OBSERVATIONS OF PROTOSTARS AND PROTOSTELLAR STAGES

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ABSTRACT. Our observational understanding of star formation and early stellar evolution is closely linked with our capability to directly measure the basic characteristics (e.g., mass, size, density, temperature) of the circumstellar matter surrounding young stellar objects (YSOs). The advent of sensitive bolometers (including arrays in some cases) on large ground-based radiotelescopes such as the IRAM 30 m or the JCMT has recently yielded significant progress in this field, by providing a very sensitive way to detect and study the dust component of the circumstellar material. In particular, it is now possible to estimate the evolutionary states of all YSOs through systematic measurements of their circumstellar dust masses. In this way, a new type of extremely obscured YSOs (designated "Class 0") characterized by virtually no near-IR/mid-IR emission but strong submillimeter emission have been identified. Class 0 "protostars", of which the jet-like outflow source VLA 1623 in ρ Ophiuchi is the prototype, are surrounded by significantly larger amounts of circumstellar material ($M_{c\star} \gtrsim 0.5\ M_\odot$) than the Class I YSOs observed in the near-infrared (which typically have $M_{c\star} \lesssim 0.1\ M_\odot$). They are also rarer and correspond to the youngest protostellar stage known to date (probable age $\sim 10^4$ yr).

1. Introduction: Protostars, Prestellar clumps, and Pre-main Sequence Stars

Stars are thought to form from the inside-out collapse of dense cloud cores (e.g., Shu et al. 1993; Stahler in this volume). After a probably very short isothermal phase, during which the liberated gravitational energy is freely radiated away (e.g., Henriksen in this volume), an opaque stellar object or *protostar* forms at the center and starts heating up, while continuing to build up its mass from a surrounding infalling envelope or cocoon. The youngest protostars are thus surrounded by large masses of circumstellar material ($M_{c\star}$) compared with their own, growing stellar mass ($M_\star$), i.e., they have $M_{c\star} >> M_\star$. Their luminosity is well approximated by the infall luminosity $L_{inf} \approx GM_\star \dot{M}/R_\star$, where $\dot{M}$ is the infall rate (cf. Stahler and Henriksen in this volume). When protostars have accumulated most of their final, main sequence mass, they become pre-main sequence (PMS) stars which evolve approximately at fixed mass (although accretion of residual amounts of material may still occur through an accretion disk). Therefore, independently of the details of any protostellar theory, and in a statistical sense at least, larger amounts of circumstellar material are expected to surround younger stellar objects .

Observationally, distinguishing the youngest protostars from pre-protostellar condensations which have not started collapsing on the one hand, and from PMS stars still embedded in their parent clouds on the other hand, is very difficult. Because dust emission remains optically thin at $\lambda \sim 1$ mm up to extremely high column densities ($N_{H_2} \lesssim 10^{26}\,cm^{-2}$), submillimeter continuum observations with large single-dish radiotelescopes equipped with sensitive bolometers provide a very sensitive way to detect both high density prestellar clumps on the verge of collapse and circumstellar structures (envelopes and/or disks) around young stellar objects (YSOs) at any evolutionary stage (e.g., protostars, embedded PMS stars, post T Tauri stars). Once circumstellar structures have been distinguished from prestellar condensations by other means (e.g., evidence for a central YSO at infrared or centimeter radio wavelengths), it is possible to use the circumstellar mass inferred from millimeter continum observations as a tracer of YSO evolutionary state. The effectiveness of this method is illustrated in § 2 by the results of an extensive 1.3 mm continuum survey of the ρ Ophiuchi IR cluster. In § 3, the basic properties of a new class of very cold YSOs recently recognized in the submillimeter band and designated "Class 0" are described, with particular emphasis on the ρ Ophiuchi source VLA 1623. Finally, § 4 proposes a revised observational scenario of early stellar evolution.

2. Evolutionary Status of the near-IR sources of the ρ Ophiuchi cluster

2.1 Millimeter continuum observations

In an effort to sample the evolution of the mass and spatial distribution of the circumstellar material as a function of time, André & Montmerle (1994; hereafter AM) have used the IRAM 30-m telescope equipped with the MPIfR bolometer to conduct a 1.3-mm continuum survey of more than a hundred YSOs located in the ρ Ophiuchi cloud and nearby related regions. In particular, single-point photometry was obtained for each of the 78 members of the ρ Oph near-IR cluster discussed by Wilking, Lada, & Young (1989; hereafter WLY), which comprise a large number of Class I ("infrared protostars"), Class II ("embedded T Tauri stars"), and Class III sources ("naked T Tauri stars") (cf. Lada 1987). With an overall (3-σ) sensitivity of ~ 20 mJy/beam, the detection rate of these systematic "ON-OFF" observations was high, on the order of 40 %. In addition, mapping observations were performed around a total of 19 YSOs (see AM for other details).

