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A DEEPLY EMBEDDED COMPANION TO LkHα 198[1]

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ABSTRACT

The region around the Herbig Ae/Be star LkHα 198 was imaged with the 10 μm CAMIRAS camera mounted on the Canada-France-Hawaii Telescope and on the Nordic Optical Telescope. We discovered, 6″ north of LkHα 198, a deeply embedded source ($A_V > 35$), which may play an important role in the region, as indicated by its observed flux (∼40% of LkHα 198 at 12.3 μm) and its position on the optical images (on the axis of the elliptical optical nebula). It is quite likely that it is in fact the new embedded source, and not LkHα 198, which drives the CO molecular outflow seen in this region. At the resolution of our observations (FWHM = 1″.3), LkHα 198 appears pointlike, so that the mid-infrared excess from this object cannot be due to an extended envelope with a large amount of transiently heated small grains.

Subject headings: astrometry — binaries: general — infrared: stars — instrumentation: detectors — ISM: jets and outflows — stars: individual (LkHα 198)

1. INTRODUCTION

It is now generally accepted that young, pre-main-sequence stars of low mass, i.e., T Tauri stars, are frequently surrounded by a circumstellar accretion disk (Bertout 1989, and references therein). The situation is much more controversial for pre–main-sequence stars of intermediate mass, the Herbig Ae/Be stars. While accretion disk models are able to reproduce the infrared (IR) excess present in the spectrum of these objects (Hillenbrand et al. 1992; Lada & Adams 1992), they often require both a large accretion rate and an inner opacity "hole"; these two conditions are difficult to reconcile (Hartmann, Kenyon, & Calvet 1993).

Alternative models with for ingredient a dusty nebula containing transiently heated very small grains (VSG) have been worked out recently (Hartmann, et al. 1993; Natta, Prusti, & Krügel 1993b). As a consequence of the introduction of VSG, a spatial extension significantly larger than previously thought is expected in the mid-IR; detailed calculations done for the well studied Herbig Ae/Be star LkHα 198 have shown that the 12 μm emission could peak as far as 3″.4 from the star (Natta et al. 1993b).

Recently, a new probe has become available to test this prediction: 10 μm imaging with two-dimensional infrared arrays. Thanks to these arrays, an angular resolution of about 1″ (the diffraction limit for a 3 m class telescope) can be obtained straightforwardly, when, up to now, most of the mid-IR observations of young stellar objects (YSOs) have been performed with photometers of beam diameter greater than 3″, and even 12″ in the case of LkHα 198 (Cohen & Schwartz 1976; Berrilli et al. 1987). With a high angular resolution, it is also possible to search for cold embedded companions, which may contribute to the IR Spectral Energy Distribution (SED), on which all the models quoted above are based.

In the next section, we present high angular resolution 10 μm images of the LkHα 198 region, obtained with the Saclay CAMIRAS camera. A discussion of the results follows in § 3 and conclusions are drawn in § 4.

2. OBSERVATIONS

Observations of LkHα 198 were performed with the CAMIRAS camera, developed by the Service d'Astrophysique at Saclay for high angular resolution imaging observations in the 8–13.5 μm atmospheric window (Lagage et al. 1992). The main originality of this camera relies upon its 64 × 64 pixel Si:Ga/DVR detector array, manufactured by the "Laboratoire InfraRouge" (LIR) of the "Centre d'Etudes Nucléaires" at Grenoble. Indeed, the storage capacity of this array has been increased to 3×10^7 electrons, so that observations with the broad-band *N* filter encompassing the entire atmospheric window can easily be done despite the huge photon background generated at 10 μm by the atmosphere and the telescope.

