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THE YOUNGEST PROTOSTARS

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ABSTRACT. A new class of cold, heavily obscured young stellar objects (YSOs) have recently been identified and designated "Class 0", which are characterized by virtually no emission shortward of 10 μm but strong dust continuum emission at submillimeter wavelengths. Class 0 YSOs are rare and correspond to very young protostars which have not yet accreted the bulk of their final stellar mass. Most, if not all, of them drive powerful jet-like outflows. The main properties of these "submillimeter protostars" are reviewed with particular emphasis on current open problems and future avenues for research.

1. Definition and Observational Properties of Class 0 Protostars

(Sub)millimeter dust continuum mapping of molecular cloud cores conducted over the last decade with large radiotelescopes such as the IRAM 30 m and the JCMT has led to the discovery of several cold, centrally condensed "protostellar clumps" which often remained totally undetected by *IRAS* (e.g., Mezger 1994; Güsten 1994; André 1995). Some of these cold protostellar condensations are associated with formed (i.e., hydrostatic) young stellar objects (YSOs) and have been designated "Class 0" protostars (André, Ward-Thompson, & Barsony 1993 – AWB). The prototype Class 0 object is the ρ Ophiuchi source VLA 1623, first detected with the VLA at 6 cm, and subsequently identified as the driving source of a jet-like CO(2–1) outflow (André et al. 1990; see Fig. 1). More specifically, Class 0 sources or "submillimeter protostars" are defined by the following observational properties (AWB):

- (1) Indirect evidence of a central YSO, as indicated for instance by the detection of compact centimeter continuum VLA emission or the presence of a collimated CO outflow.
- (2) Centrally peaked but extended submillimeter continuum emission tracing the presence of a spheroidal circumstellar dust envelope.
- (3) High ratio of submillimeter to bolometric luminosity: $L_{submm}/L_{bol} >> 5\times10^{-3}$, where L_{submm} is measured longward of 350 μm. (In practice, this often means a spectral energy distribution resembling a single temperature blackbody at T $\sim$ 15-30 K.)

Property (1) distinguishes Class 0 objects from prestellar condensations (e.g., Ward-Thompson et al. 1994). In particular, deep radio continuum VLA observations reveal no compact radio continuum sources in the centers of prestellar cores (Bontemps 1996). Properties (2) and (3) distinguish Class 0 objects from YSOs detected in the near- to mid-infrared such as the Class I sources or "infrared protostars" of Lada (1987). Combining submillimeter and infrared data, it is in fact possible to define a complete, empirical evolutionary sequence (Class 0 $\rightarrow$ Class I $\rightarrow$ Class II $\rightarrow$ Class III) for the early evolution of low-mass YSOs (e.g., Adams, Lada, & Shu 1987; André & Montmerle 1994 – AM). Adopting appropriate values for the dust mass opacity (e.g., Henning et al. 1995), millimeter continuum maps indicate that the *total* (disk + envelope) circumstellar mass decreases by a factor $\sim$ 5–10 on average from one YSO class to the next (AM). Moreover, the ratio L_{submm}/L_{bol} of submm to bolometric luminosity may be used as a quantitative evolutionary indicator for self-embedded YSOs since L_{submm}/L_{bol} is expected to increase with protostellar age (cf. AWB).

The Class 0 condition $L_{submm}/L_{bol} > 5 \times 10^{-3}$ approximately selects objects which have a ratio of circumstellar to stellar mass $M_{env}/M_{\star} > 1$ (AWB; AM). [A roughly equiv- alent, but more practical, criterion is $S^{int}_{1.3mm}(d/160pc)^2/L_{bol} \sim 0.2$ Jy/$L_{\odot}$.] Although inclination effects may a priori affect the above criterion on an individual basis (see Yorke, Bodenheimer,& Laughlin 1995), results obtained on the evolution of outflows from Class 0 to Class I (see § 2.2 below) suggest that this is statistically unimportant. In general, therefore, *Class 0 objects are excellent candidates for being very young protostars in which a hydrostatic core has already formed but not yet accreted the bulk of its final mass.* Thus, most of the mass is still in the form of a dense circumstellar envelope/cocoon at this stage.

