Millimeter and Radio Interferometry of Herbig Ae/Be Stars

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ABSTRACT

Nine Herbig Ae/Be stars have been observed at $\lambda = 2.7$ mm with the IRAM and BIMA interferometers to place constraints on the presence of disk material around these objects. Only one Herbig Ae/Be star, Elias 3-1, was detected with certainty; two additional stars, MWC 137 and V645 Cyg, were possibly detected. The remaining six Herbig Ae/Be stars were not detected. Two deeply embedded objects near the target stars, LkHα 198-MM and V1318 Cyg S, were also detected. The emission from Elias 3-1 and V1318 Cyg S is unresolved, while that from LkHα 198-MM is resolved. Two stars (Elias 3-1 and V645 Cyg) were observed with the VLA at $\lambda = 7$ mm, 1.3 cm, and 3.6 cm. Based on our VLA data and those of Skinner et al. (1993), it appears that emission from ionized gas may contribute substantially to the millimeter emission from several sources. After correcting for this component where necessary, the remaining emission from most of the sample, attributed to dust, is considerably less than that predicted by assuming that the shorter wavelength emission arises in a disk. Much of the submillimeter and millimeter emission toward most of these stars must therefore arise in an extended envelope. For Elias 3-1, the data are consistent with a disk with mass around 0.1 $M_\odot$. We place limits on the masses of disks around the other stars.

Subject headings: stars: pre-main-sequence, Herbig Ae/Be stars, disks

1. Introduction

Herbig Ae/Be stars are optically-visible, pre-main-sequence objects with masses between 2 and 10 $M_\odot$ (Herbig 1960, Strom et al. 1972, Finkenzeller & Mundt 1984, Thé, de Winter, & Pérez 1993). These young stellar objects share broad observational similarities with their low mass counterparts, T Tauri stars. These similarities led Hillenbrand et al. (1992) (HSVK) to propose that the infrared excesses observed from Herbig Ae/Be stars originate from circumstellar accretion disks, as has been suggested for T Tauri stars (Bertout, Basri, & Bouvier 1988; Beckwith et al. 1990; Osterloh & Beckwith 1995). For example, HSVK found that the dereddened spectral energy distributions (SEDs) of 30 Herbig Ae/Be stars (out of 57 examined) could be reproduced at $\lambda < 20$ μm with accretion disk models. Later, Hartmann, Kenyon, & Calvet (1993) argued that ultraviolet observations of several of these Herbig Ae/Be stars did not support the gravitational energy release expected from material accreting onto these stars at the rates determined by HSVK. They suggested that the SEDs could be reproduced instead with models of envelopes only, with outflow holes or very small grains producing the observed near-infrared and mid-infrared excesses. More recently, Miroshnichenko, Ivezić, & Elitzur (1996) have been able to fit many SEDs with models of spherical envelopes, without outflow holes. In addition, Mannings (1994) obtained submillimeter photometry for a number of Herbig Ae/Be stars; he found that some of those modeled as disks by HSVK had emission at 0.35 and 0.45 mm significantly in excess of that predicted by standard disk models.

Di Francesco et al. (1994) found that 5 of 6 Herbig Ae/Be stars observed from the KAO at $30''$–$40''$ resolution had extended emission at $\lambda = 100$ μm. Although their SEDs had been modeled by HSVK with only accretion disks, the extended emission required the presence of substantial circumstellar envelopes. However, these observations could not rule out the presence of disks within the envelopes. High-resolution observations at longer wavelengths are necessary to determine if disks are present (cf. Keene & Masson 1990; Terebey, Chandler, & André 1993).

Aperture synthesis observations at millimeter wavelengths are ideally suited to distinguish disks from envelopes because they sample emission from dust on the scale of disks ($\leq$ 1000 AU), while resolving out much of the emission on the scale of envelopes ($>$ 1000 AU). In this paper, aperture synthesis observations of 9 Herbig Ae/Be stars made with the IRAM and BIMA interferometers at $\lambda = 2.7$ mm are described. In order to assess the contribution from ionized gas, we have also obtained observations of 2 stars at 7 mm, 1.3 cm, and 3.6 cm with the VLA.

2. Observations

2.1. IRAM/BIMA Observations

The nine Herbig Ae/Be stars in Table 1 were chosen for study on the basis of their strong millimeter emission, S_ν(1.3 mm, single-dish) $>$ 90 mJy, as measured by Mannings (1994), or Sandell & Weintraub (1996). The predicted flux densities of these sources at $\lambda = 2.7$ mm exceed 10 mJy, assuming the power-law relationship for dust opacity suggested by Beckwith & Sargent (1991): $\kappa_\lambda = 0.02(\frac{\lambda}{1.0mm})^{-1.0}$ cm^2 g^{-1}. Five sources in the sample (AB Aur, MWC 137, BD+40 4124, V1686 Cyg, and MWC 1080) were classified by HSVK as belonging to "Group I" (i.e., sources of moderate infrared excess explained by optically-thick disks alone). Three sources in the sample (LkHα 198, V376 Cas, and Elias 3-1) were classified by HSVK as "Group II" (i.e., sources with large infrared excess explained by a combination of a disk and circumstellar envelope). The remaining source, V645 Cyg, was not within the HSVK sample, but Natta et al. (1993) described its SED as morphologically similar to Group II sources. Using the spectral types determined by

HSVK, this sample spans the entire spectral type range of Herbig Ae/Be stars. Therefore, this sample represents a reasonable cross section of the masses (and possibly stages of evolution) within the Herbig Ae/Be stellar population.

