INFRARED STUDIES OF PRE-MAIN-SEQUENCE INTERMEDIATE-MASS STARS: LkH α 198

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ABSTRACT

Far-infrared scans of LkH α 198 at 50 and 100 μm along several directions reveal an extended, roughly spherical source with an average FWHM of $33''$ or 2×10^4 AU at 100 μm and up to $18''$ or 1.5×10^4 AU at 50 μm .

By comparing the observed properties at optical, infrared, and millimeter wavelengths with the predictions of radiation transfer models, we estimate a luminosity of $250 L_{\odot}$ at a distance of 600 pc. The optical depth at 100 μm is 0.004–0.006, implying a mass of $\sim 2 M_{\odot}$ within a radius of 10^4 AU. The dust configuration is characterized by a power-law distribution $n(r) \sim r^{-\alpha}$, with $\alpha \sim 0.5$, in most of the directions around the star and over large distances. The inner radius of the dusty envelope is probably rather small, $r_i \lesssim 300$ AU ($0''.5$), and it may be as small as the dust destruction front: in LkH α 198 there is no evidence of a large region devoid of grains.

The fit to the observed spectral energy distribution (SED) from optical to millimeter wavelengths favors a model that includes a disk and a spherical envelope. The former is required in order to provide a good match to the SED at near-infrared wavelengths. The disk mass is $0.27 M_{\odot}$, i.e., $\sim 7\%$ of the stellar mass. Alternatively, the SED can be fitted by a spherical dust envelope only, if there is a component of very small grains and polycyclic aromatic hydrocarbons.

Within the current scenario of star formation, mostly developed for solar-mass stars, it is not easy to account for the flat density profile of the dusty envelope we observe around LkH α 198.

Subject headings: circumstellar matter — infrared: stars — stars: individual (LkH α 198) — stars: pre-main-sequence

1. INTRODUCTION

This paper is the first of a series aimed at studying in detail the far-infrared emission properties of the circumstellar matter associated with young, intermediate-mass stars. The visible objects in this class, Herbig Ae/Be stars, can in many ways be considered scaled-up versions of T Tauri stars. Like T Tauri stars, Herbig Ae/Be stars exhibit the characteristic phenomena of stellar youth, as shown below for the specific case of LkH α 198. It seems that the early evolution of stars is marked by the occurrence of the same phenomena over an extended mass interval. This is somewhat surprising from the theoretical point of view, since pre-main-sequence stars of intermediate mass, unlike T Tauri stars, are not expected to possess any surface convection (e.g., Iben 1965), thus missing one of the fundamental ingredients for the generation of stellar activity. The basic explanation for the intense activity still remains a puzzle (see Catala 1989 for a discussion), although recently Palla & Stahler (1990, 1991) have suggested the possibility that the burning of deuterium in a subsurface shell can create and maintain convection during a substantial part of the star's evolution. While most of the recent effort in the field of star formation has been concentrated on the observations and modeling of low-mass stars, more attention should be paid by both observers and theorists to the study of intermediate-mass stars.

Adams, Lada, & Shu (1987) have suggested that the infrared

spectra of pre-main-sequence stars can be used to infer the presence of disks and to place the objects in an evolutionary sequence. However, recent studies have indicated the importance of obtaining good spatial resolution data at the critical far-infrared and submillimeter wavelengths in order to distinguish disks from infalling matter (e.g., Butner et al. 1991a). More generally, the predictions of well-defined theories of star formation (e.g., Shu, Adams, & Lizano 1987) can be quantitatively tested by these kinds of observations (e.g., Evans 1991). These studies have proved difficult with current instrumentation for most T Tauri stars, because of the intrinsic weakness of the emission, a limitation that could be overcome by studying the more luminous intermediate-mass stars. In this paper we report the results of far-infrared observations of the region around LkH α 198, a Herbig Ae/Be star (Herbig 1960).

LkH α 198 is a young pre-main-sequence star of intermediate mass, located in an isolated cloud in Cassiopeia at a distance variously estimated at $d = 900$ pc (Herbig 1960) or $d = 600$ pc (Racine 1968; Chavarría-K. 1985; Shevchenko & Yakubov 1989); we adopt the latter distance in this paper. The molecular cloud associated with the star is rather small, about 2 pc, yet it contains a dozen visible stars, including V376 Cas, $37''$ to the north of LkH α 198, several embedded IR objects (Loren 1977), and three radio continuum sources (Rodríguez & Cantó 1983), indicative of B2.5 stars. From an estimate of the mass in gas and stars in the region, Shevchenko & Yakubov

(1989) find a star formation efficiency between 5% and 10%, somewhat higher than that found in larger molecular clouds (Evans & Lada 1991).

The cloud contains a molecular outflow (Loren 1977; Cantó et al. 1984; Levreault 1988) with a northwest-southeast axis of elongation. Cantó et al. (1984) and Levreault (1988) have argued that LkH α 198 is the driving source for this outflow, but Chavarría-K. (1985) has suggested V376 Cas, based on his conclusion that V376 Cas is more luminous ($517 L_{\odot}$, versus $160 L_{\odot}$ for LkH α 198). Since that conclusion was based on optical and near-infrared data, observations in the far-infrared are important for resolving this issue. There is a strong *IRAS* source, IRAS 00087 + 5833, associated with the cloud (Berrilli et al. 1990). In the *IRAS* catalog the position of this source agrees very well with LkH α 198, even though it is identified as V376 Cas.

High angular resolution molecular maps have been presented for a variety of molecular species, including CO, HCO, HCO⁺, HCN, CS (Nakano et al. 1990), and NH₃ (Fuente et al. 1990). These observations show that the dense molecular gas is more closely associated with LkH α 198 than with V376 Cas (see Fig. 1a). This result indicates that LkH α 198 is more deeply embedded and presumably younger. It favors LkH α 198 as the source of the molecular outflow, but it does not resolve the question of which source is more luminous, indicating the need for higher resolution far-infrared observations.

In addition to the bipolar outflow, virtually all of the characteristic phenomena of young stars have been found in the vicinity of LkH α 198: optical variability over a short time scale, ≈ 5 minutes (Chavarría-K. 1985); a source of H₂O maser emission (Schwartz & Buhl 1975); an optical outflow with, perhaps, a Herbig-Haro object 12" away (Strom et al. 1986; Ray et al. 1991); and, finally, conspicuous near-infrared and far-infrared excesses (Cohen & Kuhi 1979; Harvey, Thronson, & Gatley 1979). The latter have been interpreted (Harvey et al. 1979) as thermal emission from circumstellar dust distributed over a large distance from the star with a rather shallow gradient, $n_d \propto r^{-1}$. Because the source was not resolved at 100 μ m, this conclusion should be checked with higher resolution observations. There is no radio continuum emission detected from the position of LkH α 198 (Rodríguez & Cantó 1983; Evans et al. 1987); the limit of 0.44 mJy at 6 cm (Evans et al. 1987) sets a limit to the spectral type of later than B3, assuming an optically thin H II region.

