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THE FORMATION OF INTERMEDIATE-MASS STARS

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RESUMEN

Se considera la formación de estrellas de masa intermedia, comparándola con la formación de estrellas de masa pequeña. En particular, se describe la tendencia que tienen las estrellas de masa intermedia de formarse en grupos, discutiendo las dificultades que existen en obtener sin ambigüedad evidencias de discos alrededor de estrellas de masa intermedia.

ABSTRACT

The formation of intermediate-mass stars is considered in comparison to the formation of low-mass stars. In particular, the tendency of intermediate-mass stars to form in groups is described, and difficulties in obtaining unambiguous evidence for disks around intermediate-mass stars are discussed.

Key words: **ISM: DUST, EXTINCTION — ISM: MOLECULES — INFRARED: STARS — STARS: PRE-MAIN-SEQUENCE**

1. INTRODUCTION

The formation of intermediate-mass stars is of interest for several reasons. First, we can test the extent of applicability of the paradigm for the formation of low-mass stars developed by Shu and co-workers (see, e.g., Shu, Adams, & Lizano 1987). We know that high-mass stars form under different conditions, with a strong tendency to cluster, so we naturally want to know the largest mass for which the low-mass paradigm still works. Second, forming stars of intermediate mass are, in some ways, easier to study than are low-mass stars. Because they are more luminous, they produce brighter emission at most wavelengths and they can be studied at larger distances. On the other hand, most regions forming intermediate-mass stars *are* more distant, making it difficult to obtain adequate spatial resolution. This problem is aggravated by the tendency of relatively massive stars to form in groups. We will discuss this tendency in the next section. The second issue to be addressed (§3) is whether stars of intermediate mass are surrounded by disks, as have been inferred for many low-mass stars.

2. FORMATION IN GROUPS

As a first example, we consider the NGC 2071 region, which contains a compact far-infrared source with L $= 500 L_\odot$, which would correspond to a main-sequence star of about 5 $M_\odot$, if all the luminosity is attributed to a single star. Both far-infrared (Butner et al. 1990) and molecular-line (Zhou et al. 1991) studies of this region have found that the star-forming core is well described by a spherical region with a power-law distribution in density ($n(r) = n(r_0)(r/r_0)^{-\alpha}$). The best-fitting values of α ranged from 1.3 to 2, in the range anticipated for envelopes around forming low-mass stars. However, the best-fitting values of $n(r_0)$ exceeded by factors of around 10 those predicted for thermally supported isothermal spheres (Shu 1977). This clue that the situation is different from that found in regions of low-mass star formation is amply borne out by near-infrared studies. For example, images at 2 μm of the dense core (Walther et al. 1993) reveal a tight cluster of sources. Even though some are highly polarized and may be scattered light, there is clearly a very complex morphology, and the luminosity may arise from multiple sources. On larger scales, the region is home to a substantial cluster of up to 100 near-infrared sources (Lada et al. 1991). A region which appears in some ways to be a denser version of the kinds of regions found around low-mass stars is revealed to be much more complex by observations with higher resolution.

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Regions with already visible stars of intermediate mass also show these tendencies toward complexity and formation of groups. For example, the region around the Herbig Ae/Be star BD+40°4124 has recently been studied by several groups (Li et al. 1994; Palla et al. 1995; Hillenbrand et al. 1995). In addition to the other optically visible stars in this region, near-infrared images reveal at least twice as many sources which are invisible (Hillenbrand et al. 1995). Detailed study indicates that stars of both low and intermediate mass have been forming simultaneously over the last 3 million years, and that the fraction of intermediate-mass stars is enhanced relative to the usual IMF (Hillenbrand et al. 1995). The distribution of dense molecular gas (Palla et al. 1995), as well as the dust continuum emission (Aspin et al. 1994), peaks near the unusual visible object V1318 Cygni. This "star" is in fact a double which may be a pre-main-sequence binary separated by 5000 A.U. (Aspin et al. 1994). The southern component, V1318 Cygni S, is the more luminous of the pair and a likely source of the molecular outflow. This situation nicely illustrates the fact that studies at many wavelengths are necessary to identify the major players in regions of intermediate-mass star formation.