Seven sources (LkHα 198, V376 Cas, AB Aur, MWC 137, BD+40 4124, V1686 Cyg, and V645 Cyg) were observed at 109.8 GHz ($\lambda = 2.73$ mm) with the IRAM interferometer located at Plateau de Bure, France (see Guilloteau et al. 1992). The three available 15 m diameter antennas were used to observe each source in the C2 and D2 array configurations in 1992 January and 1992 February. All program sources were observed in a "snapshot" mode, consisting of a few 15 minute intervals of on-source integrations per source per day, interspersed with 5 minute intervals on phase or amplitude calibrators. In total, each program source was observed for about 2 hours per day over 4 days per array configuration. 3C273, 3C345, 3C84, and NRAO 150 served as amplitude calibrators. The phase calibrators were 0224+671 for LkHα 198 and V376 Cas, 3C84 for AB Aur, 0735+178 for MWC 137, 2005+403 for BD+40 4124 and V1686 Cyg, and 2037+511 for V645 Cyg.

MWC 1080, AB Aur, and Elias 3-1 were observed at 108.9 GHz ($\lambda = 2.75$ mm) with the 6-element BIMA interferometer located at Hat Creek, CA (see Welch et al. 1996). Each source was observed in the standard BIMA B and C configurations between 1994 October and 1995 May; AB Aur was also observed in the A configuration. A typical track lasted about 10 hours total per array configuration and was bracketed by 5–10 minute intervals on amplitude calibrators. During a track, 20 minute intervals of on-source integrations alternated with 5 minute intervals of integrations on phase calibrators. The sources W3(OH), 3C273, Mars, or Jupiter, served as amplitude calibrators, depending on the array configuration. The phase calibrators were BL Lac for MWC 1080, 0528+134 for AB Aur, and 0420–014 for Elias 3–1.

The data observed at IRAM were reduced with the Grenoble CLIC and GILDAS software packages while the BIMA data were reduced with the MIRIAD software package. The resulting CLEAN maps were analyzed using AIPS. CLEAN beamsizes (see Table 1) were obtained by fitting two-dimensional (elliptical) Gaussians to the synthesized beams. The 1 σ noise levels, which do not include an estimated 15% calibration uncertainty, are listed in Table 1.

2.2. VLA Observations

Two Herbig Ae/Be stars (Elias 3-1 and V645 Cyg) were observed at $\lambda = 7.0$ mm, $\lambda = 1.3$ cm, and $\lambda = 3.6$ cm with the Very Large Array (VLA) of the National Radio Astronomy Observatory[5], located on the Plains of San Augustin, NM. Both sources were observed in 1996 January on approximately 6.0 hour tracks of the VLA's CnB configuration (a hybrid of its B- and C-array configurations). To obtain quasi-simultaneous observations of each source at all three wavelengths, the VLA operated in two distinct subarrays: the first, consisting of 11–13 antennas, observed at $\lambda = 7.0$ mm; the second, consisting of the remaining 13–15 antennas, observed mostly at $\lambda = 1.3$ cm (for $\sim 2/3$ of the track) but also at $\lambda = 3.6$ cm (for $\sim 1/3$ of the track). For amplitude calibration, the radio sources 3C48 and 3C286 were observed, bracketing each track for both subarrays, at each respective wavelength. For phase calibration, repeated observations were made of the radio sources 0400+258 (for Elias 3-1) or 2037+511 (for V645 Cyg) at $\lambda = 7.0$ mm and 0428+205 (for Elias 3-1) or BL Lac (for V645 Cyg) at $\lambda = 1.3$ cm and $\lambda = 3.6$ cm during each track. To obtain pointing corrections at $\lambda = 7.0$ mm, observations of the phase calibrators were made at $\lambda = 3.6$ cm at intervals of ~ 1 hour.

[5]The National Radio Astronomy Observatory is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc.

