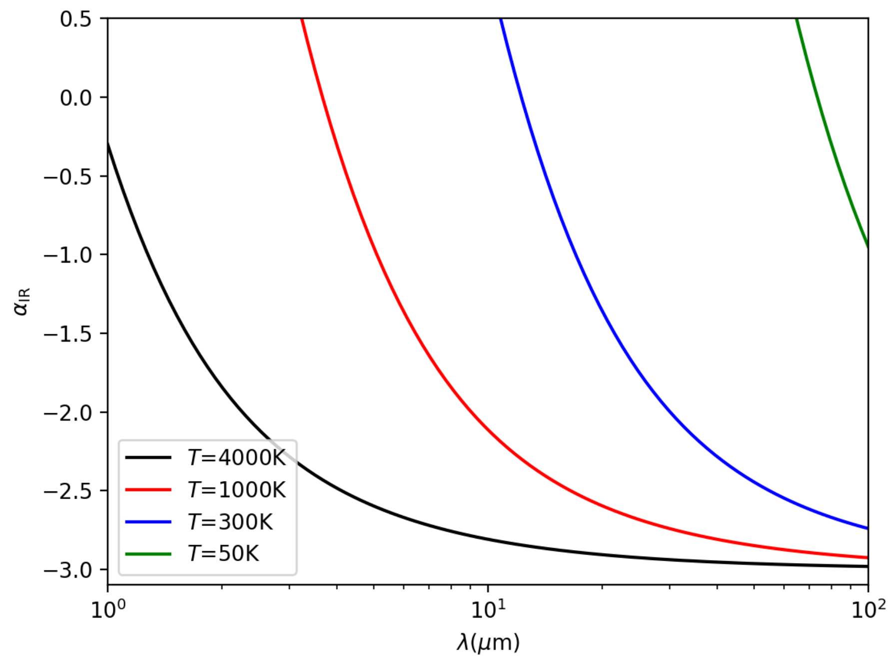
α_{IR} for different blackbodies



α_{IR} and Infrared Excess

THE ASTROPHYSICAL JOURNAL, 420:837–862, 1994 January 10

FROM T TAURI STARS TO PROTOSTARS: CIRCUMSTELLAR MATERIAL AND YOUNG STELLAR OBJECTS IN THE ρ OPHIUCHI CLOUD

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Received 1992 November 30; accepted 1993 July 20

ABSTRACT

We present the results of a 1.3 mm continuum survey for cold circumstellar dust, conducted with the IRAM 30 m telescope on a sample of over 100 young stellar objects (YSOs) in or near the ρ Ophiuchi molecular cloud. To correlate the millimeter results with other source properties, we have used the IR classification of Wilking, Lada, & Young, but revising it critically to take into account factors such as heavy extinction. We find a sharp threshold in millimeter flux density at an infrared spectral index $\alpha_{IR}(2.2\text{–}10\ \mu m) \simeq -1.5$, which is also visible in the IRAM 30 m survey of Taurus-Auriga T Tauri stars by Beckwith and coworkers. We show that this threshold is well correlated with a disk opacity transition at $\lambda \simeq 10\ \mu m$, and can be used to set a physical boundary between Class III and Class II IR sources. At a detection sensitivity of $\sim$20–30 mJy beam^{-1} (3 σ) at 1.3 mm, less than 15% of the Class III IR sources, but as much as 60% of the Class II sources and 70%–90% of the Class I sources, are detected. Statistical studies show that the peak 1.3 mm fluxes of deeply embedded Class I sources, currently referred to as "protostars," and of "classical" T Tauri stars (Class II sources) are comparable within a factor of 2 at the angular resolution of the telescope (12″ FWHM, or a linear diameter $\sim$2000 AU). Maps of the millimeter emission are consistent with the presence of unresolved disks around Class II sources and of resolved, extended envelopes around Class I sources. Therefore, the difference between Class I and Class II YSOs lies mainly in the *spatial distribution* of their circumstellar dust. Converting the integrated millimeter fluxes derived from our maps into masses, we find that (1) $\sim$30% of the Class II sources have masses larger than the "minimum-mass solar nebula" ($\sim$0.01 $M_\odot$); (2) the envelopes of Class I sources contain more circumstellar material than Class II disks, consistent with Class I sources being younger than Class II sources; but (3) their total circumstellar masses are not large ($\lesssim$0.1 $M_\odot$). This suggests that the central object has already accumulated most of its final stellar mass at the Class I stage. In contrast, a very strong 1.3 mm emission is found toward two deeply embedded outflow sources (IRAS 16293 and VLA 1623) which remain undetected shortward of 25 μm. These latter sources belong to a new class of YSOs ("Class 0") introduced by André, Ward-Thompson, & Barsony, which are surrounded by significantly larger amounts of circumstellar material ($\sim$0.5 $M_\odot$ or more), still to be accreted by the central protostellar core. Class 0 YSOs appear to be significantly younger, and therefore at an earlier protostar stage, than Class I sources.