The optical images taken by Ceccarelli et al. (1987) and by Leinert, Haas, & Lenzen (1991) over an extended area ($2' \times 2'$) show that an intense nebula is associated with the star, aligned with the CO outflow axis at a position angle of 160° . Information on the geometry of the circumstellar material also comes from the pattern of polarization vectors observed by Bastien et al. (1989), which has been interpreted as due to multiple scattering in a flattened, optically thick structure, and as the direct evidence for the presence of a circumstellar disk. This conclusion has been criticized by Leinert et al. (1991), who have used near-infrared speckle interferometry, as well as imaging and multicolor polarimetry, to probe the innermost 100 AU around LkH α 198 and V376 Cas. From their study, it emerges that the geometry is quite complicated, without an obvious preferential direction of the polarization vectors. The authors conclude that the clear alignment seen by Bastien et al. is not present down to the smallest scales ($< 10^3$ AU), and they find no evidence for the flattened disk advocated to help explain the presence of the collimated Herbig-Haro object observed by Strom et al. (1986).

In this paper we will present the results of high-resolution far-infrared scans of this region and analysis of the far-infrared and optical data, using radiative transport codes. The observations and results are presented in §§ 2 and 3. The analysis of the data is performed by means of techniques similar to those that we have employed for two other sources, NGC 2071 (Butner et al. 1990) and L1551 IRS 5 (Butner et al. 1991a). It will be described in § 4, together with a discussion of the spectral energy distribution and a comparison with theoretical models. The implications of the results for current ideas on the formation of intermediate-mass stars will be discussed in § 5. Finally, we present our conclusions in § 6.

2. OBSERVATIONS

We observed LkH α 198 in 1986 December and 1987 August and December aboard the Kuiper Airborne Observatory (KAO), using one of several multichannel scanning photometers at 100 and 50 μ m. The systems included a 6 channel system (Lester, Harvey, & Joy 1986) which permitted simultaneous measurements at 50 and 100 μ m over a single crosscut. Most of the observations were done with an 8 channel system, which has an array of 8 channels aligned along the elevation axis (Butner et al. 1990; Lester et al. 1986). While the 8 channel system does not permit simultaneous sampling at 50 and 100 μ m, scans in the cross-elevation direction produce spatially distinct scans for each channel.

The source was scanned in elevation (hereafter denoted by Y) and/or in cross-elevation (denoted by X). Because the north-south axis is generally not aligned with the elevation axis during observations, the scan direction can be different from flight to flight. The observations are summarized in Table 1; in column (5), θ is the angle of the scan direction from the declination axis, measured counterclockwise. For a scan angle $\theta = 0^\circ$, the scan direction would run from south to north, and for a scan angle $\theta = 90^\circ$, the scan direction is from east to west.

As the instrument is scanned across the source, the data are binned every 2". The total scan length is 100 bins, or 200". The source was repeatedly scanned. To determine the point-source profile (the beam response to a point source), a bright source whose known size is considerably smaller than either the 50 or the 100 μ m beam was also scanned during the same flight. The scanning techniques were similar for both the source and the point source. Callisto was used as a point source for flight 88-018, IRC +10216 was used for flight 87-012, and IRC +10420 was used for flight 87-083.

To reduce the scan data, we cross-correlated each scan with a template scan and summed the scans together. The cross-correlation was done to account for two effects: a slight shift in the scans starting position due to hysteresis in the scan procedure, and slight shifts of the scan due to guiding errors. The

TABLE 1
SCAN DIRECTIONS AND SIZES FOR LkH α 198

FLIGHT (1)	DATE (2)	SCAN DIRECTION (3)	SYSTEM (4)	θ (5)	FWHM ^a	
					50 μ m (6)	100 μ m (7)
87-012...	1986 Dec 3	Y	6 channel	258°	$\leq 18''$	33"
87-083...	1987 Aug 19	X	8 channel	165	...	33
88-018...	1987 Dec 3	X	8 channel	60	...	32
91-007...	1990 Nov 17	...	20 channel	300	≤ 19	...

^a FWHM sizes are determined by assuming that both the source and point-source profiles are Gaussians.

scans were smoothed with a filter to remove spikes before summing. Because of the smoothing process, the computed errors are correlated from bin to bin and, strictly speaking, apply to a resolution element equal to the filter size, i.e., 18", or 9 bins, for the 100 μ m 8 channel data. For the 8 channel data the shifts required for the central channel (where the source was peaked) were applied to all the other channels. In addition, we corrected for the responsivity of the individual detectors by scanning a bright point source with each detector and normalizing the response to the central detector. For the flight 87-012 50 μ m data we used the shifts obtained for the stronger 100 μ m emission. The scans were summed in the same manner as the 100 μ m scans.

In 1990 November, we observed LkH α 198 at 50 μ m, using a somewhat different technique. The system used was a 20 channel array, which has two columns of 10 channels each and is very similar to the 8 channel system. We did not scan across the source, but instead we moved the telescope to beam-switch the array on and off the source. The data were reduced by subtracting a baseline from the ends of each on-off pair and summing several pairs together. To estimate the beam response, Vesta was observed as a point source. The data for Vesta were reduced as for LkH α 198.

3. RESULTS

The observations are summarized in Table 1. The directions and lengths of the three scans are shown in Figure 1, overlaid on the map of molecular emission of Nakano et al. (1990) (*panel a*) and on the 9000 Å map of Leinert et al. (1991) (*panel b*).

The results of the central channel of the scans are shown in Figure 2 (*solid lines with error bars*), together with the corresponding profiles of point sources (*dashed lines*). The source is

clearly resolved in all three scans, which look symmetric around the peak.

The 100 μ m size estimate of LkH α 198, derived by assuming that both the source and the point-source profile are Gaussians, is given in column (7) of Table 1. The derived sizes (33", 33", and 32") are in very good agreement, even though the data were taken by scanning in different directions with different detector systems. Based on these results, we assume that the source is spherical and assign to it a 100 μ m size of $33'' \pm 5''$. The uncertainty is based on our estimate of the errors of each scan, rather than on the dispersion of the three scans themselves. The 50 μ m scan data (flight 87-012) give a size of 18", while the 50 μ m beam-switched data give an independent estimate of less than 19".

A comparison of our source sizes with the molecular line observations shows that the 100 μ m emission has a similar extent to that seen in CS and HCN $J = 1 \rightarrow 0$ emission, both of which peak on LkH α 198. The size of the optical nebulosity is also comparable to the far-infrared size, as suggested by Harvey et al. (1979).

None of the scans includes V376 Cas, 37" north of LkH α 198, in the central (and most sensitive) channel. However, in both the 87-083 and the 88-018 scans, some of the other channels show clear evidence for a separate extended 100 μ m source (with 100 μ m size of $\sim 15''$ – $20''$) at the location of V376 Cas.

Our total flux density at 100 μ m agrees with that of IRAS 00087+5833 (180 Jy). Less than 30% of the far-infrared flux originates from the V376 Cas region. Our positional data indicate that the dominant source of the far-infrared emission in this region is LkH α 198, rather than V376 Cas, and support the argument that LkH α 198 is the source of the outflow and the most embedded massive star in the region. A rough estimate of the luminosity of V376 Cas, based on the few photometric

FIG. 1a

FIG. 1b

FIG. 1.—Shown are the direction and length of the 100 μ m scans superposed (*a*) on the maps of emission of various molecules (Nakano et al. 1990) and (*b*) on the 9000 Å map of Leinert et al. (1991). Note that in (*b*) the angular scale has been expanded by a factor of 2 compared with the scale of (*a*).