In practice, the three usual attributes of Class 0 objects are: (sub)millimeter continuum strength, compact centimeter radio continuum emission, and presence of a collimated jet. Table 1 summarizes the main properties of the presently known sources that verify all the criteria listed above. Several other candidate Class 0 sources discussed in the literature, such as IRAS 08076-3556 (Persi et al. 1993), NGC1333-IRAS2 (Sandell et al. 1994), L483 (Fuller et al. 1995a), and Serpens-SMM3 (Hurt & Barsony 1996), are not included in Table 1 because they do not (yet) satisfy all the required conditions. We also point out that several massive analogs to the mostly low-mass Class 0 protostars of Table 1 have probably been identified in the vicinity of H_2O masers (Jenness et al. 1995).

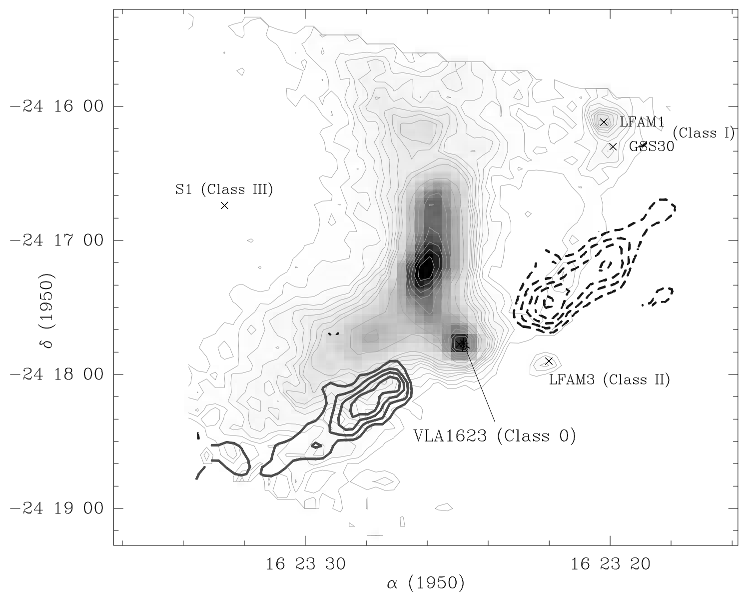

Fig. 1: Grey-scale 1.3 mm continuum map of the ρ Oph A cloud core region obtained with the IRAM 30 m telescope and the MPIfR 19-channel bolometer array. A CSO map of the jet-like CO(3–2) outflow emanating from VLA1623 is superposed (blue-shifted lobe shown by thick solid contours; red-shifted lobe by dashed contours). This figure illustrates that the strength and spatial distribution of the millimeter dust continuum emission are powerful diagnostics of the circumstellar evolution of YSOs.

The scarcity of Class 0 objects in low-mass young stellar populations such as the ρ Ophiuchi embedded cluster and the jet-like morphology of their outflows provide additional evidence that they are significantly younger (probable age $\lesssim 10^4$ yr) than Class I near-IR YSOs (which have an estimated lifetime $\sim 10^5$ yr in ρ Oph and Taurus; e.g., Greene et al. 1994).

2. Recent Related Results

2.1. Evolutionary diagrams for embedded YSOs

To gain insight into the physics of protostars, an evolutionary diagram similar to the H–R diagram for optically visible stars would be highly desirable (see Palla 1995). Unfortunately, the H–R L_{bol}-T_{eff} diagram cannot be used for YSOs since many of them are heavily obscured and have spectral energy distributions (SEDs) much broader than a stellar blackbody at a constant effective temperature T_{eff}. To circumvent this difficulty, Myers & Ladd (1993) introduced the concept of "bolometric temperature" T_{bol}, defined as the temperature of a blackbody having the same mean frequency as the observed SED, and proposed the L_{bol}-T_{bol} diagram as a direct analog to the H–R diagram (see also Chen et al. 1995). In this diagram, Class 0 sources are characterized by the lowest T_{bol} values of all YSOs. The exact physical meaning of T_{bol} is, however, unclear (e.g., Palla 1995).