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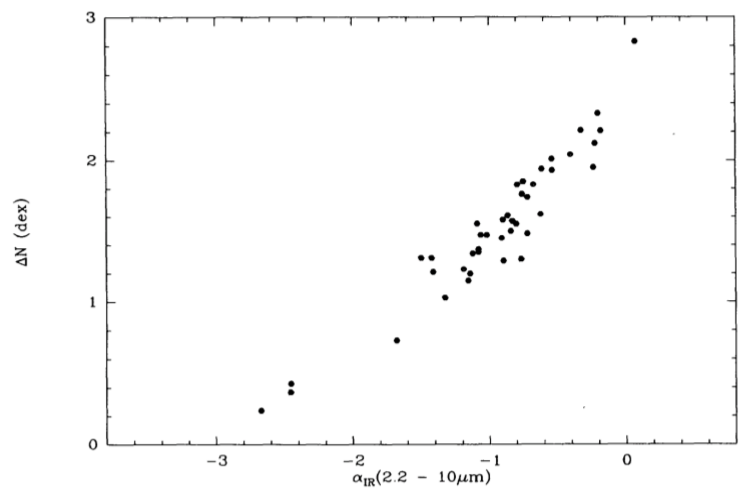
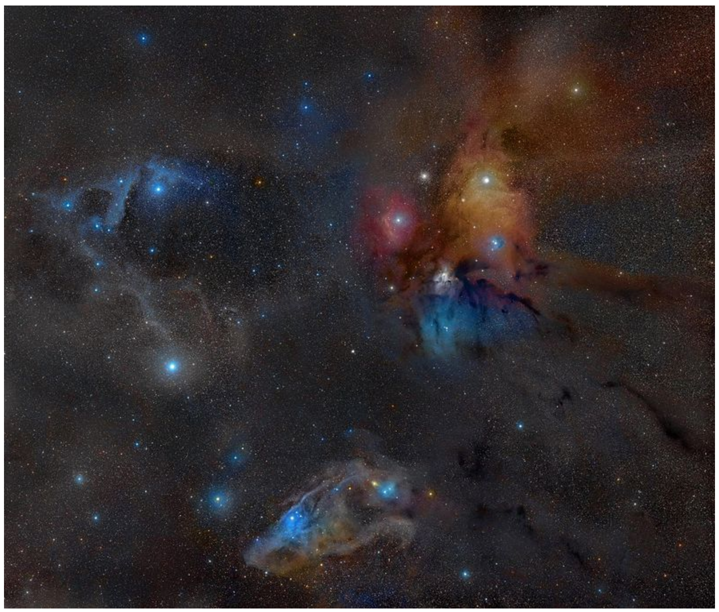


FIG. 2.—Plot of the 10 μm IR excess ΔN vs. the near-IR spectral index α_{IR} measured between 2.2 and 10 μm, for the T Tauri stars of Taurus-Auriga. The good correlation suggests that α_{IR} may be used as an indicator of the 10 μm excess for highly extinguished stars where it is difficult to measure directly by comparison with the photosphere. $\Delta N \sim 1$ marks the boundary between optically thin and optically thick disk emission at 10 μm (cf. Skrutskie et al. 1990).