FIG. 2.—The 100 μm scans are displayed. The solid curve is the source profile; the dashed curve is the point-source profile (PSP). The error bars of the PSP are not shown. All the curves have been normalized to unity.

visible and near-infrared data available (Allen 1972; Chavarría-K. 1985) and on our estimate of its far-infrared flux, gives $L \sim 150 L_{\odot}$, i.e., about 60% of the LkH α 198 luminosity.

4. THE DUST DENSITY DISTRIBUTION

4.1. Observational Constraints

The analysis developed in this section is aimed at deriving the spatial distribution of the material surrounding LkH α 198, as traced by the dust. In general, the dust extinguishes the stellar radiation and scatters it over quite a large area on the sky, giving rise to optical nebulosity, while at the same time reemitting the absorbed fraction of the stellar luminosity at longer wavelengths, in the far-infrared and submillimeter ranges. These multiple effects should all be accounted for by self-consistent models of the radiation transfer in the source.

Conversely, it is important to use a variety of different observations to constrain as many of the model parameters as possible.

In LkH α 198, as in other visible objects of lower luminosity, detailed information is available from observations over a large wavelength range. In addition to our far-infrared data, there are maps of the source in visible light. The optical nebulosity, due to scattered light and extended over about $30'' \times 45''$, has been studied by many authors (e.g., Herbig 1960). We are aware that the optical appearance of LkH α 198, as well as that of embedded sources in general, is very sensitive to inhomogeneities in the dust distribution, so that conclusions based on the comparison between far-infrared and optical data may be misleading. However, as will be shown in the following, we do not find any major contradiction between observations and model predictions resulting from the assumption that the grains which scatter the stellar light are distributed as the grains which produce the far-infrared flux. Thus, in our analysis, in addition to far-infrared data, we will use the supplementary information provided by the map at 9000 Å of Leinert et al. (1991), which covers the same spatial scale as our 100 μm scans. Figure 3 shows the intensity profiles obtained by cutting the map along chosen directions; three of them coincide approximately with the directions of the 100 μm scans; the last one, corresponding to an angle of 34° from the declination axis, follows the direction of maximum elongation of the optical nebula. The intensity profiles in different directions are well approximated by $I(\epsilon) \propto \epsilon^{-\gamma}$ for separation angle ϵ from the star between $3''$ and $15''$. The data are consistent with a smooth variation of γ between ~ 1.7 and ~ 1 . This last value is obtained for the scan at 34° which extends along the nebulosity and outflow to the southwest.

Another important diagnostic of the dust configuration and properties, as is well known from studies of T Tauri stars, is offered by the analysis of the overall spectral energy distribution (SED). In the case of LkH α 198, the SED is known from

FIG. 3.—Observed 9000 Å brightness profiles of LkH α 198 for various directions around the central object. Each curve is marked by the value of the angle between the chosen direction and the south-north direction, measured counterclockwise.

blue to millimeter wavelengths. Table 2 summarizes all the available photometric observations (also plotted as dots in Figs. 6–9). The spectrum rises very steeply in the visual ($A_V \sim 5$ –7), flattens between 2 and 100 μm , and then declines at millimeter wavelengths. Altogether, the SED of LkH α 198 looks similar to the “flat” spectra of some T Tauri stars (Rucinski 1985; Rydgren & Zak 1987; Adams, Emerson, & Fuller 1990), which have been interpreted as arising from active circumstellar disks (Adams, Lada, & Shu 1988).

We will analyze the source properties by comparing the predictions of radiative transfer models, using different assumed density distributions, with the various observed properties of the source. More specifically, a given model, and therefore the corresponding density distribution, will be considered to provide a good fit to the observations if the following conditions are satisfied:

1. The 100 μm intensity distribution from the model, convolved with the instrumental response of the multichannel scanning photometer, has a (reduced) $\chi^2 \leq 1$ when compared

to the 87-083 scan, and a computed 100 μm flux density F_{100} (in a 37" beam) in the range 80–100 Jy (see Table 2). We choose that particular scan since it is the most symmetric of the three. In general, models which successfully fit this scan will also produce intensity distributions which fit well the 87-012 data, as well as the innermost part of the 88-018 scan (say, within $\pm 30''$).

2. The intensity distribution at 9000 Å varies as a function of the projected distance from the star as a power law of exponent $\gamma \sim 1.0$ –1.7. Although this may seem a very loose criterion, we will see in the following that in fact it sets severe constraints on the dust density profile.

3. The overall shape of the SED is similar to the observed one.

The first class of models that we consider are spherically symmetric models, in which the star is surrounded by a dust envelope, optically thin in the far-infrared. This choice is motivated by the 100 μm results presented in § 3, in particular by the fact that the source is extended and appears spherically symmetric at that wavelength.

4.2. Spherical Envelope Models

To model the source, we use the radiation transfer code developed by Egan, Leung, & Spagna (1988). The code computes the dust temperature and the intensity distribution at each of 69 frequencies in a self-consistent way, taking into account the effects of multiple scattering, absorption, and re-emission of photons, assuming spherical symmetry. The code has been modified (cf. Butner et al. 1990, 1991a) so that the intensity distribution can be convolved with the appropriate instrumental response, producing normalized intensity scans across the source that can be compared directly with the observations. In addition, the intensity distribution can be convolved with Gaussian beam profiles of appropriate size to produce beam-matched fluxes at each wavelength, which can be then compared with the observed SED.

The numerical code requires that the following parameters be specified: the radiation field of the central source, which in turn can be described by the stellar luminosity and effective temperature; the dust properties, i.e., the absorption and scattering efficiency at each frequency; and the density profile between an inner radius r_i and an outer radius, which we describe as $n = n_i(r/r_i)^{-\alpha}$, where n_i is the density at r_i .

We shall adopt an effective stellar temperature of 15,000 K, corresponding to a star of late B spectral type. To the best of our knowledge, no high-resolution optical spectrum of the star is currently available, and its spectral classification is somewhat uncertain, varying from B5–A5 (Herbig 1960) to B3 (Cohen & Kuhl 1979) to A:ep (Finkenzeller & Mundt 1984). The variation of T_{eff} for these spectral types is not too large, and the choice of a specific value in this interval, as well as the assumption that the star radiates as a blackbody, is practically irrelevant for the dust and infrared properties of the envelope, although it may affect the detailed shape of the visual continuum. The luminosity of the source is estimated by Harvey et al. (1979) to be about 270 $L_\odot$, after scaling to our assumed distance of 600 pc, while Chavarria-K. (1985) obtains $L \geq 160 L_\odot$. By comparing the observed fluxes to the beam-matched predictions of our radiation transfer models, we estimate a luminosity of 250 $L_\odot$ (cf. the detailed discussion of this procedure in the case of NGC 2071 in Butner et al. 1990). With a luminosity of 250 $L_\odot$, and by its location on the H-R diagram,