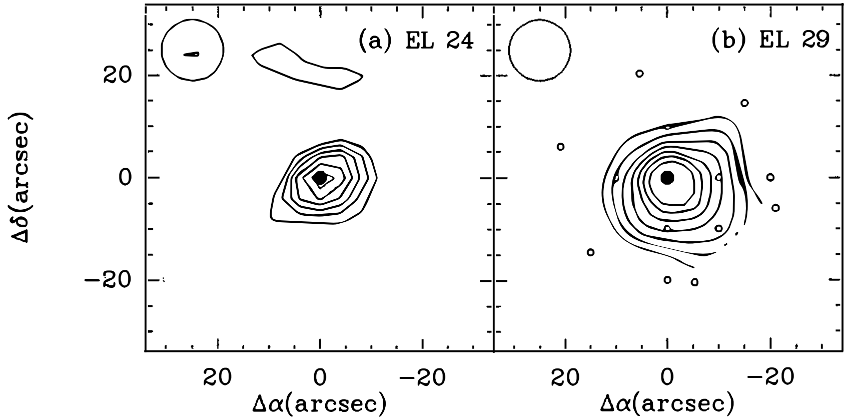

Figure 1. IRAM 30-m bolometer maps of the Class II IR source EL 24 (a) and of the Class I IR source EL 29 (b) (from André & Montmerle 1994).

2.2 Circumstellar nature of the millimeter emission

The millimeter continuum detections most likely correspond to thermal emission from cold dust around the young stars. In most of the bolometer maps (e.g., Fig. 1), the emission is centrally peaked at the nominal YSO position and well contrasted from the surrounding medium, almost independently of IR Class or strength. This is a clear indication that the emission arises from *circumstellar* dust associated with the YSOs themselves rather than from *interstellar* dust clumps related to cloud structure in regions of high column densities. In contrast, the various molecular-line maps that we have obtained so far with the *same* telescope toward the *same* sources show very little structure at the positions of the YSOs and most likely trace larger-scale emission from the ambient cloud itself (e.g., Despois et al. 1994). The single-dish continuum technique therefore appears particularly powerful to probe circumstellar material (although line observations with millimeter interferometers can also discriminate against large-scale cloud emission).

In addition, the maps show that, when detected, the millimeter emission of Class II IR sources is unresolved within the 12" beam of the telescope, consistent with the presence around these sources of circumstellar dust disks with radii significantly smaller than 1,000 AU. This supports the hypothesis of WLY that Class II sources are classical T Tauri stars (sometimes) embedded in (interstellar) cloud material. In contrast, the Class I IR sources, almost always detected at 1.3 mm, are resolved, but display a concentrated structure (FWHM $\lesssim$ 25", i.e., radii $\lesssim$ a few 10^3 AU at 160 pc). This is qualitatively consistent with Class I YSOs being protostellar sources "self-embedded" in spheroidal circumstellar envelopes, although the sizes of these envelopes appear to be $\gtrsim 5$ times smaller than predicted by the "standard" Adams, Lada, & Shu (1987; hereafter ALS) model.

2.3 Circumstellar masses

In order to make meaningful evolutionary comparisons, one needs to estimate the *total* (i.e., integrated) circumstellar fluxes $S^{int}_{1.3mm}$ from the various YSOs. We have done so on the basis of our mapping results and various extrapolation methods. In particular, because the outer parts of circumstellar envelopes may not be dense enough to emit significant dust continuum emission at 1.3 mm, we have used the standard model of protostellar envelopes (e.g., Terebey, Shu, & Cassen 1984; ALS) to infer an "effective" upper limit to $S^{int}_{1.3mm}$ based on the emission mapped in the inner regions (see AM and Terebey, Chandler & André 1993 for details).

Assuming an optically thin, isothermal dust source, $S^{int}_{1.3mm}$ is readily converted into a total (dust + gas) circumstellar mass $M_{c\star}$ by a relation of the type: $M_{c\star} = [\, S^{int}_{1.3mm}\, d^2 \,] \,/\, [\, \kappa_{1.3}\, B_{1.3}(T_{dust}) \,]$, where $B_{1.3}$ is the Planck function $\lambda = 1.3$ mm.