THE NATURE OF THE EMBEDDED POPULATION IN THE RHO OPHIUCHI DARK CLOUD: MID-INFRARED OBSERVATIONS

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AND

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ABSTRACT

We present results of mid-infrared (primarily 10 and 20 μm wavelength) observations of previously identified members of the embedded population of the ρ Ophiuchi dark cloud. In combination with previous infrared and optical data, these observations enable determination of broad-band energy distributions for 32 of the 44 sources known to be embedded in the cloud. From analysis of these observations we find that the majority of the sources emit the bulk of their luminosity between 1 μm and 20 μm. These sources apparently are surrounded by dust shells and are probably pre-main-sequence in nature. Consequently, relatively accurate bolometric luminosities of these objects are obtained by appropriately integrating their energy distributions. We find that the embedded cluster is predominantly composed of low-luminosity objects with luminosities in the range $0.1 \leq L/L_{\odot} \leq 25$. Nearly half (44%) of the sources are less luminous than the Sun and are among the lowest luminosity pre-main-sequence/protostellar objects yet observed. When corrected for observational selection effects, the resulting luminosity function constructed for the embedded population appears to be deficient in intermediate-luminosity stars compared with the luminosity function for field stars. The significance of this result and its consequences for star formation in and early evolution of open cluster systems are considered and discussed.

Subject headings: clusters: open — infrared: sources — nebulae: individual — stars: evolution

Classification of T-Tauri stars

STAR FORMATION: FROM OB ASSOCIATIONS TO PROTOSTARS

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Star formation: from OB associations to protostars.

Show affiliations

Lada, Charles J.

A scenario for early stellar formation is presented, based on the current understanding of global processes (such as spiral density waves, sequential star formation, the dynamic evolution of OB associations and clusters and the initial mass function) and the formation and early evolution of individual objects. Studies of the early dynamical evolution of OB associations support the contention that the unbound dynamical state of OB associations is a result of the combination of low star-formation efficiency and rapid and efficient gas dispersal. The question of why low star formation efficiency plays a role in the star formation process is addressed. Special attention is given to the evolution of protostars and young stellar objects. The utility of studying the optical-IR broadband energy distributions of embedded sources is emphasized, and the prospects of such studies for uncovering true protostars and directly deciphering the star

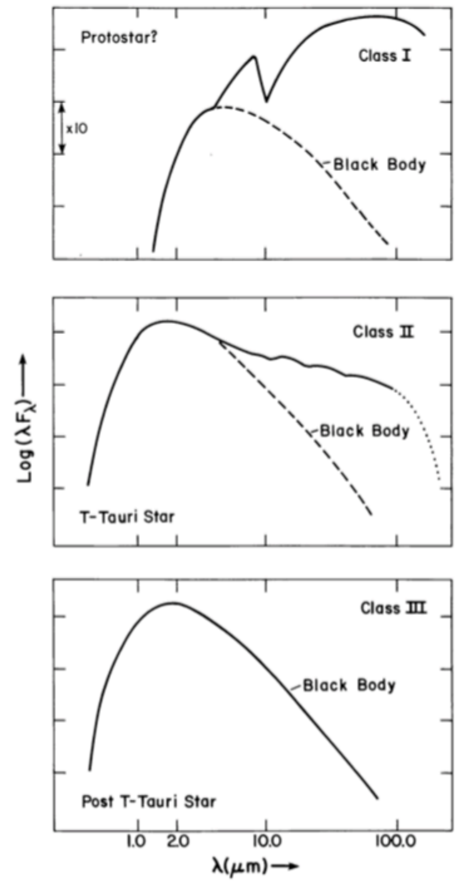
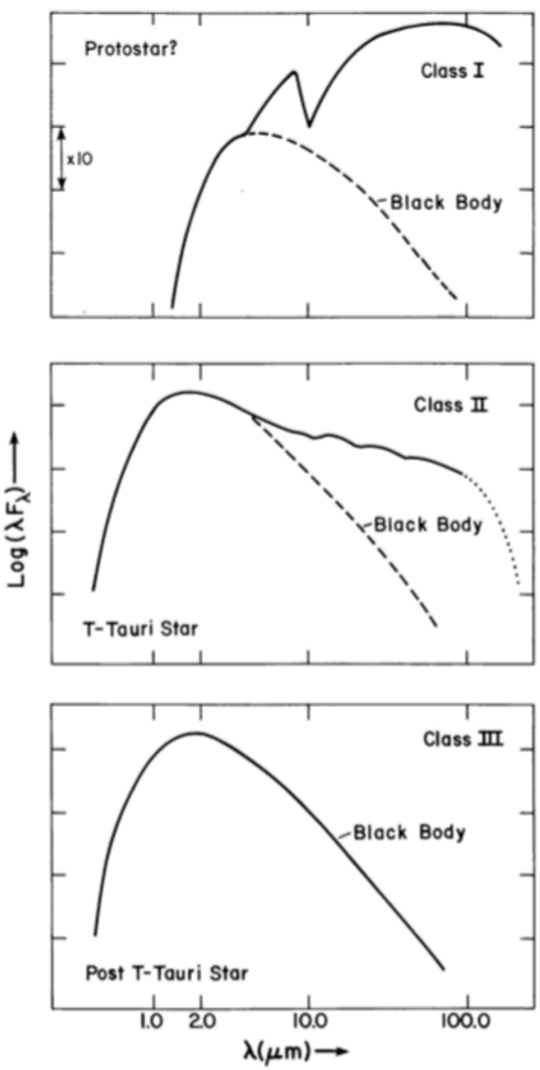