TABLE 2
PHOTOMETRY ON LkH α 198

Wavelength (μm)	F_ν (Jy)	Uncertainty (Jy)	Beam	References
0.36	1.2(–3) ^a	3(–5)	9"4	1
0.44	3.5(–3)	7(–5)	9.4	1
0.55	7.3(–3)	15(–4)	9.4	1
0.70	2.0(–2)	6(–4)	9.4	1
0.90	4.9(–2)	1(–3)	9.4	1
0.3371	2.45(–3)	1.5(–4)	~10	2
0.3751	3.63(–3)	2.5(–4)	~10	2
0.4030	3.04(–3)	1.5(–4)	~10	2
0.4571	4.40(–3)	1.8(–4)	~10	2
0.5183	6.51(–3)	4.0(–4)	~10	2
0.5827	8.0(–3)	3.0(–4)	~10	2
0.6356	1.1(–2)	4.0(–4)	~10	2
0.7241	1.6(–2)	6.5(–4)	~10	2
1.25	0.17	0.02	~11	3
1.65	0.74	0.08	~11	3
2.2	1.9	0.2	~11	3
3.4	6.5	0.7	~11	3
4.8	5.0	0.5	~11	3
2.2	1.23	0.12	12	1
3.5	2.58	0.26	12	1
4.8	2.37	0.24	12	1
8.4	5.86	0.6	12	1
11.1	9.92	1	12	1
2.2	1.6	0.16	11	4
3.85	3.2	0.2	11	4
8.65	6.2	0.6	11	4
9.97	12.8	0.5	11	4
11.55	17.6	0.9	11	4
52	80	9	37	5
100	72	5	37	5
160	108	11	37	5
350	7	0.7	19	6
450	2.3	0.4	18	6
800	0.87	0.06	16	6
1100	0.28	0.02	18.5	6
1300	60.4	0.1	28	7
12	33.4	4	...	8
25	88.1	9	...	8
60	127	13	...	8
100	183	20	...	8

^a 1.2(–3) means 1.2×10^{-3} .

REFERENCES.—(1) Cohen & Schwartz 1976; (2) Chavarria-K. 1985; (3) Lorenzetti et al. 1983; (4) Berrilli et al. 1987; (5) Harvey et al. 1979; (6) Sandell 1990; (7) Strom et al. 1991; (8) IRAS.

LkH α 198 is expected to have a mass of about $4 M_{\odot}$ and to reach the main sequence as a B3 star, making it one of the most massive stars in the region (Shevchenko & Yakubov 1989).

The dust properties are subject to great uncertainty, especially in circumstellar regions (cf. Beckwith & Sargent 1991). For the moment, we will adopt the Drain & Lee (1984, hereafter DL) dust model, modified at long wavelengths so that $Q(\lambda) \propto \lambda^{-1}$ for $\lambda \geq 100 \mu\text{m}$, to account for the observed energy distribution at the longest wavelengths (see § 4.4).

Once the stellar radiation field and the dust properties have been fixed, each model depends only on the density distribution (i.e., on α , r_i , and n_i), which is what we want to determine. In practice, it is convenient to replace n_i with the dust optical depth at $100 \mu\text{m}$ (τ_{100}). We fix the outer radius at 0.5 pc (corresponding to $172''$ at 600 pc), large enough to include all the significant emission.

We begin by selecting those density profiles that match well the $100 \mu\text{m}$ properties of the source, as described in item 1 of § 4.1. We assume that the grains are destroyed at temperatures higher than 2000 K , defining in this way a minimum value of r_i (given by the dust destruction front), which in our case turns out to be 1.7×10^{-3} (or 1.1 AU). We vary r_i from this lower bound to values comparable to the resolution of our far-infrared observations. For each r_i , we then vary α and τ_{100} .

A large set of model calculations show that the optical depth must be in all cases small, $\tau_{100} \lesssim 0.006$. Thus, the envelopes are optically thin to the secondary radiation emitted by the grains. The dust temperature profile as a function of radius follows closely a power law of exponent -0.4 , with small deviations reflecting the fact that the dust cross section itself does not obey a power law.

The results are summarized in Figure 4, in which the shaded strip shows the location in the (r_i, α) -plane of the models that satisfy requirement 1. All models with $1.7 \times 10^{-3} \lesssim r_i \lesssim 10''$

FIG. 4.—In the $(\log r_i, \alpha)$ -plane the shaded region shows the location of the models which provide a good fit to the $100 \mu\text{m}$ properties of the source, as described in the text. The dots locate three models, for which the figure gives the $100 \mu\text{m}$ optical depth τ_{100} , the size Θ_{100} , F_{100} , and the $50 \mu\text{m}$ size Θ_{50} .

FIG. 5.—Values of γ , the slope of the $9000 \text{ \AA}$ brightness profile between $3''$ and $15''$, are shown as a function of r_i for models of different α . The $9000 \text{ \AA}$ optical depth is in all models $\tau_{9000} = 1.7$. For $r_i \gtrsim 3''$, the brightness profile is not well described by a power law but has a ring structure with peak at $\sim r_i$.

produce a good fit to the $100 \mu\text{m}$ data, as long as α increases at the same time from 0.2 to 2.0 . A significant decrease of τ_{100} (from 0.006 to 0.001) with increasing r_i is also required. Models with $r_i \gtrsim 10''$ produce intensity profiles that are broader than the observed scans, independent of the values of α . Likewise, $\alpha = 0$ models produce too wide a distribution, regardless of r_i . Even though the parameter space in Figure 4 is quite restricted by the $100 \mu\text{m}$ data, they cannot, by themselves, distinguish between steep density gradients around big holes and shallow gradients around small holes.

An additional constraint can be derived from the $50 \mu\text{m}$ scans. Figure 4 shows the computed values of τ_{100} , the 100 and $50 \mu\text{m}$ sizes (Θ_{100} and Θ_{50}), and F_{100} for three models with different values of α and r_i , as indicated by their position in the diagram. As required, the models have very similar values of F_{100} and Θ_{100} . The $50 \mu\text{m}$ size, however, increases from $15''$ to $20''$ as r_i increases from $5'' \times 10^{-3}$ to $8''$, even though the density profile simultaneously steepens (α increases from 0.4 to 1.5). The observed upper limit ($\Theta_{50} \leq 18''$) favors models with $\alpha \lesssim 0.75$, $r_i \lesssim 3''$.

