 (HCO^+) 18(4)42 (^{13}CO); 1(1)8 (CS); 7(2)21 ($C^{18}O$); 0.3(0.3)2.4($C^{34}S$)

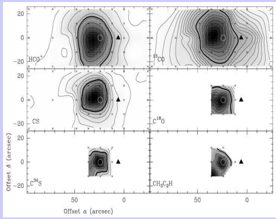

Fig.4 As Fig.2, for observations towards IRAS19092+0841. A panel is added showing the distribution of the integrated emission over the K=0,1 components of $CH_3C_2H(6-5)$. Contours (low(step)high, in Kkms^{-1}) are: 1(2)17 (HCO^+); 1(4)41(6)95 (^{13}CO); 1(2)23 (CS); 3(3)35 ($C^{18}O$); 0.5(0.5)4 ($C^{34}S$); 1(0.5)3.5 (CH_3C_2H(6-5), K=0.1)

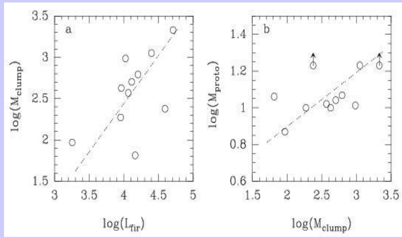

Fig. 5a Relation between clump mass and luminosity of the IRAS source. The dashed line is a least-squares fit with a slope of 1.17 ± 0.22.
b Relation between clumps mass and mass of the protostellar object. M_{proto} is derived from the models of Palla & Stahler (1992 ApJ 392, 667) for an accretion rate of 10^{-4} $M_\odot yr^{-1}$, assuming each clump contains a single object, which produces a luminosity L_{fir}. The dashed line is a least-squares fit with a slope of 0.30 ± 0.07. Note that this is similar to that found by Larson (1982 MNRAS 200, 159) who found that the maximum mass of stars is related to the mass M of the cloud as $M_{star} \propto M^{0.43}$

...AND OUTFLOWS

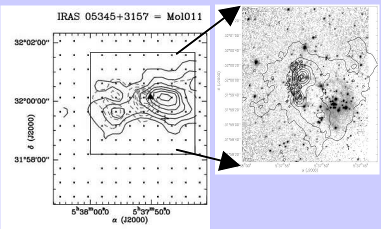

Fig.6a Molecular outflow [CO(2-1)] found in IRAS05345+3157. Blue: -40 to -21 kms^{-1}; Red: -14 to 3 kms^{-1} (dashed). Lowest contour and step: 15Kkms^{-1}. The big cross indicates the the flow. The small crosses represent the observed IRAS source position, the triangle marks the center of positions. The drawn box indicates the location shown in Fig.6b. M_{tot}=6M$_\odot$, Momentum=38M$_\odot$kms^{-1}.
b K_s-band image of the area around IRAS05345+3157. Dashed contours represent the 850μm emission (SCUBA), while the full-line contours map the HCO^+(1-0) integrated emission (OVRO). The W-part of the core has already spawned a cluster of pms objects; the E-part seems to be undergoing fragmentation, and likely presents a new star formation event in its early stages of development

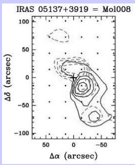

Fig.7a IRAS05137+3919
Red: -23 to +2 kms^{-1} (dashed)
Blue: -53 to -28 kms^{-1} Lowest contour and step: 16, 8 Kkms^{-1}
The large cross indicates the IRAS source position, the small crosses the observed positions.
M_{tot}=116M$_\odot$
Momentum=725M$_\odot$kms^{-1}

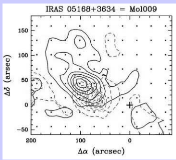

Fig.7b IRAS05168+3634
Red: -11 to +18 kms^{-1} (dashed)
Blue: -48 to -19 kms^{-1}
Lowest contour and step: 12 Kkms^{-1}
Symbols and markers as in Fig.7a
M_{tot}=16M$_\odot$
Momentum=248M$_\odot$kms^{-1}

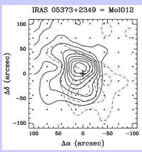

Fig.7c IRAS05373+2349
Red: 6 to 30 kms^{-1} (dashed)
Blue: -26 to 0 kms^{-1}
Lowest contour, step: 10 Kkms^{-1}
Symbols and markers as in Fig.7a
M_{tot}=3.4M$_\odot$
Momentum=27M$_\odot$kms^{-1}