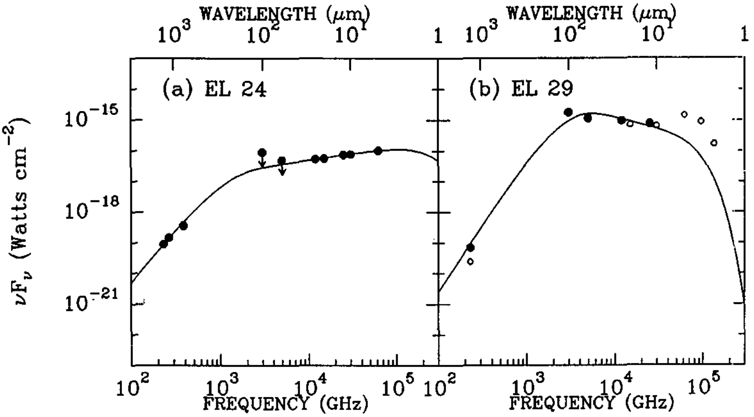

Figure 2. Spectral energy distributions of the Class II IR source EL 24 (*a*) and of the Class I IR source EL 29 (*b*); a disk fit and an (optically thin) envelope model are also shown in (*a*) and (*b*), respectively (adapted from André & Montmerle 1994).

In order to assess the influence of temperature effects on the mass estimates, we used disk models similar to those of Beckwith et al. (1990) for Class II sources and simple (optically thin) power-law envelope models for Class I sources (see examples in Fig. 2 and AM for details). This modeling study shows that the volume-averaged temperature of the emitting circumstellar material is generally well constrained by the spectral energy distributions

(SEDs) to be $< T_{dust} > \approx 30$ K.

The largest uncertainty in the mass determinations arises from the only approximately known value of the dust opacity per unit mass column density $\kappa_{1.3}$, which implicitly contains the dust-to-gas ratio. For the extended circumstellar matter seen around Class I sources which is probably quite similar to the material of dense cores, we use $\kappa_{1.3} \simeq 0.01$ cm^2 g^{-1}, as this value seems appropriate (within a factor ~ 2) for dense ($n \gtrsim 10^6$ cm^{-3}) cloud regions (e.g., Mezger 1990; André, Ward-Thompson, & Barsony 1993, hereafter AWB). In the circumstellar disks of Class II sources, the dust opacity is more uncertain since particle growth, possibly in the form of fractal aggregates, may occur prior to planet formation, which will enhance κ_ν over the value applying to dense cores (e.g., Beckwith & Sargent 1991; Ossenkopf 1991). To facilitate comparisons, we adopt the same value $\kappa_{1.3} \simeq 0.02$ cm^2 g^{-1} for Class II and Class III sources as Beckwith et al. (1990) in their related mm continuum study of T Tauri stars in Taurus.

Converting $S_{1.3}^{int}$ into $M_{c\star}$ in this way, we find that the circumstellar masses of Class III, Class II *and* (contrary to expectation) Class I near-IR sources are *small* compared to stellar masses (i.e., are $<< 1\ M_\odot$). They are also smaller than the masses (typically 0.5–3 $M_\odot$) found by Ward-Thompson et al. (1994) for *pre-protostellar* condensations, using a similar dust continuum technique. More precisely, the large majority of Class III sources are undetected at 1.3 mm, implying that their circumstellar masses are lower than our detection threshold: $M_{c\star} < 3 \times 10^{-3}$ M$_\odot$. The median value for detected Class II sources is $\sim 0.01\ M_\odot$, i.e., on the order of the mass of the "minimum solar nebula" only (but 70 % of all Class II sources have a circumstellar mass *below* this value). The median mass for Class I sources is only 6 times larger, and their maximum mass is comparable with that of Class II sources ($\sim 0.1\ M_\odot$).