The first observations were performed on 1991 August at the Canada-France-Hawaii Telescope (CFHT) in the *N*-band filter and with a pixel field of view of 0″.7. The sky and telescope emissions were subtracted using the standard chopping and nodding photometer technique. A new source was detected 6″ north of LkHα 198 with a signal-to-noise ratio equal to 7. Because of poor weather conditions, it was not possible to make absolute photometry of the source, but we determined a relative intensity compared to LkHα 198 of 14% (±2%, 1 σ). This new source is most probably associated with LkHα 198, as the chance of finding a field star within a 6″ beam is $\sim 10^{-2}$ in the visible (Reipurth & Zinnecker 1993) and even lower in the IR.

A second series of observations was made 1 year later with the CAMIRAS camera mounted on the 2.56 m Nordic Optical Telescope (NOT) located at the La Palma island (Canaries, Spain). The NOT is not an IR telescope, but the Stockholms Observatory has developed a focal plane chopper unit which also adapts the telescope beam to the IR camera beam; in these conditions, the pixel field of view is 0″.55. The 1 σ point source sensitivity achieved at this non-IR telescope (emissivity 45%)

[1] Based on observations made at the Canada-France-Hawaii Telescope and at the Nordic Optical Telescope.

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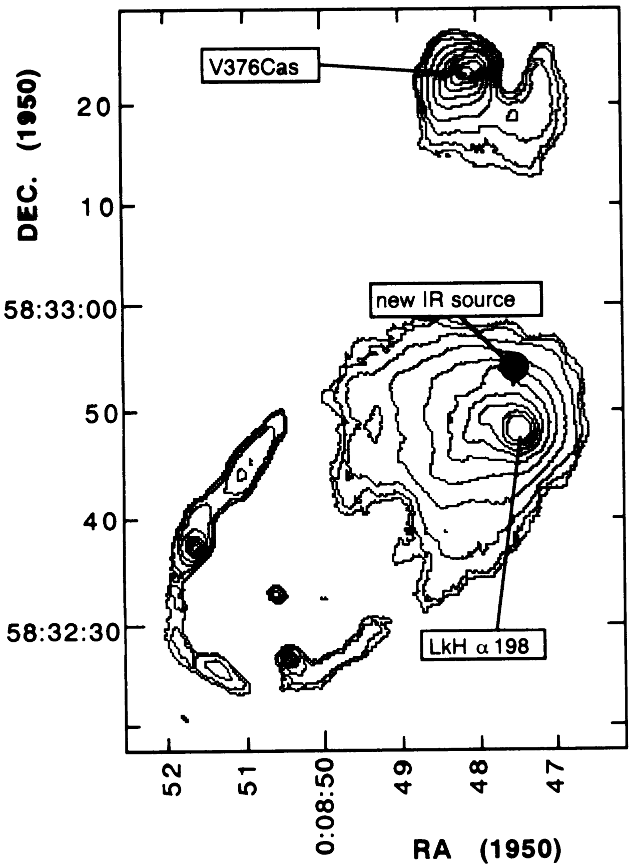

FIG. 3.—Position of LkHα 198-IR on a contour map of the *I*-CCD image (see also Fig. 2). Brightness increases by a factor of 2 between adjacent contours.

was in the 1 Jy range for most of the filters of Table 2 (below) and for an onsource integration time of 1 second. A 10–13 μm band image of LkHα 198 and its newly discovered companion is shown in Figure 1 (Plate L4). In the following, the companion will be referred to as LkHα 198-IR.

An *I*-band image of the region, including both LkHα 198 and V376 Cas, was obtained on the same nights with the standby NOT 0".2 pixel CCD camera (Olofsson 1989), which can still be used when CAMIRAS is mounted on the telescope. This image is presented in Figure 2 (Plate L5), with superposed contours of 10–13 μm emission from LkHα 198, LkHα 198-IR and V376 Cas. A contour image of the same I-CCD frame but enhancing lower flux levels is presented in Figure 3.