This result is confirmed by the analysis of the optical data. Figure 5 shows the values of γ predicted by the radiation transfer models as a function of r_i for different values of α . In these calculations, γ is defined as the slope of the brightness distribution at $9000 \text{ \AA}$ between $3''$ and $15''$, so that it can be directly compared with the observed values plotted in Figure 3. As long as $r_i \lesssim 3''$, the intensity distribution is well described by a power law of exponent $\gamma \sim \alpha + 1$, as expected if single scattering of the stellar photons dominates. For larger r_i , a ring structure appears, peaked approximately at r_i ; the power-law fit yields very small values of γ , practically independent of α . Therefore, the second requirement on the goodness of the fit described in § 4.3, namely, that $\gamma \sim 1.0$ – 1.7 , rules out models with large inner radii ($r_i \gtrsim 3''$) and steep density profiles ($\alpha \gtrsim 0.7$ – 0.8), confirming the $50 \mu\text{m}$ results and significantly

FIG. 6.—Spectral energy distribution. Dots are the observed values, as reported in Table 2; asterisks are the *IRAS* measurements. The curves show the computed SED for three envelope models, which all fit the spatially resolved 100 μm and 9000 $\text{\AA}$ observations. The short-dashed curve is for $\alpha = 0.75$, $r_i = 0''.5$, $\tau_{100} = 0.0025$; the long-dashed curve for $\alpha = 0.5$, $r_i = 5'' \times 10^{-3}$, $\tau_{100} = 0.0045$; and the dash-dot curve for $\alpha = 0.3$, $r_i = 1''.7 \times 10^{-3}$, $\tau_{100} = 0.006$.

restricting the range of the tolerable values of α . Similarly, low values of α ($\gtrsim 1$) are also derived by Leinert et al. (1991), based on near-infrared speckle interferometry data. In conclusion, from the combination of the far-infrared and visual, we obtain $0.3 \lesssim \alpha \lesssim 0.75$. According to the far-infrared prescriptions, then, in the interval r_i must increase from $\sim 1''.7 \times 10^{-3}$ (for $\alpha \sim 0.3$) to $3''$ (for $\alpha \sim 0.75$), and τ_{100} must decrease from ~ 0.005 to ~ 0.0025 .

All the envelope models predict correctly that a significant contribution to the observed flux in the visual is due to scattered photons, while the rest is stellar radiation transmitted through the envelope. For example, at 9000 $\text{\AA}$, where DL grains have an albedo of 0.51 (see also Mathis 1973; Code 1973), the contribution of scattering to the emergent flux varies from 28% (for $\alpha = 1.5$, $r_i = 8''$, $\tau_{100} = 0.0015$) to 40% (for $\alpha = 0.75$, $r_i = 3''$, $\tau_{100} = 0.0025$) and to 70% (for $\alpha = 0.3$, $r_i = 1''.7 \times 10^{-3}$, $\tau_{100} = 0.006$).

We now turn to the discussion of the last point, namely, the SEDs. In Figure 6 we show three examples of the predicted SEDs for three models that fit the 100 μm and 9000 $\text{\AA}$ data, but that have different values of α , r_i , and τ_{100} . All the models give similar results at far-infrared and millimeter wavelengths, where the predictions agree quite well with the observations. On the contrary, all models produce too little flux in the mid-infrared (between 1.6 and 10 μm) and too much at shorter wavelengths. The mid-infrared deficit cannot be alleviated in the context of simple spherical models, a point that will be discussed in the following. In the optical, models with lower τ_{100} (and therefore lower values of the optical extinction A_V) predict a flux significantly higher than observed. If we take into account that some additional extinction may be due to foreground dust ($A_V^{\text{for}} \lesssim 1$; Chavarría-K. 1985), then models with $\tau_{100} \gtrsim 0.004$ – 0.006 reproduce well the observed flux at 5500 $\text{\AA}$

and the overall behavior of the SED, except in the near-infrared. Values of τ_{100} in this range are compatible with the far-infrared data only if $\alpha \lesssim 0.5$ and $r_i \lesssim 0''.5$. This result reinforces the conclusion that α must be relatively small.

4.3. Disk Models

The major discrepancy between the model predictions and the observed SED is in the near-infrared, in this case between ~ 1.6 and $\sim 10 \mu\text{m}$, where all the theoretical curves fall below the observed data points (cf. Fig. 6). This effect is an old and well-known problem of radiative transfer models that assume spherical symmetry, and its very existence is at the base of the idea that circumstellar disks might be responsible for the observed near-infrared excesses (Rucinski 1985; Adams & Shu 1986). In fact, the very flat SED (in νF_ν) of LkH α 198 would usually be interpreted as the signature of an accretion disk (e.g., Lada 1991 and references therein). Since neither standard, viscous accretion disks nor spatially thin, passive disks can produce such a flat SED, either active disks with distributed energy sources (Adams et al. 1988) or flared, passive disks (Kenyon & Hartmann 1987) would be required.

To illustrate this point, we show in Figure 7, along with the observations, three representative disk spectra, computed following the parametric approach of Beckwith et al. (1990), which assumes power-law surface density and temperature distributions. We cannot model flared disks with this approach, but we can add an arbitrary amount of intrinsic disk luminosity in order to achieve the temperature distribution ($T \propto r^{-0.5}$) needed to produce a flat SED (Adams et al. 1988). We have assumed that the disk is seen face-on. In all cases, the total (star + disk) luminosity is about 260 $L_\odot$. As is well

FIG. 7.—Spectral energy distribution. Dots and asterisks as in Fig. 6. The three curves show the theoretical SED, as predicted by three disk models: the solid line is for a disk with $L_D/L_T = 0.7$, temperature $T \propto r^{-0.5}$, surface density $\Sigma = 2.0 \times 10^7 (r/r_i)^{-1.5} \text{ cm}^{-2}$, dust absorption efficiency $Q \propto \lambda^{-1}$, inclination angle with the plane of the sky 0° ; the dashed line is for $L_D/L_T = 0.4$, $T \propto r^{-0.5}$, $\Sigma = 2.0 \times 10^6 (r/r_i)^{-1.5} \text{ cm}^{-2}$, with the same values of the other parameters; the dash-dot line is for a passive disk ($L_D = 0$), $\Sigma = 2.0 \times 10^7 (r/r_i)^{-1.5} \text{ cm}^{-2}$, with the same $Q(\lambda)$ and inclination.

known, the passive disk model (*dotted line*) does not produce a flat SED and cannot explain the excess in the 5–10 μm region. However, active disk models (*solid line*) provide an excellent fit to the SED.

This disk interpretation of the SED of LkH α 198 would, however, be incorrect. In fact, the high-resolution far-infrared data imply that the disk emission cannot dominate the 100 μm emission, which, as we have seen, arises in a large region of very low optical depth, and not in an optically thick disk that would appear unresolved to the best currently available resolution at all wavelengths where scattering is negligible. This conclusion does not depend on the size of the disk. Independent of the physical size, the temperature distribution needed to fit the SED produces an intensity distribution at 100 μm which would appear pointlike in our data. We shall discuss later (§ 6) the growing body of evidence that the extended emission observed around LkH α 198 is not a peculiar feature of this star but is rather common among Herbig Ae/Be stars.

4.4. Models with Disks and Envelopes

Since neither models with only spherical envelopes nor those with only disks are able to explain all the data, we are justified in considering two-component models, which include both of these structures. The method of constructing these models is discussed more fully by Butner, Evans, & Natta (1991b), so we only summarize it here. We use the spherical radiative transport code described above, but we change the spectrum of the central source from that of a star to that of a star + disk system. When computing the dust temperature profile, we neglect the deviation of the star + disk radiation field from spherical symmetry. This approximation (a *spherical* disk) is not too bad as long as the disk emission at short wavelengths, which contributes to the heating of the envelope, comes from regions small with respect to r_i . The intensity distribution and the beam-matched flux densities are then computed by adding the star + disk emission, attenuated by the dust in the envelope, to the intrinsic emission of the envelope.