Reduction and analysis of data at all three wavelengths was accomplished using standard procdures in AIPS. However, the bootstrapping of flux densities at λ = 7.0 mm and λ = 1.3 cm observations used only data taken at similar elevations to offset the elevation-dependent gains of the antennas at these wavelengths. In addition, observations at these wavelengths required extensive editing to remove spurious data, given the lower antenna efficiencies and generally weak calibrators. For example, the best maps at λ = 7.0 mm and λ = 1.3 cm were made by excluding data from baselines larger than 130 kλ and 200 kλ respectively. CLEAN beamsizes were obtained by fitting elliptical Gaussians to the synthesized beams. These beamsizes and the 1 σ noise levels of the CLEANed maps at each wavelength are listed in Table 1. The noise levels in Table 1 do not include an estimated 15% calibration uncertainty.

3. Results

3.1. Millimeter Interferometry (λ = 2.7 mm)

Figure 1 shows maps of the regions around six Herbig Ae/Be stars. Two criteria were applied to determine if emission was detected and associated with the Herbig Ae/Be stars, following the example of Skinner, Brown, & Stewart (1993). Namely, peaks were required to be greater than 4 σ in strength and to lie within one-half of the synthesized beamwidth of the optical position of the Herbig Ae/Be star. Optical positions for each star were taken from the catalogue of Herbig & Bell (1988). Sources were classified as "possible detections" if they had peak flux densities of 3–4 σ in strength or were >4 σ but located between half and one beamwidth of the optical position.

In Table 2, we present the peak (S_ν(peak)) and total (S_ν(total)) flux densities at λ = 2.7 mm (or their upper limits). S_ν(total) or upper limits were calculated by integrating the observed map intensities within boxes of reasonable size (3 beams on a side for undetected sources) encompassing the sources. For the possibly detected sources, the tabulated values plus their respective uncertainties can be taken as firm upper limits to S_ν(peak) or S_ν(total). For the undetected sources, we give 3 σ limits for S_ν(peak); for S_ν(total), we give the result of the integration and the uncertainty, including the 15% calibration uncertainty.

Based on the detection criteria described above, only one Herbig Ae/Be star, Elias 3-1 (Elias 1978; this source is also known as V892 Tau), has associated emission. This detection is 15 σ and is located within 1$''$ of the optical position of Elias 3-1. Two other stars, MWC 137 and V645 Cyg, were possibly detected. The map centered on MWC 137 (Figure 1b) has a S_ν(peak) of 6.8 σ toward a position $3\farcs3$ southwest of the stellar position listed by Herbig and Bell (1988). Using the position of Clements & Argyle (1984), the separation between the source and the star is $3\farcs0$, exactly half the synthesized beamwidth. To be conservative, we consider MWC 137 as a possible detection. The map centered on the optical position of V645 Cyg (see Figure 1c) has a peak 1$''$ south of the star, but this peak is only 3.7 σ.

For the other six Herbig Ae/Be stars in our sample (LkHα 198, V376 Cas, AB Aur, BD+40 4124, V1686 Cyg, and MWC 1080), no emission was found within a full beamwidth of their optical positions at a level $\geq$ 2 σ. Figure 1d shows a typical non-detection, MWC 1080. In the map centered on AB Aur made at IRAM a significant peak was seen, nearly one full synthesized beamwidth ($\sim$7$''$) from the stellar position. However, our BIMA observations of AB Aur revealed no source at either the stellar position or the location of the source in the IRAM map. Recently, Mannings (1996) has detected an unresolved source at the stellar position with $S_\nu(\mathrm{peak}) = 8.2 \pm 0.7$ mJy beam^{-1}. Despite the slightly higher noise level of the BIMA map (3.1 mJy beam^{-1}), the IRAM peak should have been detected at >3 σ and Manning's detection should have been >2.6 σ. For this paper, we treat AB Aur as a non-detection, but further work is necessary to resolve this discrepancy.

Figures 1e and 1f show maps of fields containing Herbig Ae/Be stars with serendipitous detections of other sources. In Figure 1e, a source peaks $3''$ north of the position of LkHα 198 MM, the local peak of emission at $\lambda = 800$ μm discovered by Sandell & Weintraub (1994). Considering the $\pm 1''$ positional uncertainties quoted by these authors, our peak is located within a half-beamwidth ($2''\!.5$) of LkHα 198 MM. In Figure 1f, a source peaks $15''$ east of the optical position of V1686 Cyg, within $4''$ of V1318 Cyg N and within $1''$ of V1318 Cyg S. V1318 Cyg S is also associated with emission at $\lambda = 800$ μm (Aspin, Sandell, & Weintraub 1995; Palla et al. 1995).

For Elias 3-1, examination of the variation in visibility amplitude with spatial frequency did not indicate that it was resolved. In addition, the difference between the S_ν(total) and S_ν(peak) was less than the uncertainties. Based on this criterion, V1318 Cyg S and both possibly detected sources (MWC 137 and V645 Cyg) are unresolved, while LkHα 198 MM is resolved.