Figure 2. Proposed classification scheme for the energy distributions of embedded young stellar objects. Class I objects have broader than blackbody distributions with slopes or spectral indices which are positive longward of 2 microns wavelength; these objects may be protostars. Class II objects have broader than blackbody distributions which are flat or have negative slopes longward of two microns. Class II distributions are characteristic of T Tauri stars. Class III distributions are fit well by reddened blackbody functions and represent reddened stellar photospheres of stars very near to or on the ZAMS.



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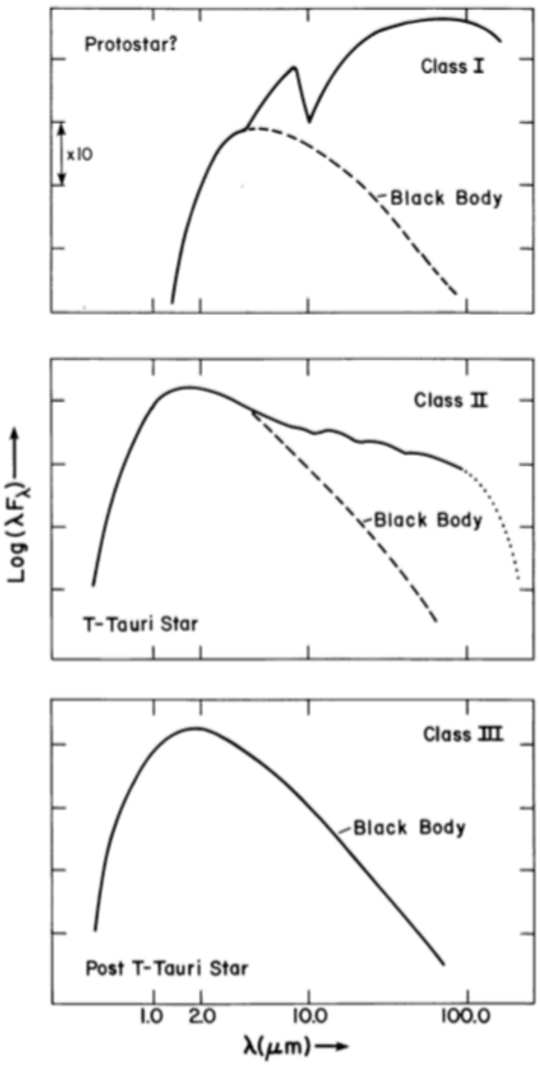
4.2. An Evolutionary Sequence?

Does the more or less continous variation in the spectral shapes of embedded infrared sources represent a sequence of evolution for protostars and young stellar objects? Most class II and III objects are associated with visible stars, mostly T Tauri stars and PMS stars. On the other hand, most class I objects are invisible and heavily obscured. Consequently their nature is difficult to ascertain. They could be protostars, or very deeply embedded T Tauri-PMS stars or some intermediate type of object. However, it is unlikely that they are merely more heavily reddened versions of T Tauri stars because examples of such stars exist in the Ophiuchi cluster and their energy distributions are typically flat or decreasing at long wavelengths (similar to optically visible T Tauri stars but unlike class I objects), but are considerably steeper at shorter wavelengths than the visible T Tauri stars. It is possible that class I objects are protostars, although many are the driving sources of molecular outflows a circumstance that has been interpreted to indicate that such objects are in a post-protostar phase of very early stellar evolution (Wynn-Williams 1982; Lada 1985). Recent theoretical models which predict the emergent energy distributions of low mass protostars strongly suggest that class I objects are indeed objects in the process of building up mass by the accretion of infalling circumstellar matter (Adams and Shu 1985, Shu, Lizano and Adams, this conference). In any event it appears evident and it is reasonable to assume that class I objects are in a much younger stage of development than class II sources. Since class III sources are stars with very little near in circumstellar dust it also seems reasonable to assume that they are the most removed in time from the events of stellar formation and the most evolved of the infrared sources.