The disk properties are well constrained by two requirements, namely, that the disk emission should account for the observed near-infrared flux and should contribute only marginally to F_{100} . As noted earlier, a flat passive disk cannot reproduce the observed SED out to 10 μm (cf. the dotted line in Fig. 6). To comply with that requirement, the disk must have a temperature profile ($T_d \sim r^{-0.5}$), with an intrinsic luminosity $L_D \gtrsim 40\% L_{\text{bol}}$. The second requirement rules out the more luminous and massive disk (Fig. 7, *solid line*) which was acceptable in the models of the last section with a disk only. Quite independent of the envelope properties, there is good agreement between the observed and predicted SEDs if the disk has $M_D = 0.27 M_\odot$ and $L_D/L_{\text{bol}} = 0.44$. Such a disk contributes only 20% to the observed flux at 100 μm .

Figure 8 shows the SEDs of one of the successful two-component models. In these models, the SED is the result of the superposition of three components: the stellar radiation scattered by the spherical envelope, which dominates at short wavelengths; the disk emission between ~ 1.6 and ~ 10 μm ; and the thermal emission in the far-infrared of the dust in the envelope. At millimeter wavelengths, the disk contributes about 30%–40% to the total flux. The resulting SEDs now agree quite well with the observations, especially if we consider, as discussed previously for the envelope models, that some foreground extinction may further decrease the flux in the visual. An important property of the disk + envelope models is

FIG. 8.—Spectral energy distribution. Dots and asterisks as in Fig. 6. The two curves show the SED of two-component models, in which a central source, formed by a star + disk, is surrounded by a spherical envelope of dust. The disk parameters are $L_D/L_T = 0.4$, $T \propto r^{-0.5}$, $\Sigma = 2.0 \times 10^6 (r/r_i)^{-1.5} \text{ cm}^{-2}$, $Q \propto \lambda^{-1}$, inclination angle with the plane of the sky 0° (cf. dashed curve in Fig. 7); the envelope parameters are $\alpha = 3$, $r_i = 0.75$, $\tau_{100} = 0.0055$ (*solid curve*). The three thin lines show the contribution of the central star, the disk, and the envelope to the total flux.

that the presence of the disk does not affect significantly either the 100 μm or the optical brightness distributions of the system. In other words, the best values of α , r_i , and τ_{100} that specify the dust density profile in the envelope remain the same. Thus, the addition of a disk improves the fit to the SED for both models but does not weaken the arguments in favor of small values of α .

4.5. Dust Properties

Because some of our conclusions may in principle depend on the absorption properties of the dust grains, it is appropriate to consider how uncertainties in those properties would affect our conclusions. As reviewed by many authors (e.g., Draine 1990), grain opacities are still subject to many uncertainties, even for grains in the diffuse interstellar medium (compare, for example, the extinction curve of DL with those of Mathis, Mezger, & Panagia 1983, hereafter MMP, and Mathis & Whiffen 1989). The uncertainties only grow when one considers the possibility of physical or chemical processing in dense molecular clouds and circumstellar disks.

The absorption efficiency $Q(\lambda)$ is particularly uncertain at far-infrared and submillimeter wavelengths. In particular, in cold dense regions there is increasing evidence of a wavelength dependence of $Q(\lambda)$ less steep than λ^{-2} , as is usually assumed for the diffuse interstellar medium (see Woody et al. 1989; Weintraub, Sandell, & Duncan 1989; Beckwith et al. 1990; Casey 1991; Beckwith & Sargent 1991). Clumping, accumulation of mantles, and formation of amorphous rather than crystalline grains may well occur in the circumstellar environment, and these effects will tend to increase the far-infrared efficiency of the grains (Tielens & Allamandola 1987). As discussed earlier in this section, the SED of LkH α 198 requires that the envelope dust have $Q(\lambda) \propto \lambda^{-1}$ for $\lambda \geq 100$ μm . Beckwith &

Sargent (1991) have argued for still shallower dependence on λ for the dust in disks surrounding T Tauri stars.

Of the results discussed in this section, the density profile of the envelope, derived from the 100 μ m data, does not depend critically on the dust parameters. If, for example, we compare the results obtained with MMP and DL grains, we find that the former produce broader intensity distributions, for a given value of τ_{100} . This difference is due to the fact that the MMP grains produce a lower equilibrium temperature in the inner part of the envelope, which is heated directly by the stellar radiation. Hence, the inner parts contribute comparatively less emission at all wavelengths. Therefore, MMP grains tend to require slightly steeper density profiles (by less than 0.2 in α) and/or higher values of τ_{100} , typically by factor of 2. These effects are relatively minor compared to other uncertainties.

On the contrary, the SED depends strongly on dust parameters. For example, the same MMP models which give a good fit to the 100 μ m and optical brightness distributions produce too much flux at visible wavelengths, typically a factor of 40–60 higher than the DL grains, because of their lower ratio τ_V/τ_{100} . The resulting SEDs with the dust grains from DL and MMP, respectively, are shown in Figure 9.

The possibility that DL grains give a better fit to the properties of Herbig Ae/Be stars in general is strengthened by the results of Casey (1991), who derives values of the relative extinction efficiency $Q(V)/Q(250 \mu\text{m}) \sim 500\text{--}2500$ for three Herbig Be stars. Our adopted DL grain properties, modified at $\lambda \geq 100 \mu\text{m}$ so that $Q(\lambda) \propto \lambda^{-1}$, have $Q(V)/Q(250 \mu\text{m}) = 2200$, while MMP grains have instead a lower value, $Q(V)/Q(250 \mu\text{m}) = 320$, outside the range suggested by Casey.

In the previous discussion we have implicitly assumed that the dust mixture is composed only of *classical* grains in thermal equilibrium with the radiation field at the temperature T_d . Thus, in the calculations we have ignored the presence of very small grains (VSGs) and polycyclic aromatic hydrocarbons

(PAHs). It has been suggested that a significant absorption of the ultraviolet stellar radiation may be due to this component, which is out of thermal equilibrium (Puget & Léger 1989; Désert, Boulanger, & Puget 1990). These grains are expected to radiate most of the absorbed radiation in the near- and mid-infrared, and therefore they could add a substantial contribution to the SEDs at these critical wavelengths (e.g., Cohen, Tielens, & Allamandola 1985). Usually, VSGs and PAHs have been neglected in the theoretical simulations of the SEDs of T Tauri stars, on the assumption that the stellar ultraviolet field is unimportant (cf., however, the discussion in Bertout 1989). The situation is different for the hotter Herbig Ae/Be stars, whose radiation at the shortest wavelengths is no longer negligible (see the case for AB Aur discussed by Sorrell 1990). We have made an estimate of the fraction of the stellar luminosity which is absorbed by small grains and PAHs, in order to test the possibility that the near-infrared deficit shown by the envelope models could be filled in by this component. Using a stellar effective temperature of 15,000 K and the extinction curves for the various components (VSGs, PAHs, and large grains) given by Désert et al. (1990), we estimate that VSGs and PAHs absorb about 25% of the total luminosity. This figure is indeed very close to the observed *excess* between ~ 1.6 and $\sim 10 \mu\text{m}$, which is about 20% of the total luminosity.