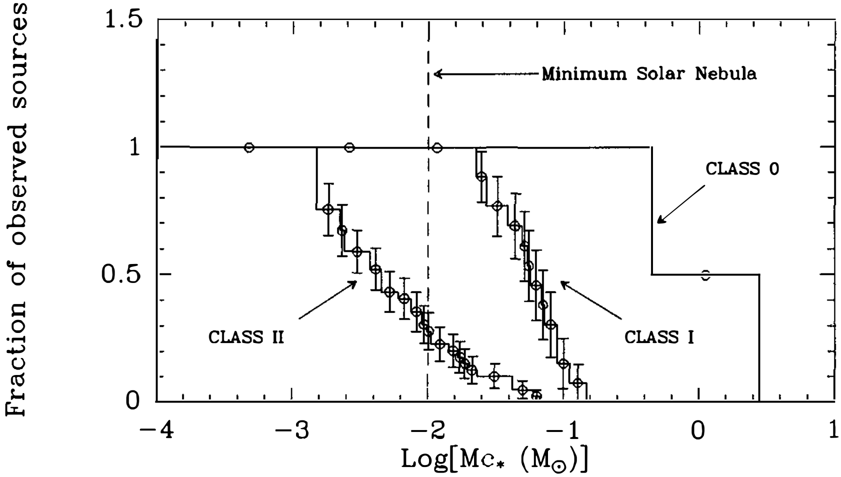

Figure 3. Cumulative distributions of the circumstellar mass $M_{c\star}$ for the ρ Oph Class II, Class I sources, and "Class 0" sources (see § 3) (from André & Montmerle 1994).

These results are illustrated in Figure 3. They confirm the evolutionary sequence Class I → Class II → Class III inferred from IR studies (Lada 1987). However, the small values of the circumstellar masses measured around the near-IR sources of ρ Ophiuchi suggest that, *as early as the Class I stage, YSOs have already accumulated most of their final stellar mass, and thus are no longer in the main accretion phase* (here defined by $M_{c\star} > M_\star$).

3. A New Class of YSOs: The "Class 0" protostars

A posteriori, the failure to find an object in the early protostellar stage when $M_{c\star} > M_\star$ among near-IR sources is perhaps not too surprising since detailed numerical calculations of protostellar collapse suggest that the spectral appearance of the youngest protostars should more closely resemble that of a blackbody at 10–30 K (cf. Boss & Yorke 1990) than that of a relatively broad Class I SED (as in ALS). The youngest stellar objects are thus likely to be found among strong (sub)millimeter continuum sources so highly obscured by their own circumstellar material that they are virtually undetectable at near-IR wavelengths.

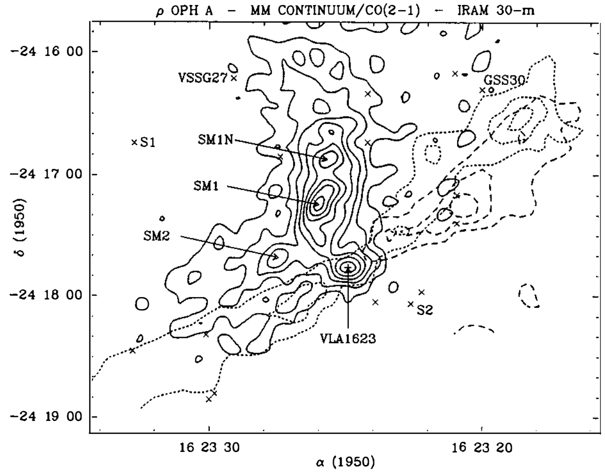

Figure 4. Millimeter continuum map of ρ Oph A obtained with the IRAM 30 m telescope and MPIfR bolometer (cf. AWB). The jet-like CO outflow driven by the candidate low-mass protostar VLA 1623 is superposed (cf. André et al. 1990).

3.1 Protostellar and/or prestellar condensations in ρ Oph A

It was recently recognized that the source VLA 1623 in the ρ Ophiuchi cloud core A is very likely a stellar object with such characteristics (AWB). VLA 1623 was first discovered with the VLA at 6 cm as part of a radio continuum study of the B3 star S1 and its surroundings (André et al. 1988; Leous et al. 1991). It was subsequently identified as the driving source of a jet-like CO outflow by André et al. (1990). Follow-up continuum mapping of ρ Oph A at 1.3 mm with the IRAM 30 m telescope (see Fig. 4) and 800, 450, and 350 μm with the JCMT showed that VLA 1623 coincides with a compact, roughly spherical clump of radius $\sim$ 1000 AU, total mass $\sim$ 0.6 $M_\odot$, average density $\sim 2 \times 10^7$ cm^{-3}, luminosity $\sim$ 1 $L_\odot$, and outer temperature $T_d \lesssim 20$ K (AWB; see also Fig. 5). This clump is thus a candidate protostellar condensation reminiscent of those described by Güsten in this volume (see also Mezger 1993). In fact, our submilimeter mapping of ρ Oph A reveals at least three more compact clumps (labeled SM1, SM1N, and SM2 in Fig. 4) which have apparent characteristics (e.g., M $\lesssim$ 1 M$_\odot$) very similar to VLA 1623 and are also invisible at infrared wavelengths.