3.2. Radio Interferometry ($\lambda\lambda = 7$ mm, 1.3 cm, 3.6 cm)

Figure 2 presents maps of the regions surrounding Elias 3-1 and V645 Cyg, two Herbig Ae/Be stars observed at the VLA. Elias 3-1 was detected at $\lambda = 7$ mm, $\lambda = 1.3$ cm, and $\lambda = 3.6$ cm, with peaks of emission found only $0''\!.28$ (S/N = 7.8), $0''\!.34$ (S/N = 7.0), and $0''\!.31$ (S/N = 15), respectively, from its optical position. V645 Cyg was detected only at $\lambda = 3.6$ cm, with an emission peak $0''\!.17$ (S/N = 4.6) from its optical position.

Table 2 contains S_ν(peak) (or their 3 σ upper limits) and S_ν(total), determined as described above for the IRAM and BIMA data, at all three wavelengths. For both sources, S_ν(total) at $\lambda = 3.6$ cm were consistent with the results of Skinner et al. (1993). All detections appear unresolved, given the criteria described in §3.1, except V645 Cyg at $\lambda = 3.6$ cm, again consistent with Skinner et al. The extent of V645 Cyg at $\lambda = 3.6$ cm, however, is due primarily to a long, low-intensity, southeastern "tail", and hence may be artificial.

4. Discussion

Compact emission at $\lambda = 2.7$ mm may arise from several processes. In the following sections, we first examine the evidence for emission from an ionized component. Next, we consider isothermal, optically-thin dust envelopes. Finally, we investigate accretion disks as a possible origin of the emission.

4.1. Emission from Ionized Gas

Possible emission from ionized gas can be constrained by analyzing centimeter wavelength observations of the 9 Herbig Ae/Be stars in our sample. Twelve of the 57 Herbig Ae/Be stars surveyed by Skinner et al. (1993) were detected at $\lambda = 3.6$ cm, including Elias 3-1, MWC 137, V645 Cyg, and AB Aur. Four other stars were possibly detected, including BD+40 4124 and MWC 1080. Skinner et al. used circumstantial evidence, including the lack of detected circular polarization and short-term variability (i.e., over a few days), to argue that this emission was thermal in most cases and possibly wind-related. Estimating the contributions of this emission at $\lambda = 2.7$ mm is difficult because the spectral indices for these sources are not well defined. We obtained VLA observations for two sources to clarify the situation by improving the wavelength coverage.

Using our 3.6 cm data and the 6 cm data of Skinner et al. for Elias 3-1, we find a spectral index (α, where $S_\nu \propto \nu^\alpha$) of 0.87 ± 0.78. If this emission continues to shorter wavelengths with $\alpha = 0.87$, the contributions at 1.3 cm, 7 mm, 2.7 mm, and 1.3 mm are 94%, 35%, 10%, and 4% of the observed S_ν(total), respectively. We detected V645 Cyg only at 3.6 cm, obtaining a value consistent with that of Skinner et al.; consequently, we use their spectral index of $\alpha = -0.2 \pm 0.3$, resulting in a maximum contribution at $\lambda =$ 2.7 mm of 41% of the observed flux density. For BD+40 4124, the derived spectral index over the same wavelength range ($\alpha = -0.3 \pm 0.7$) suggests a maximum contribution at $\lambda =$ 2.7 mm of 1.4 mJy, or 29% of the 3 σ upper limit. For MWC 137, α is unknown. Free-free emission from an optically-thick, constant-velocity, spherical wind gives $\alpha = +0.6$ (Panagia & Felli 1975; Wright & Barlow 1975). With this α, free-free emission could produce 69% of the observed $\lambda = 2.7$ mm flux density of MWC 137.

Evidence for non-thermal emission was found by Skinner et al. associated with two sources in our sample, Elias 3-1 and MWC 137. For Elias 3-1, Skinner et al. detected a second radio source $4\farcs1$ northeast (P.A. = 22°) of the stellar position, dubbed Elias 1-NE, which they suggested to be non-thermal in origin. We see no evidence for emission from Elias 1-NE in our data. For MWC 137, Skinner et al. noted a decrease in its flux density at $\lambda = 3.6$ cm by more than factor of 2 after ∼5 months, suggesting a non-thermal component. MWC 137 was originally classified as a planetary nebula (Perek & Kohoutek 1967) and may remain misclassified as a pre-main-sequence Herbig Ae/Be star.

These examples indicate that observations at longer wavelengths are advisable before attributing all the emission at millimeter wavelengths to dust.