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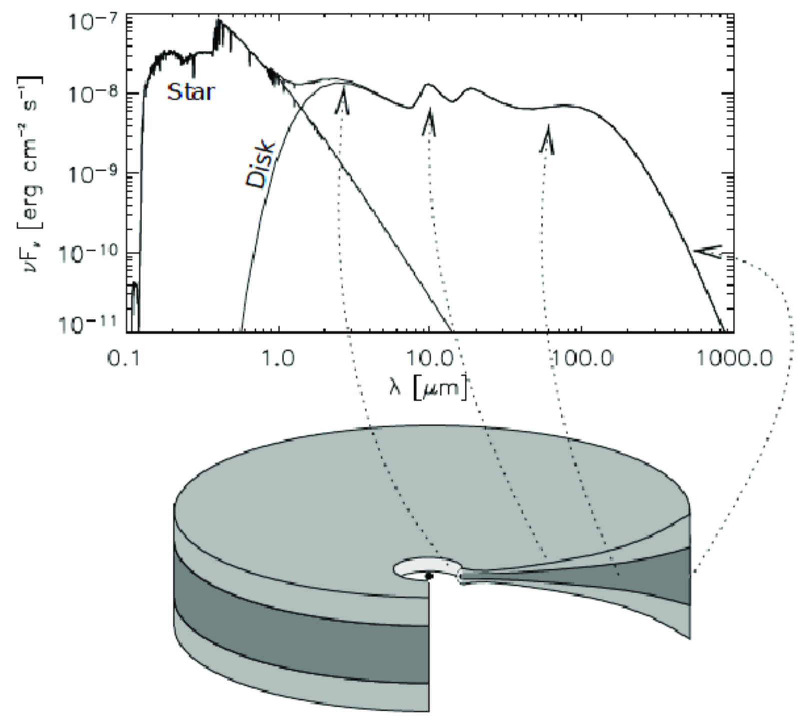
The hypothesis that the empirical sequence of spectral shapes corresponds to an evolutionary sequence of young stellar objects would be much more convincing if supported by physical arguments. Indeed, a qualitative physical evolutionary model is in fact suggested from the observed sequence. This is apparent when one considers the fact that the variation in the shape of the source energy distributions represents a variation in the amount of luminous circumstellar dust around each object. Class I sources have very large amounts of luminous circumstellar dust while class III objects have almost no luminous circumstellar dust. It is likely therefore that the inferred evolutionary sequence is a sequence of the gradual dissipation of dust and gas envelopes around newly forming or formed stars. The fact that many but not all class I objects and many but not all T Tauri stars are associated with energetic outflows and or stellar wind activity suggests that the outflow/wind phase is a transition between the protostellar stage and the T Tauri stage and that the outflow/wind is the agent that dissipates the circumstellar envelopes and drives the evolution of objects from class I to class III.