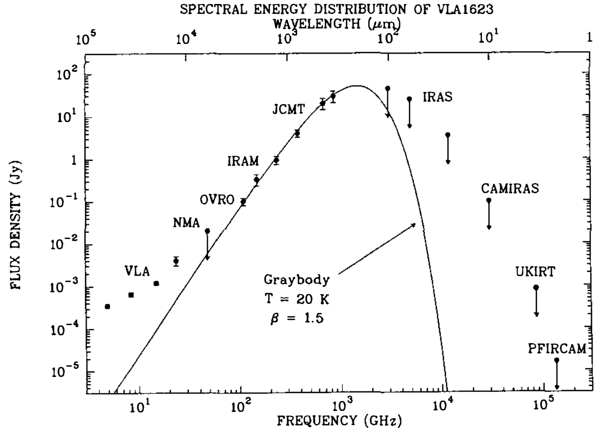

Figure 5. Spectral energy distribution of VLA 1623 along with a graybody fit (adapted from André, Ward-Thompson, & Barsony 1993).

Mezger et al. (1992) independently mapped the same region at IRAM with very similar results, and interpreted all these clumps as low-mass, "isothermal protostars". However, based only on dust continuum observations, it is very difficult to distinguish true *protostellar* condensations from *pre-protostellar* condensations similar to those found by Ward-Thompson et al. (1994) in their JCMT continuum mapping survey of "Myers" dense cores with no embedded sources. The reason is that these condensations are expected to form relatively slowly through a quasi-static phase of ambipolar diffusion during which they remain approximately in virial equilibrium. Since the collapse is expected to proceed from the inside-out (see Stahler in this volume), most of the material in the youngest protostellar condensations (those which have just started collapsing) is still in equilibrium, making them virtually indistinguishable from pre-protostellar condensations. (Spectroscopic signatures of collapse are often ambiguous, although claims have been made in the case of some "Class 0" objects such as B335 – Zhou et al. 1993; see also Güsten in this volume.)

In ρ Oph A, all four submillimeter clumps are within a factor of 2 of virial equilibrium (see AWB). In the case of VLA 1623, the compact VLA continuum emission (which most likely traces the existence of shock-ionized gas at $T \sim 10^4$ K), together with the presence of the bipolar flow, strongly suggest that the brief isothermal phase has been passed and that a *stellar* object has already formed at the center. On this basis, AWB interpreted VLA 1623 as a *protostar* in the main accretion phase (see also *3.2* below). In contrast, none of the other submillimeter condensations of ρ Oph A are associated with a molecular outflow or a compact radio continuum source. Furthermore, closer inspection reveals that these other clumps are more amorphous in shape than VLA 1623 (for instance, their peak positions tend to depend on the wavelength of observation), suggesting the absence of any central attracting and/or heating source inside them. On these grounds, AWB hypothesized that SM1, SM1N, and SM2 are *pre-protostellar* in nature and have *not yet* entered the isothermal collapse phase.

3.2 VLA 1623 as the prototype of a new class of YSOs

Independently of any model, the cold temperature, low bolometric luminosity, relatively massive circumstellar structure, and high internal obscuration ($A_V \gtrsim 1000$) of VLA 1623 all point to an extremely young object, perhaps a true protostar. For instance, the location of VLA 1623 in various theoretical evolutionary diagrams for (low-mass) protostars (e.g., Appenzeller & Tscharnuter 1975; Adams 1990) suggests an age ranging from $\sim 10^3$ yr to 3×10^4 yr (this "age" has to be understood as the time elapsed since the formation of a central, opaque protostellar core, i.e., since the end of the isothermal phase).

AWB suggested that VLA 1623 and a few other low-luminosity YSOs, all characterized by unusually high values of the ratio L_{submm}/L_{bol} and undetected in the near-IR, make up *an entirely new class of YSOs* (the "Class 0"), corresponding to the "theoretical" concept of a protostar in the main accretion phase (defined by $M_{c\star}/M_\star > 1$; cf. § 1). Indeed, while the submillimeter luminosity L_{submm} (or almost equivalently $L_{1.3mm}$) of a protostellar source provides a relative measure of its *circumstellar* mass $M_{c\star}$, the bolometric luminosity L_{bol} may be used to infer the central *stellar* mass $M_\star$ on the basis of various plausible mass–luminosity relations for protostars (e.g., Fig. 6). In the youngest (accreting) sources at least, the measurable ratio $L_{1.3mm}/L_{bol}$ should thus tend to reproduce the variations of the mass ratio $M_{c\star}/M_\star$. The boundary between the Class I and the Class 0 is by definition set at the critical luminosity ratio corresponding to $M_{c\star}/M_\star = 1$ (see AWB for explicit values). However, because of uncertainties in the relations between L_{bol} and $M_\star$ on the one hand and between $L_{1.3mm}$ and $M_{c\star}$ on the other hand, the actual boundary is necessarily somewhat vague. In practice, the two classes are best distinguished in diagrams plotting $S_{1.3mm}^{int}$ (or equivalently $M_{c\star}$) against L_{bol} (cf. Fig. 6). When studying highly obscured protostellar objects, such diagrams appear to be more appropriate equivalents of the H–R diagram than the L–A_V diagram of Adams (1990) (cf. Saraceno et al. 1994).