4.2. Dust Emission

If the emission at submillimeter wavelengths arises from compact structures, our IRAM and BIMA observations should detect the same S_ν(total) at 2.7 mm as would a single-dish telescope. In contrast, if the submillimeter emission arises in an extended envelope, the interferometers will resolve out some of it. One technical problem is that the single-dish measurements usually are available only for $\lambda \leq 1.3$ mm; we have used the measurements at 1.3 mm to predict the 2.7 mm flux densities (S_ν(pred.)) for comparison to our data, assuming that $S_\nu \propto \nu^\alpha$. Table 2 has two values: one assumes a spectral index $\alpha = 3$; the second uses the spectral indices (α(M)) derived by Mannings (1994). The first estimate is based on the opacity law suggested for disk material by Beckwith & Sargent (1991) ($\kappa_\lambda = 0.02$ cm^{2}g$^{-1}(\frac{\lambda}{1.0\text{mm}})^{-\beta}$, with $\beta = 1$) and the assumption that the emission is optically thin and in the Rayleigh-Jeans limit. The difference between these two estimates is not significant except for Elias 3-1. After subtracting the possible contribution from gaseous emission, we found S_ν(total) at 2.7 mm of 39 mJy, midway between the two predictions for Elias 3-1. Combined with the fact that this source is unresolved, the data are consistent with the hypothesis that most of the emission arises from a compact (< 1500 AU) region, such as a disk.

For MWC 137, the observed S_ν(total) is half of the predicted values, or 16% if the estimated contribution from gaseous emission is subtracted. For the other sources, our upper limits are all less than the predicted values, with an average of S_ν(total)/S_ν(pred.) of 0.3 to 0.4, depending on which extrapolation technique is used.

The fact that S_ν(total) $< S_\nu$(pred.) could be explained by a steepening of the spectral slope (increasing α) for $\lambda > 1.3$ mm or by the source emission being extended enough that the interferometers resolve some of it out. The 3 σ upper limits on S_ν(peak) give values of $\alpha > 3 - 4$ between 1.3 and 2.7 mm; using 2 σ upper limits requires $\alpha > 5$. Such steep spectral indices would be more likely to arise from an optically thin envelope than from a disk. The emission from an envelope would also be extended, lowering S_ν(peak) still further.

To test whether extended emission would be resolved out, we modeled the emission from circular Gaussian sources using the spatial frequency coverage obtained on an actual source (MWC 1080, observed from BIMA, was used for this experiment). The *total* flux density of the Gaussian sources were required to match the predicted S_ν(total) at 2.7 mm in Table 2. For Gaussian sources larger than 5″ (FWHM), the model S_ν(peak) falls below our detection criterion. Thus, even a modestly extended envelope could readily explain our failure to detect most of these sources.

HSVK derived masses for material around Herbig Ae/Be stars by assuming that the emission at $\lambda = 1.3$ mm was optically thin emission from dust following the opacity law (with $\beta = 1$) of Beckwith & Sargent (1991). They also assumed isothermal emission at 37 K and used the following expression:

$$\frac{M}{M_\odot} = 6.31 \times 10^{-6} \left(\frac{d}{pc}\right)^2 \left(\frac{\lambda}{1.3mm}\right)^3 \left(\frac{37K}{T}\right) \left(\frac{S_\nu}{Jy}\right). \tag{1}$$

If we apply this same expression to our observations of Elias 3-1, corrected for gaseous emission, we get a mass of 0.04 $M_\odot$, about half the value found by HSVK. In sources not detected at 2.7 mm, the upper limits on mass are considerably less than the masses estimated by HSVK, as reflected in the fact that our observed S_ν is considerably less than those predicted from the 1.3 mm data (see Table 2).

The mass estimates are only useful in a comparative sense. The opacity at millimeter wavelengths is uncertain by at least a factor of 10 and may vary from place to place (e.g., Men'shchikov & Henning 1996 and references therein). Furthermore, the dust around a forming star cannot be isothermal unless it is all at the same distance from the star. More realistic dust distributions such as disks or envelopes will have temperature gradients. We will explore some consequences of these gradients in the next section.

4.3. Disk Models

Because the original interpretation of the millimeter continuum emission from Herbig Ae/Be stars invoked a disk, we will compare our results for Elias 3-1 to a simple disk model. We will then use the outcome of that comparison as a guide to assessing the role of disks around the other stars. We use a dust code based on the equations of Beckwith et al. (1990) and Adams, Lada, & Shu (1988); a detailed description of the code can be found in Butner et al. (1994). We restrict our modeling to parameters commonly used to model disks, in order to compare the possible masses of disks around Herbig Ae/Be stars to those around T Tauri stars.

Figure 3 shows the SED of Elias 3-1 from 60 μm to 6 cm; the open diamonds at 2.7 mm, 7 mm, and 1.3 cm are the S_ν remaining after gaseous emission has been subtracted, as described above. An acceptable disk model must fit the S_ν at 2.7 and 7 mm, with $\chi^2 < 2$, and not exceed the values at 1.3 mm, where envelope emission may be important, or at 1.3 cm, where only an upper limit is left after the gaseous emission has been subtracted. Models of disks opaque at all wavelengths fail to meet the last criterion, so we do not consider them further. For disks which are not opaque at all wavelengths, the simplest way to characterize them is by their mass, using the Beckwith & Sargent (1991) opacity to convert the surface density to a mass: $M_{\rm disk} = \int 2\pi r \Sigma(r) dr$ where the surface density $\Sigma(r) \propto r^{-3/2}$, and the optical depth $\tau_\lambda(r) = \kappa_0(\lambda/\lambda_0)^{-\beta}\Sigma(r)$. However, we allow the opacity power law exponent β to vary, rather than fixing it at unity, while keeping the value at 1 mm (κ_0) fixed at 0.02 cm^2 g^{-1}. We consider only face-on disks with outer radii of 100 AU, in order to obtain estimates comparable with those Beckwith et al. (1990).