The situation described above is by no means unique. Near-infrared images of 16 Herbig Ae/Be stars revealed that 13 had infrared sources within $10''$, and 5 out of 16 had extended emission (Li et al. 1994). The brightest visible star cannot be assumed to be the only, or even the most luminous, object in regions of intermediate-mass star formation. Near-infrared images have been extremely useful in giving a clearer picture of these regions, but they too do not give the whole story.

Some sources will be too deeply embedded to appear even at near-infrared wavelengths (1-5 μm). This fact has been underscored once again by recent discoveries of new objects at longer wavelengths in two regions of intermediate-mass star formation, raising the question of how much we are still missing.

For example, a very red object was detected about $6''$ north of LkHα 198 at 10 μm by Lagage et al. (1993), who suggested that it might drive the outflow and represent the main luminosity source for the far-infrared emission in this region. While Butner & Natta (1995) have shown that the latter suggestion is unlikely, it is possible that hidden sources drive many of the outflows previously attributed to visible stars. The picture of the LkHα 198 region has become even more complex recently, with the discovery that the submillimeter continuum emission peaks toward neither the visible star nor its infrared companion, but instead $19''$ northwest of the visible star in a region devoid of 2 μm emission (Sandell & Weintraub 1994). This very deeply embedded object, named LkHα 198-MM, may be responsible for the outflow, or there may be several outflows in the region (Sandell & Weintraub 1994). This situation was also found in the case of several FU Orionis stars (Evans et al. 1994).

Complementary to observations at longer wavelengths, polarimetric imaging is another powerful tool for revealing hidden sources. For example, Weintraub et al. (1994) inferred that the main source in the LkHα 234 region is none of the visible stars nor 2 μm sources, but rather a source $3''$ northwest of the visible star, which is identified by being at the center of a centrosymmetric pattern of polarization vectors.

The lesson of these studies is that high-resolution polarimetric imaging, mid-infrared maps, and submillimeter maps are needed before firm conclusions can be drawn about stellar populations, the sources of far-infrared emission (where most of the luminosity is often carried), and the drivers of outflows.

3. DISKS AROUND HERBIG AE/BE STARS?

Based on theoretical considerations, we expect disks to play a role in the formation of stars, and much indirect evidence supports this expectation, at least for low-mass stars. For example, Beckwith et al. (1990) found continuum emission at millimeter wavelengths toward 42% of a sample of 86 T Tauri stars, which they interpreted as arising from circumstellar disks. Do such disks exist also around the intermediate-mass versions of T Tauri stars, the Herbig Ae/Be stars?

Of a sample of 47 Herbig Ae/Be stars, Hillenbrand et al. (1992) found that 41 had infrared excesses, indicative of substantial circumstellar matter. The spectral energy distributions (SEDs) of 30 of these could be modeled with disks, while eleven required more than accretion disks, possibly additional surrounding envelopes. Quite high accretion rates (6×10^{-7} to 5×10^{-5} $M_\odot$ yr^{-1}) were required to match the SEDs modeled without envelopes, a range about 100 times that used to model T Tauri stars, and a correlation between mass accretion rate and stellar mass was suggested (Hillenbrand et al. 1992).

Lada & Adams (1992) also modeled the near-infrared colors of Herbig Ae/Be stars with disks, finding that central holes were needed to match the observations. Hillenbrand et al. (1992) reached a similar conclusion. The holes were needed inside disk radii where the temperatures would have reached 2000–3000 K, suggesting that the holes were opacity gaps, caused by sublimation of dust grains. Since the analysis of Lada & Adams relied on photometry from the literature, often non-contemporaneous and obtained with different beam sizes, it was possible that nebulosity or infrared companions were distorting the colors. Using a near-infrared camera, Li et al. (1994) obtained new, quasi-simultaneous photometry and found that, while nebulosity and companions were indeed common, as mentioned above, the near-infrared colors of the dominant source were rarely affected significantly.

The disk models proffered by Hillenbrand et al. eventually led to problems. For example, Hartmann, Kenyon, & Calvet (1993) noted that such large accretion rates would make the inner disk opaque even if dust grains sublimated. Thus, the holes must be physical, not opacity, gaps. This conclusion led to other difficulties, prompting Hartmann et al. to suggest alternative explanations for the source of the near-infrared to mid-infrared emission, including envelopes extending close to the star, companions, and small grains. The latter suggestion was explored in detail by Natta et al. (1993), who found that very small grains and polycyclic aromatic hydrocarbons could make substantial contributions in the 2–20 μm region. Until geometry and dust composition in these regions are better understood, observations made solely at near-infrared and mid-infrared wavelengths are probably unreliable diagnostics for disks around Herbig Ae/Be stars.