millimeter – the optically thin limit



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Millimeter

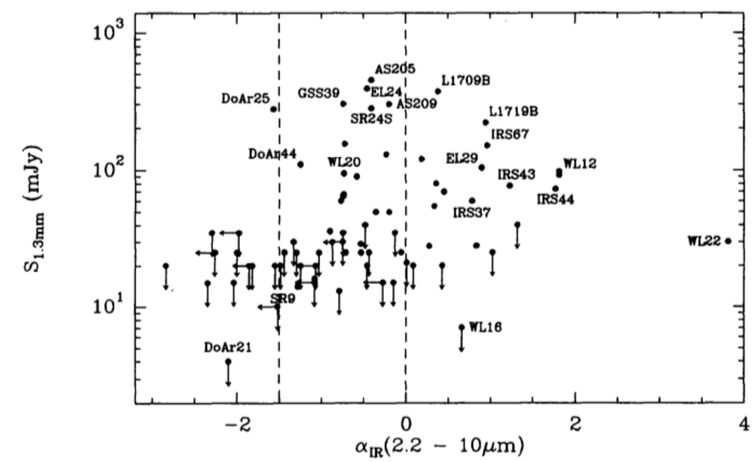
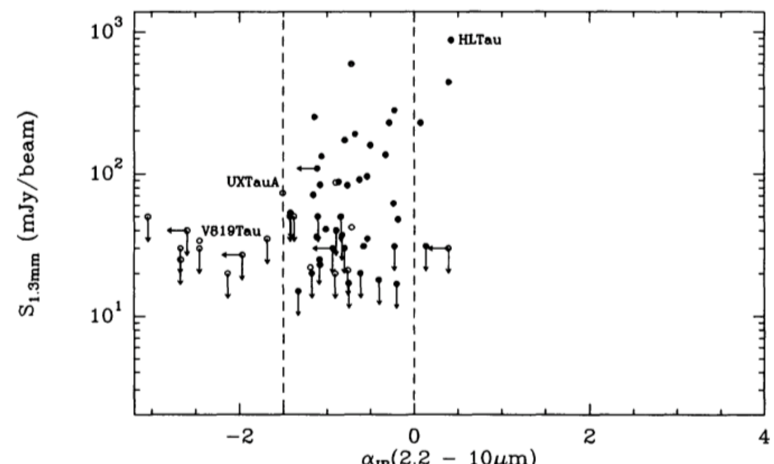


FIG. 1*a*



Infrared

FIG. 1*b*

Masses

The Astrophysical Journal, 420:837–862, 1994 January 10

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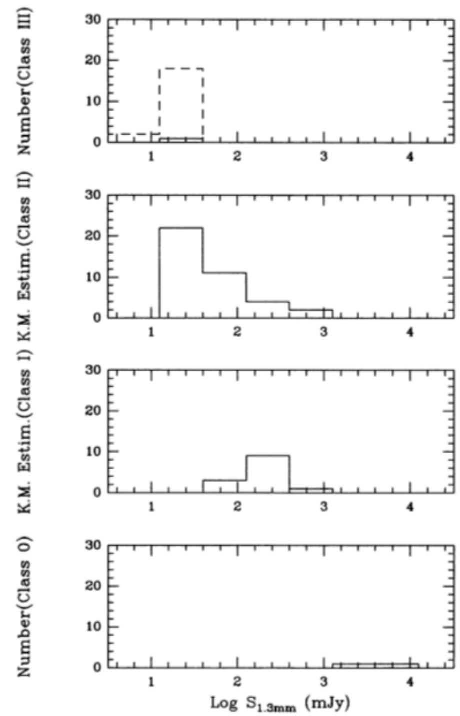

Fig. 7*a*

Fig. 7.—Histograms of the integrated millimeter flux density $S^{int}_{1.3\ mm}$ for (*a*) the ρ Oph sources and (*b*) the TTS sample of BSCG in Taurus, according to their IR/mm class (*top to bottom:* Class III to Class 0). For Class II and Class I sources these distributions were obtained using the differential Kaplan-Meier estimator. For Class III and Class 0 sources, this was not possible owing to the small number of detections, and the distributions of detections and upper limits are plotted as actually observed (dashed lines indicate the fractions of upper limits).