As Figure 6 shows, there is continuity between Class I and Class 0 sources. However, while objects still well in the main accretion phase are dominated by the effects of their circumstellar cocoon ($M_{c\star} >> M_\star$) and are likely to retain detailed information about their genesis, those with $M_{c\star} << M_\star$ are at the end of their accretion phase and are probably already dominated by stellar rather than protostellar processes. In that sense, Class 0 sources, which provide good observational candidates for being in the former stage, cannot just be considered as "extreme Class I" sources.

It is important to point out that Class 0 sources are statistically very young. For instance, in the ρ Oph central region where the IRAM 30 m mapping study of Mezger et al. (1992) provides an essentially complete survey for Class 0 sources down to $M_{c\star} \approx 0.1\ M_\odot$, VLA 1623 is the *only* good candidate while there are between 11 and 24 near-IR Class I sources known with $L_{bol} \gtrsim 1\ L_\odot$ (cf. WLY and AM). This suggests that the lifetime of Class 0 sources is at least an order of magnitude shorter (i.e., $\lesssim 10^4$ yr) than the estimated lifetime of Class I sources ($\lesssim 10^5$ yr; cf. WLY and Kenyon et al. 1990).

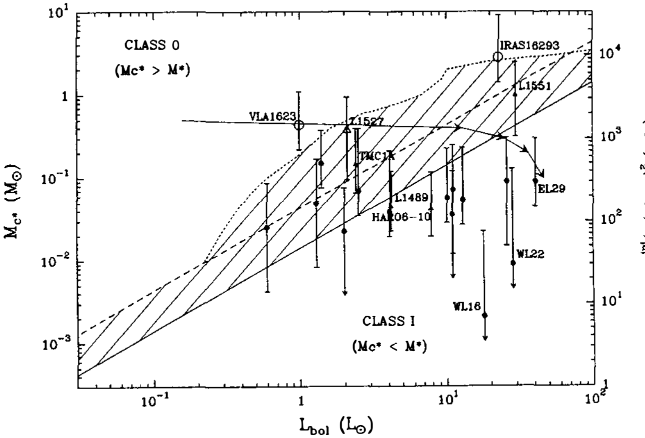

Figure 6. Circumstellar mass $M_{c\star}$ against bolometric luminosity L_{bol} for the ρ Oph Class I and Class 0 sources (filled and open circles). The hatched area represents the border zone between Class I and Class 0 (see AM for details). The locations of the Taurus infrared protostellar candidates modeled by ALS are shown (as triangles) for comparison. An indicative protostellar evolutionary track for an initial cloud core mass $\sim 0.5\ M_\odot$ and a mass infall rate $\sim 10^{-5}\ M_\odot\,\mathrm{yr}^{-1}$ is superposed.

3.3 Jet-like outflows from class 0 protostars

One of the most outstanding features of the newly recognized Class 0 sources is that virtually all of them drive spectacular CO molecular outflows. These outflows are highly collimated or "jet-like" (with length-to-width ratios exceeding 10 and opening angles smaller than 30°; see, e.g., Fig. 4), relatively fast (with typical characteristic velocities $V_{char} \gtrsim 50\ \mathrm{km\,s^{-1}}$), apparently very young (with dynamical timescales $t_{dyn} << 10^4$ yr), and powerful (with mechanical powers $L_{CO} = 1/2\,\dot{M}_{CO}\,V_{char}^2$ approaching ~ 50 % of the bolometric luminosity of the central sources). Two of the most remarkable of these jet-like CO outflows are those driven by the Class 0 sources L1448-C (Bachiller et al. 1990) and VLA 1623 (André et al. 1990). In contrast, while there is growing evidence that some outflow activity exists throughout the embedded phase (e.g., Terebey et al. 1989; Parker et al. 1991), the CO outflows from Class I sources tend to be poorly collimated, slower, and much less energetic than those from Class 0 sources. In an effort to characterize the evolution of molecular outflows during the protostellar phase, Bontemps et al. (1994) have recently obtained and analyzed a homogeneous set of CO(2–1) data around a large sample of low-luminosity ($L_{bol} < 100\ L_{\odot}$) embedded YSOs, including 28 Class I sources and 5 Class 0 sources. Their results shows that Class 0 sources are distinguished from Class I sources not only by stronger submillimeter continuum emission (which is the criterion defining the Class 0), but also by more collimated and *more powerful CO outflows* (see Fig. 7). This clear evolution of outflow characteristics from Class 0 to Class I is consistent with the most recent theoretical views on the structure of molecular outflows (e.g., Stahler 1993), according to which the observed CO outflows represent ambient gas that has been progressively entrained (in a turbulent fashion) by an underlying jet directly originating in the central star and/or circumstellar structure. In this picture, the youngest CO outflows are indeed expected to be the fastest and most highly collimated flows, i.e., to appear " jet–like". Evidence for the driving jet has very recently been found toward some Class 0 sources in the form of shock-excited molecular hydrogen emission (Bally et al. 1993; Davis et al. 1993) or Herbig-Haro objects (Eiroa et al. 1993).