At somewhat longer wavelengths, other problems arise. Hillenbrand et al. noted that the *IRAS* data gave higher flux densities than the ground-based data at 12 and 25 μm, and the far-infrared data from *IRAS* often exceeded the predictions of a disk model, even in the sources they modeled without envelopes. Given the large *IRAS* beam sizes, the origin of the far-infrared emission was unclear; it could have come from other sources or from diffuse emission included in the beam. Observations made with a higher-resolution scanning photometer aboard the KAO indicate that the far-infrared emission from a sample of 6 Herbig Ae/Be stars modeled without envelopes is usually compact and well-centered on the star (Di Francesco et al. 1994). While the emission is compact, it is clearly resolved in all but one of the sources; resolved far-infrared emission cannot be produced by an accretion disk and is better attributed to envelopes (Di Francesco et al. 1994). The presence of envelopes around the vast majority of Herbig Ae/Be stars lends credence to the suggestions of Hartmann et al. and suggests that inferences about disks based solely on modeling the SEDs of Herbig Ae/Be stars are suspect. For example, Natta (1993) found that even a small amount of matter out of the disk plane can significantly alter the temperature distribution in a disk, perhaps explaining the many “flat-spectrum” disks (cf. Beckwith et al. 1990).

If the near-infrared to far-infrared regions are ambiguous diagnostics of disks, what wavelength region is more trustworthy? While envelopes emit very readily in the far-infrared, their emission falls off at longer wavelengths because the opacity of dust grains declines. The success of the continuum survey of T Tauri stars at 1.3 mm (Beckwith et al. 1990) suggests a similar approach for Herbig Ae/Be stars. Indeed, Hillenbrand et al. (1992) detected 17 of these stars at 1.3 mm. However, five were extended, suggesting that some of the emission arises in an envelope.

Currently, the best method for distinguishing the disk component from other sources of emission is probably interferometry at millimeter wavelengths. An interferometer resolves out extended emission, so envelopes, already weak emitters at long wavelengths, are unable to produce strong, compact emission (see, e.g., Keene & Masson 1990 and Butner et al. 1994). The crucial test is whether the emission comes from an unresolved source. The expected size of an accretion disk (as distinct from a pseudodisk) is about 100 A.U.; at a distance of 1000 pc (typical for Herbig Ae/Be stars), the disks will subtend only $0\overset{''}{.}1$. Consequently, their emission at millimeter wavelengths will be unresolved with current instruments, except perhaps for the CSO-JCMT interferometer, observing the nearest regions (Carlstrom in his Conference talk).

Based on these arguments, Di Francesco et al. (1995) observed six Herbig Ae/Be stars using the IRAM interferometer at 2.7 mm to achieve beam sizes of typically $6''$. The expected signals were predicted by scaling single-dish 1.3 mm flux observations of these sources by Hillenbrand et al. (1992), Mannings (1994), and Sandell & Weintraub (1995) by λ^{-3}. This scaling is correct for grains with opacities declining as λ^{-1}, appropriate for a circumstellar disk (cf. Beckwith & Sargent 1991). The expected fluxes were found to be in the range of 20–80 mJy, and therefore detectable with the IRAM interferometer if all the 1.3 mm emission were unresolved.

In Fig. 1, we present preliminary reductions of the 2.7 mm emission maps for regions surrounding each of the six Herbig Ae/Be stars. Each contour represents 2 mJy/beam and the rms noise for each map is typically 1.5 mJy/beam. Five sources were detected at 3σ or better, but the observed flux densities were all much less than predicted. More disturbingly, the peaks of most of the detections are clearly offset from the target stars, suggesting that the 2.7 mm sources are not associated with the Herbig Ae/Be stars at all.