Class I vs Class II

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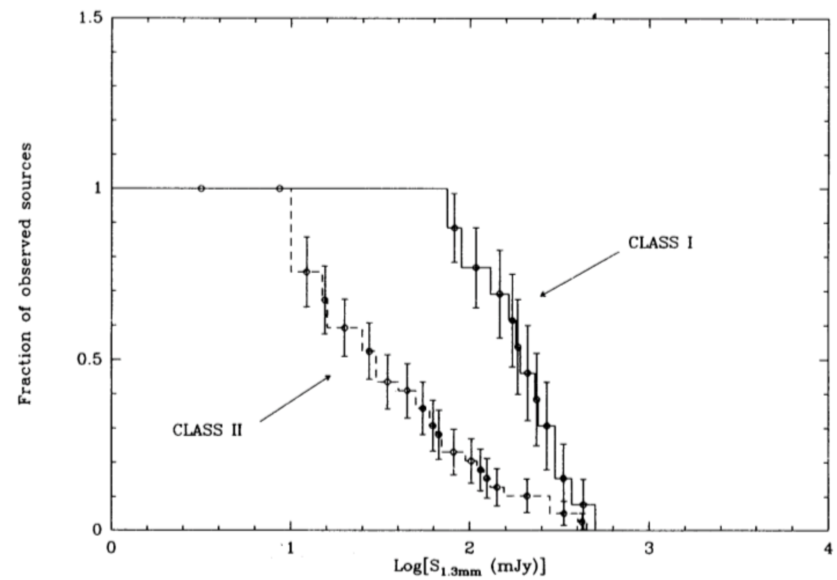
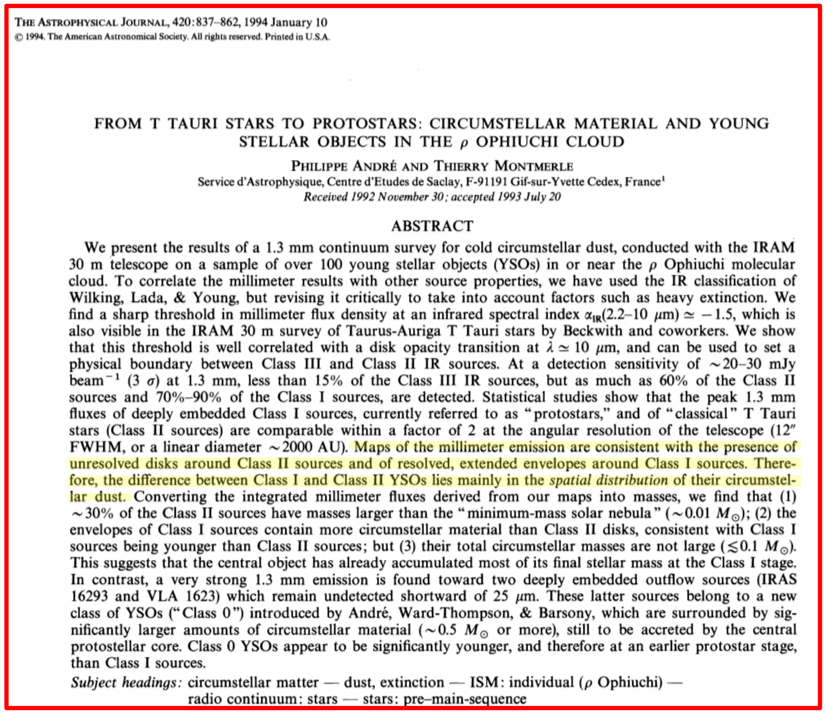


FIG. 8.—Cumulative distributions of the integrated millimeter flux density $S^{int}_{1.3\ mm}$ for the ρ Oph Class I and Class II sources, as obtained by the standard Kaplan-Meier estimator. Class I sources are, on average, stronger than Class II sources, but the maximum values of $S^{int}_{1.3\ mm}$ are comparable.