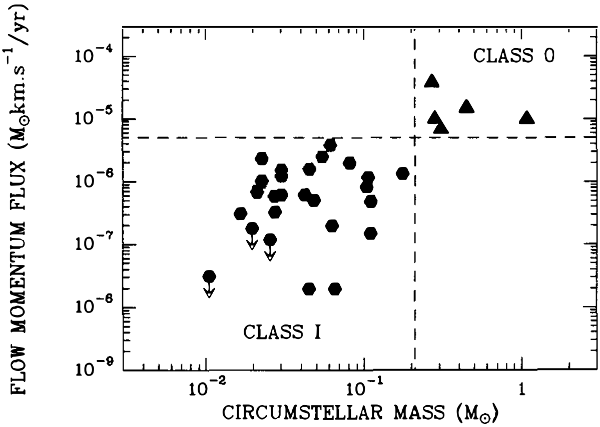

Figure 7. Outflow momentum flux against circumstellar mass of the driving source for a sample of nearby, low-luminosity Class I and Class 0 YSOs (from Bontemps et al. 1994).

4. Conclusions: A Revised Observational Scenario of Early Stellar Evolution

The recent (sub)millimeter continuum results obtained on low-mass YSOs (e.g., AM) confirm the usefulness of SEDs to infer the evolutionary states of YSOs, as first pointed out by Lada (1987) in the infrared range. However, it is now apparent that observing the SEDs at wavelengths significantly longer than 100 μm (e.g., at 1.3 mm) is of prime importance to get at a complete evolutionary picture. In particular, the strength and spatial distribution of the millimeter continuum emission of YSOs may be used as *quantitative* tracers of the progressive