In another approach, and following up on the work of Yorke & Shustov (1981), Adams (1990) suggested to use the internal visual extinction A_V towards the central sources instead of the temperature. He plotted evolutionary tracks in the L_{bol}-A_V diagram following the "standard" protostellar model of Adams, Lada, & Shu (1987). A disadvantage is that A_V is not a directly observable, model-independent quantity, and is highly dependent on viewing angle.

A perhaps more promising and more practical approach has been recently proposed by Saraceno et al. (1996) in the spirit of the L_{submm}/L_{bol} age indicator. Using millimeter continuum photometry and mapping, they place YSOs in a bolometric luminosity *vs.* millimeter luminosity diagram and show indicative evolutionary tracks. While L_{mm} is well correlated with L_{bol} for the majority of Class I embedded YSOs (Reipurth et al. 1993), Class 0 sources clearly stand out in the L_{bol}-L_{mm} diagram as objects with excess (sub)millimeter emission. The advantage of this diagram is that it exploits the fact that the submillimeter part of a YSO SED is optically thin and directly traces the circumstellar mass.

2.2. Decline of outflow and accretion activity with age

Most, if not all, Class 0 protostars drive highly collimated or "jet–like" CO molecular outflows (e.g., Fig. 1; see Bachiller 1996 for a review). The mechanical luminosities of these outflows are often of the same order as the bolometric luminosities of the central sources (e.g., AWB). In contrast, while there is growing evidence that some outflow activity exists throughout the embedded phase, the CO outflows from Class I sources tend to be poorly collimated and much less powerful than those from Class 0 sources.

In an effort to quantify this evolution of molecular outflows during the protostellar phase, Bontemps et al. (1996a) have recently obtained and analyzed a homogeneous set of CO(2–1) data around a large sample of low-luminosity ($L_{bol} < 50\ L_{\odot}$), nearby ($d < 450$ pc) embedded YSOs, including 36 Class I sources and 9 Class 0 sources. Their results show that essentially *all* embedded YSOs have some degree of outflow activity, suggesting the outflow phase and the infall/accretion phase coincide. In particular, the outflow phase must start virtually as soon as a hydrostatic core forms at the center of a collapsing cloud (e.g., AWB; Bontemps et al. 1996b). This is consistent with the idea that accretion cannot proceed without ejection and that outflows are directly powered by accretion (e.g., Ferreira & Pelletier 1995).

In the Bontemps et al. (1996a) study, Class 0 objects are found to lie an order of magnitude above the well-known correlation between outflow momentum flux and bolometric luminosity holding for Class I sources. This confirms that Class 0 objects differ qualitatively from Class I sources, *independently of inclination effects*. On the other hand, outflow momentum flux is roughly proportional to circumstellar envelope mass in the *entire* sample (i.e., including both Class I and Class 0 sources). As illustrated in Figure 2, this new correlation is independent of the F_{CO}–L_{bol} correlation and most likely results from a progressive decrease of outflow power with time during the accretion phase.