Disks with no internal luminosity have $T \propto r^{-0.75}$ and can fit the data for $0.8 < \beta < 2.4$ and $0.1 < M < 0.8$ in units of $M_\odot$, with higher β giving higher M. The best fit is for $\beta = 1.2$ and $M = 0.12$ $M_\odot$. Flatter temperature laws have been advocated (e.g., Adams, Lada, & Shu 1988). Models of Elias 3-1 with $T(r) \propto r^{-0.5}$ and assuming half the total luminosity originates in the disk give fits for $0.6 < \beta < 1.2$ and $0.01 < M < 0.02$ $M_\odot$, but they produce slightly more emission at submillimeter wavelengths than is observed.

Beckwith et al. (1990) modeled this source with $T(r) \propto r^{-0.49}$ and found $M = 0.013$ $M_{\odot}$, consistent with our values. Their temperature dependence was constrained by fitting the far-infrared data, which they assumed to arise in a disk.

HSVK argued that an envelope is present in Elias 3-1, and both a disk and an envelope probably contribute to the emission at shorter λ (e.g., in the far-infrared). Observations in the far-infrared (Di Francesco et al. 1997) indicate that the emission is indeed resolved; models which combine disks and envelopes will be presented by Di Francesco et al. (1997). The more conventional $T(r) \propto r^{-0.75}$ temperature distribution could be acceptable if the far-infrared emission comes from an envelope. Curiously, larger disk masses are allowed if the far-infrared emission is *not* attributed to the disk!

Our modeling of Elias 3-1 shows that the mass of a disk can be greater or smaller than that found from optically-thin, isothermal emission, depending on assumptions about temperature and emissivity laws. The results of modeling the other sources in our study, using the upper limits on S_{ν}(peak) to set upper limits on the disk mass, assuming disk outer radii of 1000 AU, are presented in Table 3. Substantial disks could be present in most cases without producing emission strong enough for the millimeter interferometers to detect. The low detection rate of disks around Herbig Ae/Be stars compared to T Tauri stars may be caused by their larger distances.

4.4. Serendipitously Detected Sources

The source LkHα 198 MM was discovered by Sandell & Weintraub (1994), as a local emission peak at $\lambda = 800$ μm, located 19″ NW of LkHα 198. The peak flux density at $\lambda = 800$ μm is 1.4$\pm$0.1 Jy beam^{-1}; the deconvolved size was 8″ $\times$ 6″. The apparent center of high-velocity outflow lobes seen in ^{12}CO 2 $\rightarrow$1 observations is closer to LkHα 198 MM than to LkHα 198. No near-infrared source has been detected toward LkHα 198 MM. Sandell

& Weintraub obtained additional photometry of LkHα 198 MM at $\lambda = 1.1$ mm, 1.3 mm, and 2.0 mm. Assuming an optically-thin dust cloud, their models suggested that the circumstellar material has an emissivity with $\beta \approx 0.8$. Using this value of β and their data at 2.0 mm, we predict S_ν(total) at 2.7 mm of 92 ± 15 mJy. Our observations (see Figure 1e) reveal a resolved source (Table 2) that peaks within the positional uncertainties of LkHα 198 MM (Sandell & Weintraub 1994); S_ν(total) at 2.7 mm is 24 ± 6.9 mJy, indicating that the source is quite extended.

V1318 Cyg (LkHα 225) comprises two sources, V1318 Cyg N and V1318 Cyg S, separated by $5''$ in the north-south direction. A ridge of optical and infrared nebulosity between these sources suggests that they may be physically related (Aspin, Sandell, & Weintraub 1994). Recent analyses of this region have shown that V1318 Cyg S is closest to the emission peak at $\lambda = 800$ μm, the center of the local CO outflow, and the H_2O maser emission (Aspin, Sandell, & Weintraub 1994; Palla et al. 1995). Sandell & Weintraub (1996) observed V1318 Cyg between $\lambda = 350$ μm and $\lambda = 1.3$ mm. From the data at 1.1 and 0.8 mm, we calculated a spectral index, $\alpha = 3.6$, leading to a predicted S_ν(total) at 2.7 mm of 19 ± 9 mJy. Our observations reveal a strong, unresolved source $0\farcs9$ N of V1318 Cyg S. Our observed S_ν(total) at 2.7 mm of 24 ± 6.7 mJy is consistent with the predicted value, indicating that this source is compact and could be a disk.