Although the possibility that VSGs and PAHs could account entirely for the near-infrared excess should be checked by self-consistent calculations, the energetic considerations just developed seem to indicate that this may indeed be the case. If so, the only evidence for the presence of a disk around LkH α 198 that we have found in the currently available data would then disappear.

In fact, the very compact disk emission at millimeter wavelengths predicted by our models (~ 0.1 Jy at 1.1 mm) could be detected with current interferometers. The expected disk contribution does not dominate the flux density at millimeter wavelengths observed with single-dish telescopes. More specifically, its contribution amounts to 30%–40% of the flux inside the 18''6 beam of the observations at 1.1 mm obtained by Sandell (1990) at the James Clerk Maxwell Telescope (JCMT), while it is $\sim 15\%$ –25% at 1.3 mm, according to the measurements of Strom et al. (1991) with the Caltech Submillimeter Observatory (CSO). These figures are in good agreement with the description that both these authors give of LkH α 198 as being *extended*. Recent diffraction-limited observations at 450 μm by Sandell Weintraub, & Duncan (1991) of a small sample of low- and intermediate-mass pre-main-sequence (PMS) stars have confirmed the extended nature of the emission at submillimeter wavelengths and suggest that the interpretation in terms exclusively of disk emission could be inappropriate. Other indicators not discussed in this paper that favor a spherical geometry of the circumstellar material can be found in Berrilli et al. (1991).

5. DISCUSSION

5.1. Comparison with Other Data

The main result of the previous section, namely, that most of the matter in the vicinity of LkH α 198 is in a spherical extended envelope, characterized by a flat density profile, can be checked further by a comparison of the mass estimates existing in the literature. The value of τ_{100} required by the best values of α and r_i , namely, $\tau_{100} \sim 0.004\text{--}0.006$, can be turned into an estimate of the mass of the dust emitting in the far-

FIG. 9.—Spectral energy distribution for two models, one with DL grains and one with MMP grains. Dots and asterisks as in Fig. 6. The envelope parameters are $\alpha = 0.5$, $r_i = 5'' \times 10^{-3}$, $\tau_{100} = 0.012$ for the MMP model, and $\alpha = 0.5$, $r_i = 5'' \times 10^{-3}$, $\tau_{100} = 0.0045$ for the DL model.

infrared. From the adopted DL grain properties (i.e., for a ratio of the visual extinction to the gas column density of $A_V/N_H = 5.35 \times 10^{-22} \text{ cm}^{-2}$), the mass within 10,000 AU ($16''.7$) from the central star is $M_{\text{FIR}} \sim 2 M_\odot$. Recently, Sandell et al. (1991) have resolved the source at $800 \mu\text{m}$, finding a size of $14'' \times 11''$. They conclude that the primary contribution to the long-wavelength emission is the surrounding cloud, and they derive a mass in the range $0.002\text{--}0.3 M_\odot$ (scaled to 600 pc) for a region about half the size of ours. On the other hand, assuming that the emission at 1.3 mm arises from dust distributed in a disk, Strom et al. (1991) calculate a mass of $M_{\text{mm}} \sim 1.9 M_\odot$ within a radius of $14''$ ($\sim 8.4 \times 10^3$ AU), corresponding to the beam of the CSO telescope.

High angular resolution molecular maps presented by Nakano et al. (1990) show that LkH α 198 is surrounded by clumps of molecular emission, extended on scales similar to those sampled by the far-infrared and millimeter observations. Assuming a mean density of 10^5 cm^{-3} , Nakano et al. argue that the amount of molecular matter in a region $0.1 \text{ pc} \times 0.2 \text{ pc}$ in size (therefore a geometric mean radius of 2.8×10^4 AU) is about $M_{\text{mol}} \sim 20 M_\odot$, comparable to the virial mass $M_{\text{vir}} \sim 10 M_\odot$, calculated using a typical line width of 1 km s^{-1} . The average gas density that we derive from our data, $\langle n \rangle \sim 10^5 \text{ cm}^{-3}$, is consistent with that required to excite the CS emission detected by Nakano et al. The fact that $\langle n \rangle$ is not larger than this critical density indirectly supports our claim of shallow density gradients over a region of the size of the CS emission. On a smaller scale, probed by near-infrared speckle interferometric observations, Leinert et al. (1991) derive a mass of $\sim 0.005 M_\odot$ (recomputed for DL grains) within a distance of ~ 370 AU from the central object.

Overall, the quoted mass estimates are consistent with a density gradient of circumstellar matter $n_d \sim r^{-0.5}$, although the uncertainties are sufficiently large that somewhat steeper distributions cannot be ruled out. Density gradients with small α have been suggested to be typical of the dust envelope surrounding newly formed massive stars associated with ultra-compact H II regions. Churchwell, Wolfire, & Wood (1990) have modeled the infrared emission of dust cocoons around O stars, and found that the best overall fit to the observed SEDs comes from constant density distributions, the steepest gradient tolerable being $\alpha = 0.5$.

5.2. Evolutionary Status of LkH α 198

Assuming that the lower values of α (~ 0.5) represent the actual matter distribution around LkH α 198, a natural question is what kind of physical and dynamical processes are responsible.

A possibility suggested in principle by the youth of the star is that the material could be remnants of the collapsing envelope. For instance, this was indeed the case for the two more embedded objects L1551 and NGC 2071. However, existing models of gravitational collapse (Larson 1969; Penston 1969; Shu 1977) all predict steeper density gradients for the infalling material ($\alpha \sim 1.5\text{--}2$) than determined by our analysis. It is true that all the collapse models have been developed to explain the early stages of the formation of Sunlike stars, not of more massive objects, such as Herbig Ae/Be stars. However, within the framework of the existing theories, the existence of matter with a relatively flat density gradient, extending over large distances ($300\text{--}10,000$ AU) from the star is very hard to understand.

A first possibility is that we are seeing not the region of the

infalling gas but rather material above and below the plane of a disk, which should have $\alpha = 0.5$ (Terebey, Shu, & Cassen 1984). If we assume an effective sound speed a of 0.35 km s^{-1} , as was used to model L1551 IRS 5, and a velocity gradient of $3.3\text{--}4.2 \text{ km s}^{-1} \text{ pc}^{-1}$ as given by Nakano et al. (1990), and take the mass of the star to be $4 M_\odot$, we calculate that the infall radius is $r_2 = 1.1 \times 10^4$ AU, or $18''$, about the size of the source that we see, and that the centrifugal radius is $R_c = 3.5\text{--}5.7 \times 10^3$ AU, or $6''\text{--}10''$. Between r_2 and R_c , $\alpha = 1.5$ according to the models of Terebey et al. (1984). Inside R_c , we would expect a disk to form, which contains most of the matter. The computed values of R_c and r_2 , taken at their face value, imply that the far-infrared emission should come from the infalling matter. Still, these numbers are subject to considerable uncertainty, and R_c is extremely sensitive to the choice of a . Thus, it is possible that R_c has grown in this system to include all of the material that we probe in the far-infrared, while the infalling envelope appears only on the larger scales where Loren (1977) interpreted the pattern of CO line widths in terms of collapse. However, while the material above and below the disk plane may fit the $\alpha = 0.5$ that we see, there is no evidence in our scans for a disk of the size of R_c . Moreover, the much smaller disk that we find to be consistent with the observations contains only 28% of the mass within R_c .