Figure 2 is a histogram of upper limits to the masses of circumstellar disks at the locations of the Herbig Ae/Be stars. These masses were calculated from the 3σ upper limits on the emission (or the flux density at the position of the star plus 1σ for V645 Cyg, a marginal detection). We assumed that the disks were optically thin, vary in temperature with radius as $T(r) \propto r^{-0.75}$, and are composed of grains with opacities declining as

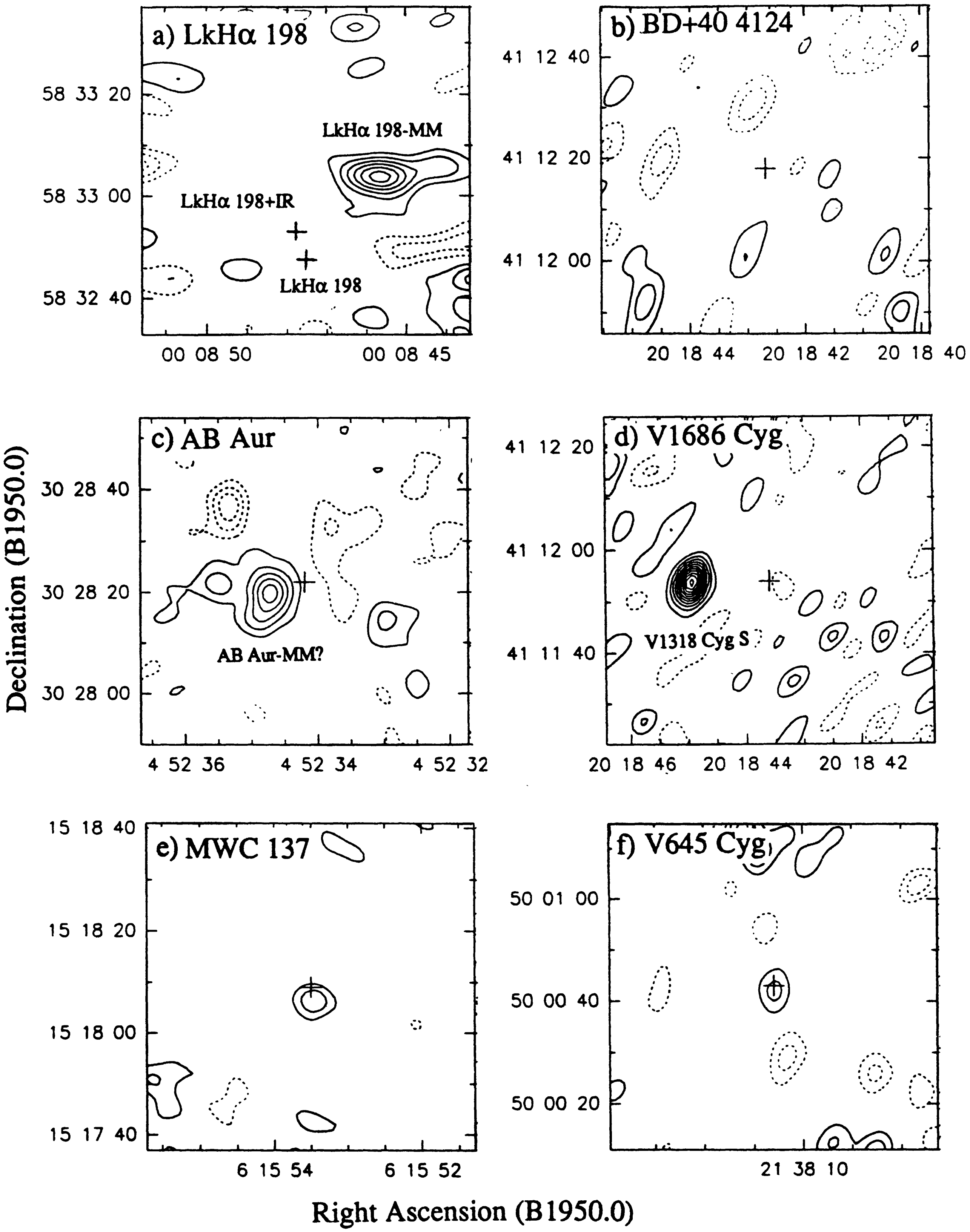

Fig. 1.— Interferometer maps at 2.7 mm of the regions around six Herbig Ae/Be stars.