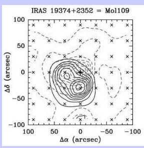

Fig.7d IRAS19374+2352
Red: 41 to 58 kms^{-1} (dashed)
Blue: 24 to 33 kms^{-1}
Lowest contour and step: 3 Kkms^{-1}
Symbols and markers as in Fig.7a
M_{tot}=17M$_\odot$
Momentum=122M$_\odot$kms^{-1}

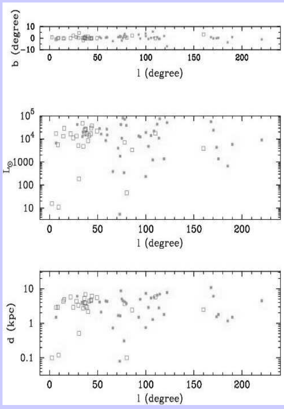

Fig.8 The distribution of the sample in galactic coordinates (top), luminosity (middle), and kinematic distances (bottom panel). The filled squares are the IRAS sources with identifiable outflows, the open squares those without. The lack of outflow detections towards 0°<*l*<50° is not due to distance or luminosity effects, but to the presence of multiple velocity components along the l.o.s. toward the molecular ring: outflow signatures are obscured by emission from clouds at slightly different velocities.

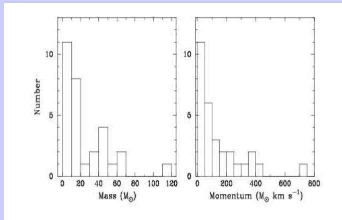

Fig.9 The distribution of outflow mass (left) and momentum (right) for 30 objects with luminosities >10^{3}L$_\odot$ and for which reliable mass estimates are determined

CO OUTFLOW DETECTION RATE

Category		No. of outflows and detection rate l<50°	l>50°	Total
Total		4/26	35/39 (90%)	39/65
	High	1/7	22/24 (92%)	23/31
	Low	3/19	13/15 (87%)	16/34
with H_2O	High	0/2	16/17 (94%)	16/19
	Low	0/3	7/7 (100%)	7/10
no H_2O	High	1/5	6/7 (86%)	7/12
	Low	3/16	6/8 (75%)	9/24

† Outflow detection rate toward 0°<l<50° may not be representative because of confusion in CO spectra by multiple cloud components along line-of-sight

SUMMARY

1. IRAM All observed sources are associated with well-defined molecular clumps. Typically the cores have *average* diameters of 0.5-1 pc, and masses of a few tens to a few thousand solar masses. Compared to a similar analysis of *High* sources, the present sample has molecular clumps that are more massive, larger, cooler, and less turbulent. They also tend to have a smaller ratio of virial-to-luminous mass, indicating they are less dynamically stable than their counterparts in which the *High* sources are embedded. The large sizes suggest these clumps should still undergo substantial contraction (their densities are ~10 times smaller than those of the *High* sources). The lower temperatures and small linewidths are also expected in objects in an earlier evolutionary state. In various sources indications are found for outflowing gas.

We find that the masses of the molecular clumps associated with our objects increase with L_{fir} ($M_{clump} \propto L_{fir}^{1.17}$), and that there is a (weak) relation between the clumps mass and the mass of the embedded protostellar object $M_{proto} \propto M_{clump}^{0.30}$.

2. NRAO Among the 69 sources observed, 65 have data suitable for outflow identification: 39 (60%) of these show spatially confined high-velocity CO wing emission. Leaving out sources with 0°<*l*<50°, where outflow signatures are confused by multiple emission components along the line of sight, we find an outflow detection rate of 90% (35/39), the same for *Low* and *High* separately. The outflows are massive, typically having M>10M$_\odot$. This unbiased survey of luminous (10^3-10^5 L$_\odot$) objects shows that outflows are common in high-mass star regions, and suggests that high-mass stars may form via an accretion-outflow process, similar to their low-mass counterparts.

RELATED PUBLICATIONS

- **Palla et al. 1991 A&A 246, 249; 1993 A&A 280, 599**
"H_2O masers associated with compact molecular clouds and UCHII regions"
- *"A search for precursors of UCHII regions in a sample of luminous IRAS sources"*
Molinari et al. 1996 A&A 308, 573 I. Association with NH_3 cores
Molinari et al. 1998 A&A 336, 339 II. VLA observations
Molinari et al. 2000 A&A 355, 617 III. Circumstellar dust properties
- **Molinari et al. 1998 ApJ Lett 505, L39**
"IRAS23385+6053: A prototype massive Class 0 object"
- **Brand et al. 2001 A&A 370, 230**
"A molecular-line study of clumps with embedded high-mass protostar candidates"
- **Zhang et al. 2001 ApJ Lett 552, L167**
"Search for CO outflows toward a sample of 69 high-mass protostellar candidates: frequency of occurrence"