T-Tauri classes as an evolutionary sequence



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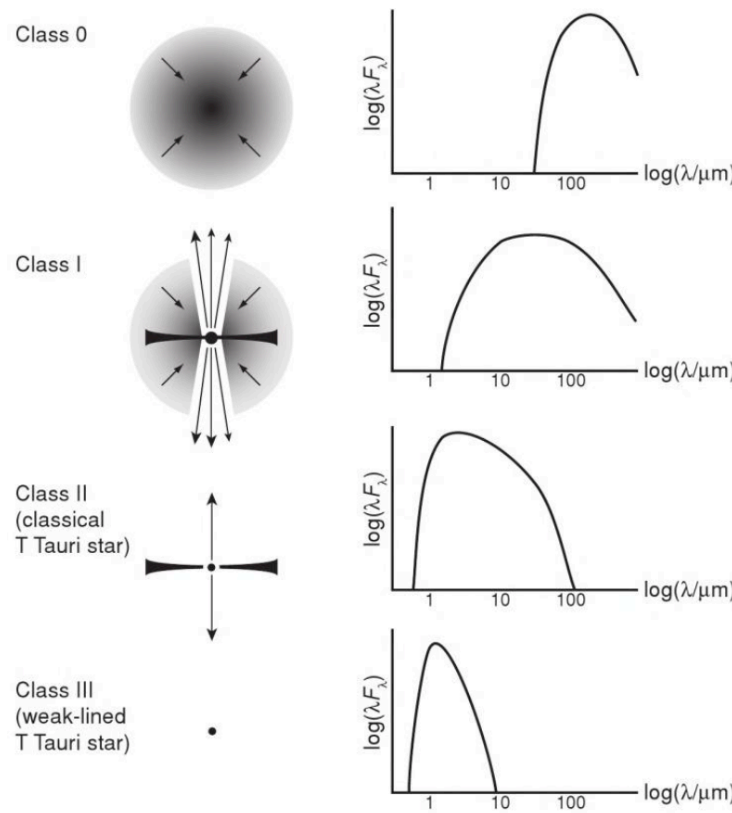
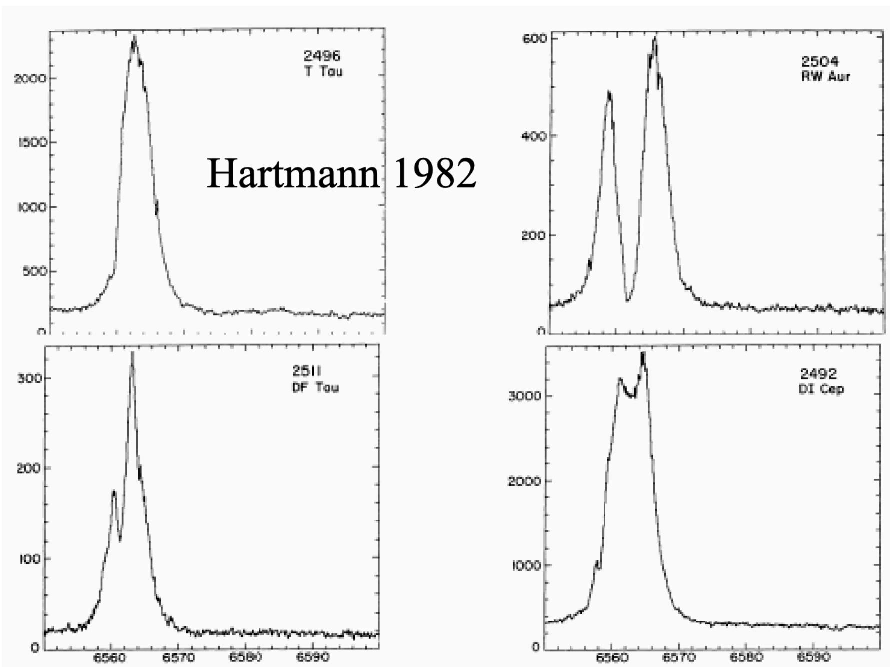
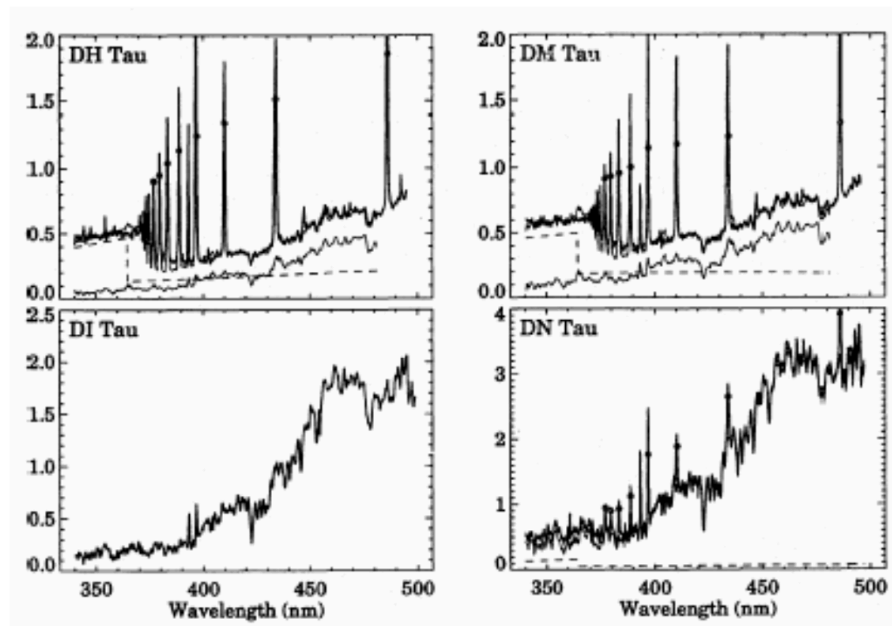


Classical T Tauri Stars (CTTS)
vs
Weak-lined T Tauri Stars (WTTS)





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