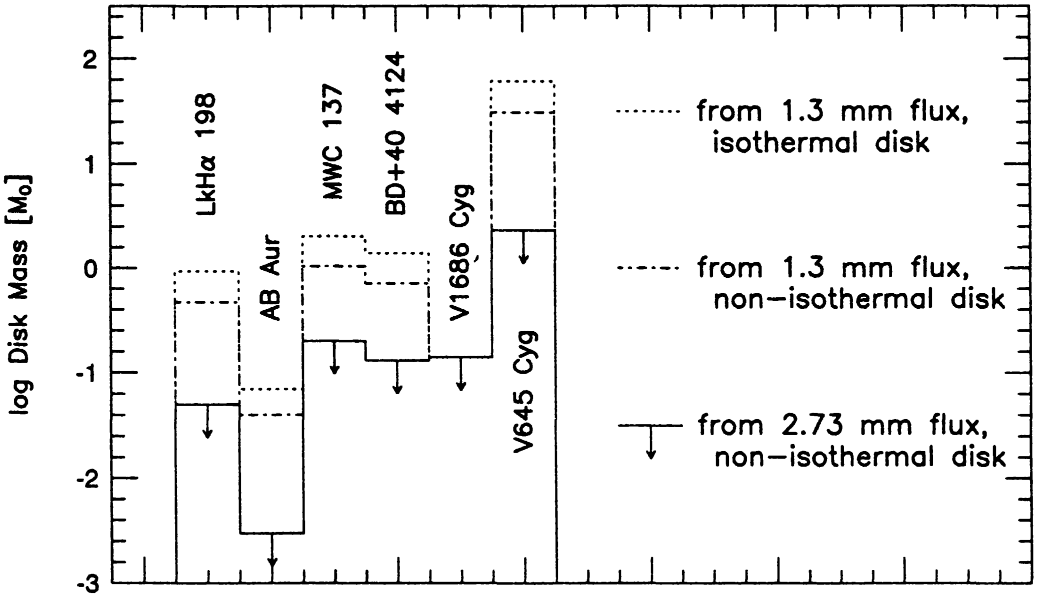

Fig. 2 — Histogram of disk mass upper limits from 1.3 mm and 2.7 mm fluxes.

λ^{-1}. These upper limits are compared to those found from single-dish 1.3 mm fluxes. Two limits from the 1.3 mm fluxes are given in Fig. 2, one assuming an isothermal disk, with $T = 37$ K (Hillenbrand et al. 1992), and one assuming $T(r) \propto r^{-0.75}$. Our limits on the disk masses are typically an order of magnitude less than the previous values, indicating either that the opacity law is steeper than expected for a circumstellar disk or that some of the 1.3 mm emission is quite extended.

Most intriguingly, the strongest 2.73 mm sources are clearly displaced from the stars which had been assumed to be the source of the millimeter continuum emission. The source previously attributed to V1686 Cygni appears to arise from the southern component of V1318 Cygni, the deeply embedded source discussed in §2 (see Fig. 1*d*). In addition, the source in the LkHα 198 region peaks at the position of the submillimeter peak, LkHα 198-MM, found by Sandell & Weintraub (1994) (see Fig. 1*a*). Thus, it appears that disks previously attributed to visible stars may instead be associated with more deeply embedded (i.e., younger) sources. However, the attribution of the emission to disks is even in question. Two sources are resolved, a result unexpected for a disk but expected for an envelope. In addition, the radio spectral index of MWC 137 suggests a nonthermal origin for its radio emission, placing its classification as a Herbig Ae/Be star in doubt (Skinner et al. 1993). At this point, none of the Herbig Ae/Be stars targeted in this study have compelling evidence for massive disks. The best candidate is V1318 Cyg S, suggested to be a very young Herbig Ae/Be star by Aspin et al. (1994).

4. SUMMARY

We need high-resolution studies at every possible wavelength to develop clear pictures of regions forming intermediate-mass stars. These studies can reveal previously unknown sources, sort out the correct sources of luminosity and outflows, and constrain the location and extent of millimeter continuum emission. We can expect improved mid-infrared data from space-borne telescopes like *ISO*, but improved resolution in the far-infrared awaits the deployment of larger airborne telescopes.

At this point, direct evidence for disks around intermediate-mass stars is elusive. To put it more strongly: ¿En dónde demonios están los discos?

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