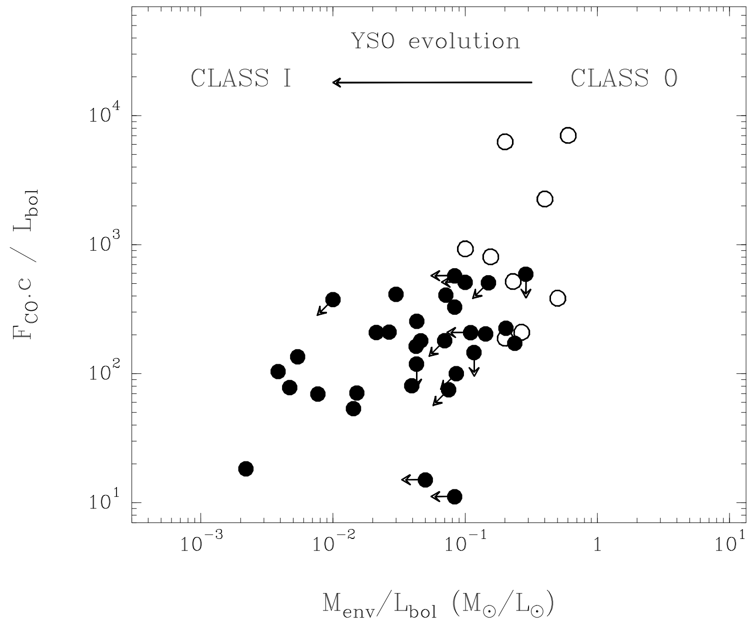

Fig. 2: Outflow efficiency $F_{CO}\,c/L_{bol}$ versus M_{env}/L_{bol} for a sample of nearby Class I (filled circles) and Class 0 (open circles) YSOs (Bontemps et al. 1996a). This diagram, which is essentially free of any luminosity effect, indicates a decline of outflow strength from Class 0s to Class Is.

Since many theoretical models of bipolar outflows (e.g., Ferreira & Pelletier 1995) predict a direct proportionality between accretion and ejection, Bontemps et al. (1996a) further suggest that the observed decline in outflow energetics reflects a corresponding decrease in the mass accretion/infall rate: In this view, $\dot{M}_{acc}$ would decline from $\sim 10^{-5}\,M_\odot\,yr^{-1}$ for the youngest Class 0 protostars to $\sim 10^{-7}\,M_\odot\,yr^{-1}$ for the most evolved Class I sources and most active T Tauri stars.

2.3. Direct evidence of infall in some Class 0 sources

Although depletion of molecules onto grains often renders (sub)millimeter line observations of the youngest protostars difficult, rather convincing spectroscopic signatures of gravitational infall have recently been reported towards several candidate Class 0 sources, confirming their protostellar nature. Good examples include B335 (Zhou et al. 1993), IRAS 16293 (Walker et al. 1994), L1527 (Zhou et al. 1994, Myers et al. 1995), GF9-2 (Güsten 1994), and L483 (Myers et al. 1995). In contrast, there appears to be very little or no net transfer of mass to the inner $\sim$ 2000 AU radius region around Class I sources (cf. Fuller et al. 1995b and Cabrit et al. 1996 for detailed studies of L1551-IRS5 and HL Tau, respectively).

2.4. Outflow/Jet structure

Because of their prominence and their youth, Class 0 outflows offer a unique opportunity to learn more about the ejection mechanism and entrainment process. Recent interferometric CO observations of Class 0 sources (e.g., Bachiller et al. 1995; Gueth et al. 1996) clearly favor jet-driven outflow models (e.g., Stahler 1993) and suggest that molecular outflows are primarily entrained in jet bow shocks (cf. Raga & Cabrit 1993).

2.3. Growth of the circumstellar disk

Although a recent MHD 'cored-apple' model shows that a thin disk may not be necessary to generate an outflow (Henriksen & Valls-Gabaud 1994, Fiege & Henriksen 1996), the presence of a disk (even if tiny) is generally expected in those Class 0 sources with well-developed outflows. Recent (sub)millimeter interferometric measurements do indeed point to the existence of compact ($\lesssim 100$ AU), disk-like structures around IRAS 16293 (Mundy et al. 1992), HH24MMS (Chandler et al. 1995), NGC1333-IRAS4 (Lay, Carlstrom, & Phillips 1995). However, it is important to point out that these compact "disks" appear to be a factor $\gtrsim 10$ less massive than the surrounding circumstellar envelopes (e.g., Chandler et al. 1995; see also AWB for the case of VLA 1623). At the Class 0 stage, therefore, most of the circumstellar mass resides in an extended envelope rather than in a disk. This situation contrasts with more evolved (e.g., Class I) sources such as L1551-IRS5 and HL Tau in which the disk is a very significant (sometimes dominant) component (e.g., Lay et al. 1994).