The energetic molecular outflow associated with LkH α 198 could have communicated some energy to the surrounding cloud. This possibility is suggested by the increase of the CO line width to 3 km s^{-1} near the star observed by Nakano et al. (1990). The entrained gas could therefore have altered its density distribution. In order to assess whether the outflow could have *anything* to do with the material we see, we note that its momentum ($0.7 M_\odot$ times about 1 km s^{-1} , assuming that the line width of the high-density tracers applies) is comparable to the momentum in the outflow ($1.4 M_\odot \text{ km s}^{-1}$; Nakano et al. 1990) and that the dynamical lifetime of the outflow, $t_{\text{dyn}} \sim (1.5\text{--}2.5) \times 10^5 \text{ yr}$ (Levreault 1988; Nakano et al. 1990), is comparable to the age of the star. On this last point, it is interesting to notice that Nakano et al. consider t_{dyn} to be much shorter than the typical ages of Herbig stars of similar mass ($\sim 10^6 \text{ yr}$), based on classical PMS evolutionary tracks. However, the age of LkH α 198 must be computed using the appropriate initial conditions for the PMS contraction phase provided by the birth line for intermediate-mass stars (Palla & Stahler 1990). In fact, with the estimates of the luminosity and effective temperature discussed in § 4, it turns out that the position of LkH α 198 in the H-R diagram falls exactly on the theoretical birth line. This fact implies that the star is much younger than suggested by Nakano et al. and that it is just beginning its PMS evolution.

Myers, Ladd, & Fuller (1991) have found that cores associated with luminous stars have larger nonthermal line widths than those hosting sources of lower luminosity. They argue that the nonthermal motions are likely to arise from a combination of magnetic fields and turbulence, *prior* to the formation of the star, and not from the action of an energetic outflow. The numerical simulations of Lizano & Shu (1989) have explicitly investigated the coupled effects of turbulence and magnetic fields on the structure of a molecular cloud core, finding that turbulence can produce shallow density gradients. Density gradients with $\alpha < 1$ could indeed be obtained for large values (> 12) of the turbulent parameter, $K = (\rho/\rho_0)(v_t/a)^2$, where ρ is the density at which a turbulent line width $\Delta v = 2(2 \ln 2)^{1/2} v_t$ is observed, $a = (kT/m)^{1/2}$ is the sound

speed, and ρ_0 is a fiducial density, taken to be $1 \times 10^3 \text{ cm}^{-3}$ in their models.

A first problem with this explanation is that in the Lizano & Shu calculations (which, however, only apply to a core of $0.96 M_\odot$), clouds with large K never collapse to form a star. Second, the values of K observed in the LkH α 198 cloud appear to be too small to affect the density distribution. The line widths of CO at large distances ($6' - 8'$) from LkH α 198, where one may be free of the effects of the outflow, are about 1 km s^{-1} (Loren 1977). Since these lines are optically thick, they probably set an upper limit to Δv before the star formed. If we take the density at large distances from the star to be less than $1 \times 10^3 \text{ cm}^{-3}$ and the temperature before star formation to be at least 10 K, we get $K < 5$, too small to change α significantly. Interestingly, the line widths of the CS, HCO $^+$, and HCN near the star are also about 1 km s^{-1} (Nakano et al. 1990); since this gas is probably 100 times denser, it would suggest much larger values of K , but the relationship assumed by Lizano & Shu (1989), i.e., $\Delta v \propto \rho^{-0.5}$, would not appear to be satisfied in this cloud.

Finally, we suggest another possibility that is ad hoc but not unreasonable, namely, that the envelope we see is in fact a slow outflow, caused by a stellar wind eroding a disk at a rate that is decreasing with time. In this picture the wind would be pushing the dense material (perhaps the remnants of a disk or torus) at about 1 km s^{-1} , while the $5 - 10 \text{ km s}^{-1}$ outflow seen in CO would be the result of the wind accelerating the lower density material above and below the disk plane to higher velocities. This would be a scaled-down version of the low- and high-velocity outflows around IRc2 in Orion. However, it is not obvious that the morphology of such a system would be consistent with the properties of the far-infrared emission seen in the three directions we scanned.

6. CONCLUSIONS

We have presented far-infrared scans of LkH α 198 at 50 and $100 \mu\text{m}$ along several directions. The observations reveal an extended, roughly spherical source diameter of $33''$, or $2 \times 10^4 \text{ AU}$, at $100 \mu\text{m}$ and $\leq 18''$, or $1.5 \times 10^4 \text{ AU}$, at $50 \mu\text{m}$.

We have combined our scans with maps of the optical brightness distribution to derive the spatial distribution of the matter surrounding LkH α 198, using a radiative transfer code. By comparing the observed fluxes to the beam-matched predictions of the models, we estimate a luminosity of $250 L_\odot$ at a distance of 600 pc. The optical depth at $100 \mu\text{m}$ is $0.004 - 0.006$, implying a mass of $\sim 2 M_\odot$ within a radius of 10^4 AU . The dust configuration is characterized by a flat density profile, a

power-law distribution $n(r) \sim r^{-\alpha}$, with $\alpha \sim 0.5$, in most of the directions around the star and over large distances. The inner radius of the dusty envelope is probably rather small, $r_i \lesssim 300 \text{ AU}$ ($0''.5$), and it may be as small as the dust destruction front: in LkH α 198 there is no evidence of a large region devoid of grains.

The fit to the observed spectral energy distribution from the optical to the millimeter favors a model that includes a disk and a spherical envelope. The former is required in order to provide a good match at near-infrared wavelengths, but it does not affect at all either the $100 \mu\text{m}$ or the optical brightness distribution of the system and does not weaken the arguments in favor of small values of α . The disk mass is $0.27 M_\odot$, i.e., $\sim 7\%$ of the stellar mass. Alternatively, the SED can be fitted by a spherical dust envelope only, which includes a component of very small grains and PAHs.

The best direct proof of the presence of a compact and cold source around LkH α 198, i.e., *the disk*, may come from interferometric observations at low frequencies (cf. the case for L1551 IRS 5 in Butner et al. 1991a, b), as discussed in § 4. In fact, the disk emission that we predict could be detected at 1.1 mm with current interferometers.

The modern scenario of star formation, mostly developed for solar-mass stars, does not easily account for the flat density profile of the dusty envelope around LkH α 198. Simple energy considerations suggest that an important role may be played by the outflow associated with LkH α 198.

Clearly, LkH α 198 is just one example of a young PMS star of intermediate mass. Given the lack of comparable information on similar objects, it is still premature to consider the present conclusions as typical of the whole class of Herbig Ae/Be stars. Much more observational effort and theoretical understanding are needed in order to elucidate the main issues that we have addressed in this paper. In a forthcoming paper (Natta et al. 1992), we will discuss the emission properties of a sample of several such stars for which high-quality data at 50 and $100 \mu\text{m}$ have been collected.

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