5. Summary and Conclusions

Nine Herbig Ae/Be stars have been observed at $\lambda = 2.7$ mm with the IRAM and BIMA interferometers and two of the stars have been observed with the VLA at 7 mm, 1.3 cm, and 3.6 cm. Only one Herbig Ae/Be star (Elias 3-1) was detected with certainty at millimeter wavelengths; two Herbig Ae/Be stars, MWC 137 and V645 Cyg, were possibly detected. The remaining six Herbig Ae/Be stars were not detected above the 2 σ level. In addition, two deeply embedded objects near Herbig Ae/Be stars, LkHα 198 MM and V1318 Cyg S, were serendipitiously detected.

Emission at λ = 2.7 mm from some Herbig Ae/Be stars may include substantial emission from ionized gas. After accounting for gaseous emission, the dust emission at 2.7 mm associated with Elias 3-1 is consistent with that predicted from extrapolating emission at shorter wavelengths (HSVK, Mannings 1994). For the remaining sources, we observe only 30% to 40% of the predicted emission, suggesting that extended envelopes are contributing most of the observed emission at submillimeter wavelengths. For Elias 3-1, the emission at λ = 2.7 mm could be reproduced by disks with M = 0.1–0.8 $M_\odot$, with a best fit for 0.12 $M_\odot$. For the other sources, upper limits to M are given in Table 3.

Our low number of detections may be caused by the large distances to the Herbig Ae/Be stars (see Table 3). For example, if the disk that may surround Elias 3-1 at $d = 140$ pc is "typical" of disks around Herbig Ae/Be stars, then we could have detected disks only around AB Aur, LkHα 198, and V376 Cas. On the other hand, the very large massive disks inferred from previous single-dish observations should have been detected. Therefore, the bulk of the emission at λ = 1.3 mm from these sources probably originates from extended envelopes. Far-infrared observations and modeling of such envelopes will be presented in a subsequent paper (Di Francesco et al. 1997).

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Table 1: Observations of Herbig Ae/Be Stars

Source Name	Wavelength (mm)	Array	Synthesized Beamsize	P.A. (°)	rms (mJy beam^{-1})
LkHα 198	2.7	IRAM	$9''.7 \times 5''.1$	96	1.6
V376 Cas	2.7	IRAM	$9''.7 \times 5''.1$	96	1.6
Elias 3-1	2.7	BIMA	$8''.1 \times 7''.2$	78	2.9
	7.0	VLA	$1''.9 \times 1''.7$	72	0.55
	13.	VLA	$1''.6 \times 0''.8$	−31	0.20
	36.	VLA	$2''.3 \times 0''.8$	64	0.030
AB Aur	2.7	IRAM	$7''.9 \times 6''.3$	171	1.3
	2.7	BIMA	$4''.4 \times 3''.7$	−70	3.1
MWC 137	2.7	IRAM	$6''.0 \times 6''.0$	0	0.9
BD+40 4124	2.7	IRAM	$8''.4 \times 4''.7$	145	1.6
V1686 Cyg	2.7	IRAM	$6''.8 \times 4''.6$	159	1.6
V645 Cyg	2.7	IRAM	$6''.6 \times 5''.3$	150	1.3
	7.0	VLA	$1''.5 \times 0''.5$	88	0.32
	13.	VLA	$1''.1 \times 0''.6$	7	0.17
	36.	VLA	$2''.4 \times 0''.8$	−73	0.053
MWC 1080	2.7	BIMA	$6''.2 \times 5''.0$	−74	2.9

Table 2: Observed and Predicted Flux Densities at $\lambda = 2.7$ mm

Source Name	λ (mm)	S_ν(peak) (mJy beam^{-1})	S_ν(total) (mJy)	S_ν(pred.) $\alpha = 3$	S_ν(pred.) α(M)
Elias 3-1	2.7	45	42 ± 10	26 ± 2	48 ± 6
	7.0	4.3	5.8 ± 2.0	...	...
	13.	1.4	1.1 ± 0.65	...	...
	36.	0.46	0.48 ± 0.12	...	...
MWC 137	2.7	6.0	5.7 ± 3.1	10 ± 1.4	11 ± 2
V645 Cyg	2.7	$\sim$4.9	3.3 ± 4.4	...	...
	7.0	$<$0.96	-0.64 ± 2.1	...	...
	13.	$<$0.50	0.91 ± 0.75	...	...
	36.	0.24	0.55 ± 0.18	...	...
LkHα 198	2.7	< 4.8	2.4 ± 4.5	26 ± 5	20 ± 5
V376 Cas	2.7	< 4.8	2.3 ± 4.5	12 ± 2	8.5 ± 1.8
AB Aur	2.7	11[a]	21.4 ± 5.0	12 ± 2	8.3 ± 1.8
	2.7	< 9.3[b]	10 ± 9.7	12 ± 2	8.3 ± 1.8
BD+40 4124	2.7	< 4.8	-3.0 ± 5.0	25[c]	...
V1686 Cyg	2.7	< 4.8	0.3 ± 5.6	...	...
MWC 1080	2.7	< 8.7	11 ± 10	26 ± 3	27 ± 5
LkHα 198 MM	2.7	13	24 ± 6.9	87 ± 14	92 ± 15[d]
V1318 Cyg S	2.7	23	24 ± 6.7	33 ± 5	19 ± 9[e]

[a] Data from IRAM; the peak is 6.″7 from the optical position.