3. Open Problems and Future Prospects

Since Class 0 YSOs appear to characterize the beginning of protostar evolution ($M_{env} >> M_\star$), they should still be dominated by the effects of their circumstellar cocoon and are likely to retain detailed information about their genesis. These young protostars are thus ideal targets for further detailed observational studies to shed light on the physics of protostellar collapse. A few important unanswered questions are listed below and may be viewed as a plan for future work.

3.1. Magnetic field structure in protostars

While the magnetic field is believed to play a fundamental role in the star formation process (e.g., Mouschovias 1991), it remains poorly constrained by present observations. (Sub)millimetre-wave polarimetry observations on JCMT and OVRO have just started to probe the magnetic field morphology in dense cloud cores and Class 0 protostars, with only preliminary conclusions at this stage. The average magnetic field direction in the dense circumstellar "apple" surrounding VLA 1623 seems to be *perpendicular* to its jet-like CO outflow (Holland et al. 1996), in possible agreement with the MHD 'cored-apple' model of Henriksen & Valls-Gabaud (1994). However, the opposite result is found in the case of IRAS 16293 and NGC1333-IRAS4 (e.g., Tamura et al. 1993; Akeson et al. 1996). Clearly, more studies of this type on large source samples are required to settle the question.

3.2. Density structure of Class 0 envelopes and prestellar cores

Sensitive dust continuum observations with bolometer arrays are a powerful tool to study the density structure of protostellar cores/envelopes and gain insight into the initial conditions of star formation. Although a larger number of sources should be mapped before definitive conclusions can be drawn, several clear trends already emerge from present bolometer-array maps. The envelopes around (Class 0 and Class I) protostars are always found to be strongly peaked towards their centers, even if the associated density gradients may vary from source to source. In general, protostellar envelopes in regions of "isolated" star formation (e.g., Taurus) have density gradients which are roughly consistent with the predictions of the "standard" protostar theory from Shu and collaborators (e.g., Shu et al. 1993): the estimated radial density profiles range from $\rho(r) \propto r^{-1.5}$ to $\rho(r) \propto r^{-2}$ (e.g., Ladd et al. 1991; Motte et al. 1996). However, this simple situation does not seem to hold in star-forming clusters (e.g., ρ Ophiuchi) where some sources at least appear to have steeper density profiles and/or sharp edges (Motte et al. 1996).

The structure of *prestellar* cores is in marked contrast with that of *protostellar* envelopes, whether in clusters or not. Recent submillimeter continuum results (Ward-

Thompson et al. 1994; André, Ward-Thompson, Motte 1996) show that the radial density profiles of prestellar cores flatten out near their centers, being much flatter than $\rho(r) \propto r^{-2}$ at small radii (i.e., less than a few thousand AU). This is illustrated in Fig. 3 which compares the radial intensity profiles observed for the Class 0 object L1527 and the prestellar core L1689B. The results of Ward-Thompson et al. (1994) suggest that the transition from flat to steep inner density profile occurs on a relatively short timescale $\lesssim 10^5$ yr, i.e., *after* the onset of fast dynamical collapse as predicted by ambipolar diffusion models of magnetically-supported cores (e.g., Ciolek & Mouschovias 1994).

One important implication is that the initial conditions for protostellar collapse may depart significantly from a singular isothermal sphere. Consequently, the mass infall rate is likely to be strongly time-dependent at the beginning of the main accretion phase (Foster & Chevalier 1993; Henriksen 1994). This would be consistent with the observed decline of outflow activity with age (§ 2.2).

