1994ApJ...420

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

PHILIPPE ANDRÉ AND THIERRY MONTMERLE
Service d'Astrophysique, Centre d'Etudes de Saclay, F-91191 Gif-sur-Yvette Cedex, France[1]

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 $\alpha_{\rm IR}(2.2\text{–}10\ \mu{\rm m}) \simeq -1.5$, 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 ∼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 ∼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) ∼30% of the Class II sources have masses larger than the "minimum-mass solar nebula" (∼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 (∼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.

Subject headings: circumstellar matter — dust, extinction — ISM: individual (ρ Ophiuchi) — radio continuum: stars — stars: pre–main-sequence

1. INTRODUCTION

Until recently, and for more than a decade, most observations relating to young stellar objects (YSOs) and early stellar evolution have been done in the infrared (IR) domain only, both from the ground (near-IR/mid-IR: between 2 and 10 or 20 μm) and in space (mid-IR/far-IR: *IRAS*, 12–100 μm). One of the most extensively studied regions is the nearby ρ Ophiuchi cloud (adopted distance $d = 160$ pc; for a recent review see, e.g., Wilking 1992). Observations of the IR spectral energy distributions (SEDs) between ∼1 and ∼100 μm of the hundredfold YSOs it contains have allowed Lada (1987) to propose a general IR classification scheme. The sources are divided into three classes according to their infrared excess (with respect to stellar blackbodies), as measured by the spectral index $\alpha_{\rm IR} = d \log (\lambda F_\lambda)/d \log \lambda$ between $\lambda = 2.2$ and 10–25 μm. The three classes are currently defined as follows: "Class I" corresponds to $\alpha_{\rm IR} > 0$, "Class II" to $-2 < \alpha_{\rm IR} < 0$, and "Class III" to $\alpha_{\rm IR} < -2$. Because their strong IR excesses are attributed to large amounts of circumstellar dust, Class I sources are often interpreted as candidate protostars. Based on current protostellar theory (e.g., Terebey, Shu, & Casen 1984, hereafter TSC; Shu, Adams, & Lizano 1987), the standard model of these objects calls for a hydrostatic stellar core surrounded by a compact circumstellar disk ∼10–100 AU in radius, itself embedded in a more extended infalling envelope ∼10^4 AU in size (Adams, Lada, & Shu 1987, hereafter ALS). The IR excesses of Class II sources are more moderate and can be modeled as arising from circumstellar disks on the order of ∼100 AU in size (e.g., Adams, Lada, & Shu 1988; Bertout, Basri, & Bouvier 1988). Thus, Class II sources are interpreted as embedded T Tauri stars. Finally, Class III sources, which display little or no IR excess, are thought to be essentially devoid of any circumstellar material. The IR classes are interpreted as an evolutionary sequence with progressive decrease of the amount of circumstellar material from Class I to Class III (Lada 1987).

However, for various reasons, infrared observations can only give qualitative indications on the amount of circumstellar material around YSOs. Indeed, as we will see in particular in this paper, shortward of ∼100 μm the disk emission of YSOs is generally optically thick, so that only poor estimates

---

[1] E-mail (I): andre@sapvxg.saclay.cea.fr; montmerle@sapvxg.saclay.cea.fr.