[b] Data from BIMA.

[c] Based on the 1.3 mm data of Hillenbrand et al. 1992.

[d] Based on the 2.0 mm data of Sandell & Weintraub (1994) and their estimate that $\beta \sim 0.8$.

[e] Based on the 1.1 mm data of Sandell & Weintraub (1996) and $\beta = 1.6$, determined from their data at 1.1 and 0.8 mm.

Table 3: Disk Models

Source Name	Spectral Type	T_*^a (K)	L_*^b ($L_\odot$)	Distance (kpc)	r_i^c (AU)	M(disk) ($M_\odot$
Elias 3-1	A6	8100	21	0.14	0.011	0.12
MWC 137	B0	30900	1565	1.3	0.006	< 8.6
V645 Cyg	A0	9840	40000	3.5	0.32	< 4.4
LkHα 198	B3	17900	100	0.6	0.0048	< 1.3
V376 Cas	B5	13800	144	0.6	0.0098	< 0.8
AB Aur	A0	9840	57.8	0.16	0.0120	< 0.02
BD+40 4124	B2	20510	330	1.0	0.0067	< 2.8
V1686 Cyg	B0	30900	250	1.0	0.0026	< 6.3
MWC 1080	B0	30900	7920	2.5	0.014	< 20

[a]Assumed stellar temperature.

[b]Assumed stellar luminosity.

[c]Assumed inner radius of disk, set equal to the radius of the star.

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Fig. 1.— Aperture synthesis maps of selected Herbig Ae/Be stars at $\lambda = 2.7$ mm. Solid lines represent contours of positive intensity, starting at the +2 σ level and increasing in steps of 2 σ. Dashed lines represent contours of negative intensity, starting at the -2 σ level and decreasing in steps of 2 σ. The 1 σ noise levels for each map are listed in Table 1. Solid stars represent the optical positions of various objects in B1950.0 coordinates, uncorrected for proper motions. Filled ellipses denoting the FWHM of the Gaussian-fit synthesized beams are shown in the lower-left corners of each respective panel. *Panel a*: Elias 3-1, the only detected source, with optical position from Herbig & Bell (1988). *Panel b*: MWC 137, the first possibly detected source, with optical position from Herbig & Bell. *Panel c*: V645 Cyg, the second possibly detected source, with optical position from Skinner, Brown, & Stewart (1993). *Panel d*: MWC 1080, an undetected source, with optical position from Herbig & Bell. *Panel e*: LkHα 198 and V376 Cas, two undetected sources with another source (LkHα 198 MM) seen to the west; optical positions are from Herbig & Bell and Sandell & Weintraub (1994). *Panel f*: V1686 Cyg, an undetected source with another source (V1318 Cyg S) seen to the east; optical positions are from Palla et al. (1995). *Note*: the map of LkHα 198 and V376 Cas is centered 17$''$ north of the true 1950.0 position of LkHα 198, due to an error in the Herbig & Bell catalogue (see Lagage et al. 1994).

Fig. 2.— Aperture synthesis maps of Elias 3-1 and V645 Cyg at $\lambda = 7.0$ mm, $\lambda = 1.3$ cm, and $\lambda = 3.6$ cm. Contours, stars, and ellipses are as defined as in Figure 1 but optical positions are taken only from Skinner, Brown, & Stewart (1993).

Fig. 3.— The SED for Elias 3-1, along with disk models. Open circles are IRAS measurements, triangles are submillimeter measurements from Mannings (1994), and solid diamonds are interferometer data at 2.7 mm, 7.0 mm, 1.3 cm, and 3.6 cm, along with 6.0 cm data from Skinner et al. (1993). The open diamonds represent the flux density remaining after contributions from ionized gas with $S_\nu \propto \nu^\alpha$ are removed, with $\alpha = 0.87$ (best fit to 3.6 and 6.0 cm data, shown by dotted line). The open diamond with the arrow is an upper limit, since the emission from ionized gas could account for all of the observed emission. The solid line is the best-fitting disk model with $T(r) \propto r^{-0.75}$; the dashed line is the best-fitting disk model with $T(r) \propto r^{-0.5}$, in which half the total luminosity originates in the disk.