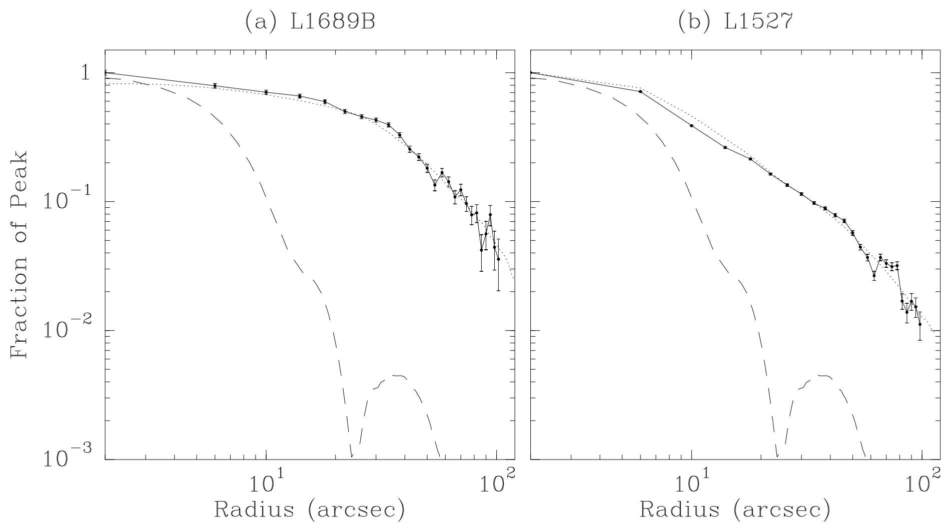

Fig. 3: Azimuthally-averaged radial 1.3 mm intensity profiles of the prestellar core L1689B (a) and of the isolated Class 0 protostar L1527 (b) (see Motte et al. 1996). Model profiles that fit the data are shown as dotted lines. The L1689B model is isothermal and has $\rho(r) \propto r^{-0.4}$ for $r < 4000$ AU (i.e., $\theta < 25''$) and $\rho(r) \propto r^{-2}$ for $r \geq 4000$ AU; the L1527 model has $T(r) \propto r^{-0.4}$ and $\rho(r) \propto r^{-1.5}$. The beam profile is shown as dashed lines.

3.3. Nature of the centimeter radio emission

The centimeter radio continuum emission from Class 0 sources is consistent with free-free radiation, but the physical mechanism responsible for the ionization of the emitting gas is not entirely clear yet. According to the most likely proposed scenario, the radio emission arises from shock-ionized gas as the powerful jet driving the observed molecular outflow shocks against the dense circumstellar environment (e.g., Torrelles et al. 1985; Curiel, Cantó, & Rodríguez 1987). This interpretation is in agreement with the correlation observed between radio luminosity and outflow momentum flux (e.g., Rodríguez et al. 1989, Anglada 1995, Yun et al. 1996). Although the shock-ionized model provides a satisfactory explanation for the optically thin, resolved radio jets observed in some sources (e.g., Bieging & Cohen 1985), it remains to be seen whether the same idea also applies to the compact, partially optically thick emission detected towards the central objects themselves. For the latter emission, another scenario might be photoionization by the soft X-rays emitted by the accretion shock that occurs at the surface of the hydrostatic core (e.g., Bertout 1983) or of the circumstellar disk (e.g., Neufeld & Hollenbach 1994). This alternative mechanism is however severely constrained by the large optical depth of the protostellar envelope to X rays (Bontemps 1996).

With the advent of major new ground-based and space-borne facilities at infrared and longer wavelengths, the above-mentioned problems should not remained unanswered very long. More generally, the next few years should witness much progress in our understanding of star formation. For instance, by combining ISO infrared images with deep submillimeter continuum maps taken with bolometer arrays such as SCUBA, it should soon be possible to obtain complete, unbiased surveys of all nearby star-forming regions for Class I and Class 0 protostars as well as for prestellar dense cores. This will make statistical studies on large, representative samples possible, providing much better estimates of the timescales associated with the various protostellar phases than presently available. Detailed physical studies of the most promising objects will also become feasible with the currently planned large (sub)millimeter interferometer arrays.

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