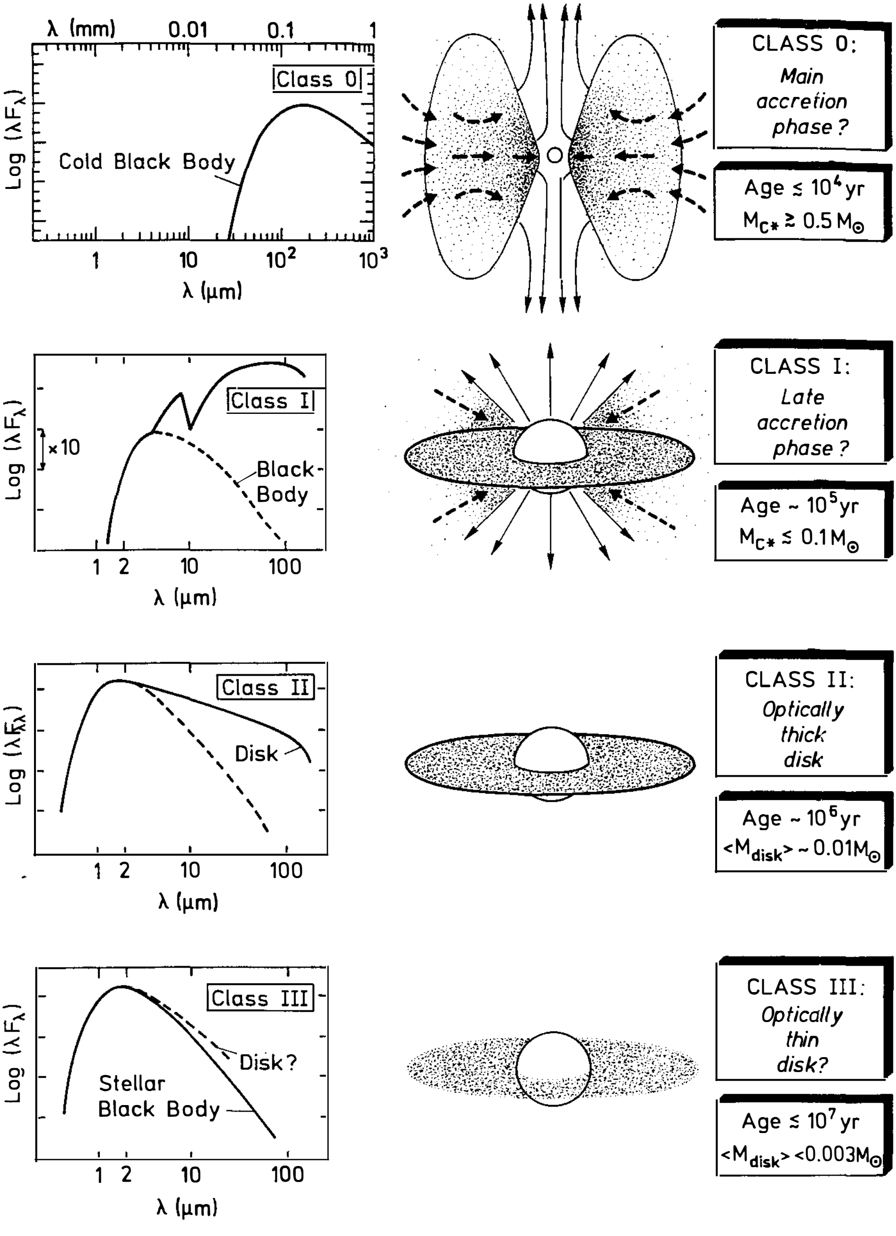

Figure 8. Our revised, quasi-continuous evolutionary sequence of SEDs for low-mass YSOs.

decrease and condensation of the circumstellar material as early stellar evolution proceeds. We thus propose a revised evolutionary scenario from Class 0 to Class III (see Fig. 8).

In this scheme, the Class 0 sources are the youngest stellar objects, probably true protostars at the beginning of the main accretion phase. They are virtually *undetectable in the near-IR* ($\lambda < 10\mu$m) and their SEDs closely resemble that of a *single temperature blackbody* at T ~ 10–30 K. These objects are in the process of assembling the bulk of their final stellar mass which is still in the form of an "apple–like" circumstellar structure. Although they probably have not developed a significant disk yet, they are already driving jet–like outflows (see Henriksen & Valls-Gabaud 1993 and Henriksen in this volume for a possible mechanism). Present observations are indeed consistent with the outflow phase starting *as soon as a protostellar core forms* at the center of a collapsing dense cloud fragment. Inflow and outflow must therefore occur *simultaneously* (see also Lada & Shu 1990). Virtually all Class 0 sources known to date are associated with VLA radio continuum emission, which probably traces free-free radiation from shock-ionized material in the associated wind and/or the accretion shock at the surface of the central object (this VLA emission is one of the least understood observed characteristics of this stage).

The next stage is that of the near-IR Class I sources or "infrared protostars" of Lada (1987), which have much broader spectra than Class 0 sources, clearly implying a wide range of temperatures. Based on their millimeter continuum properties, these objects are confirmed to be *self–embedded* in spheroidal envelopes, but the new result is that these envelopes contain only *residual (i.e., substellar) amounts of circumstellar material.* In that sense, Class I sources have passed the main accretion phase and probably are in a late (and perhaps slower) accretion phase, affecting the highest angular momentum material of the parent cloud core. For this reason, they are likely to have developed a significant disk (with radius up to $\lesssim$ 100 AU; e.g., Terebey et al. 1984), although millimeter interferometric observations show that this disk cannot be very massive (Terebey et al. 1993). Class I sources also drive CO outflows, but these outflows are much broader, slower, and less "penetrating" than those of Class 0 sources (e.g., Bontemps et al. 1994).

The last two stages in our revised scenario correspond to the near-IR Class II and Class III sources, and are virtually unchanged with respect to Lada's scenario (see AM for details). These two classes group PMS stars which have passed the self-embedded phase but are in some cases still obscured by *interstellar* material from their parent clouds.

Although this evolutionary progression of SEDs is in fact continuous and may be parameterized by a "mean frequency" or a "bolometric temperature" (Myers & Ladd 1993), the break down of YSOs into of four distinct classes is justified by the fact they correspond to conceptually different stages of evolution.

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