There is some confusion in the literature about the coordinates of LkHα 198. This star is included in the *Hubble Space Telescope* Guide Star Catalog and after cross-checking a number of nearby SAO stars and comparing to the plate of the region by Herbig (1960), we conclude that the Guide Star Catalog position is correct and that the position given by Herbig & Bell (1988) is off by 17" to the north. The position of V376 Cas relative to LkHα 198 was measured on our CCD image. Using two CAMIRAS images of the new IR source, one including LkHα 198 and the other V376 Cas, we were then able to infer an absolute position for LkHα 198-IR (see Table 1).

The magnitudes and fluxes found at various wavelengths for LkHα 198-IR, as well as those for LkHα 198 and V376 Cas, are shown in Table 2 and Figure 4. Both LkHα 198 sources were observed in five filters covering together the whole atmospheric

TABLE 1

POSITIONS OF THE THREE SOURCES AT 10 μm AND *I*

Object	Right Ascension (1950)	Declination (1950)
LkHα 198[a]	00ʰ08ᵐ47ˢ.45	58°32′48″.1
V376 Cas	00 08 48.09	58 33 23.1
LkHα 198-IR	00 08 47.51	58 32 54.0

[a] The widely used position of LkHα 198 in the Herbig & Bell 1988 catalog is off by 17" in declination.

window and centered below, in and above the silicate feature at 9.7 μm. The nights were photometric; the reference star used for the photometry was HD 34029 (α Aur), considered as a blackbody of magnitude −1.94 (Tokunaga 1984). Photometry was performed over the 21 pixels contained in a beam diameter of 2".8 (about 77% of the total flux); this choice results from a trade-off between statistical uncertainties and photometric uncertainties. The photometric precision, determined by repeated observations of the same object, was found to be 4% for most of the filters, except the silicate filter where it is 10%. All the observations of the LkHα 198 region were performed at low air masses (typically: 1.2–1.3), similar to the air mass of the reference star. Extinction curves, obtained in the last three filters of Table 2, show a zenith sky transmission of 93%, proving the adequacy of the La Palma sky for 10 μm observations. To avoid the problems of flat-fielding and vignetting, the reference star was set successively at the position of LkHα 198 and LkHα 198-IR. This was not the case for V376 Cas for which the photometric accuracy is only of 10%.

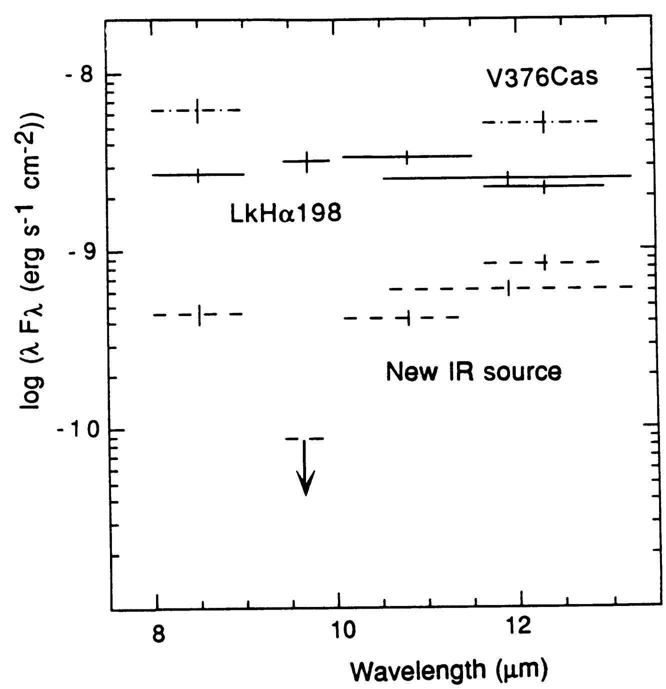

FIG. 4.—Fluxes observed from LkHα 198, V376 Cas, and the IR source discovered 6" north of LkHα 198, in various filters. Only an upper limit is found in the silicate filter (9.7 μm) for the new source, LkHα 198-IR. The horizontal bar indicates the width of the filter. The vertical bar represents the uncertainty on the measurement (both photometric and 1 σ statistical) (see Table 2).

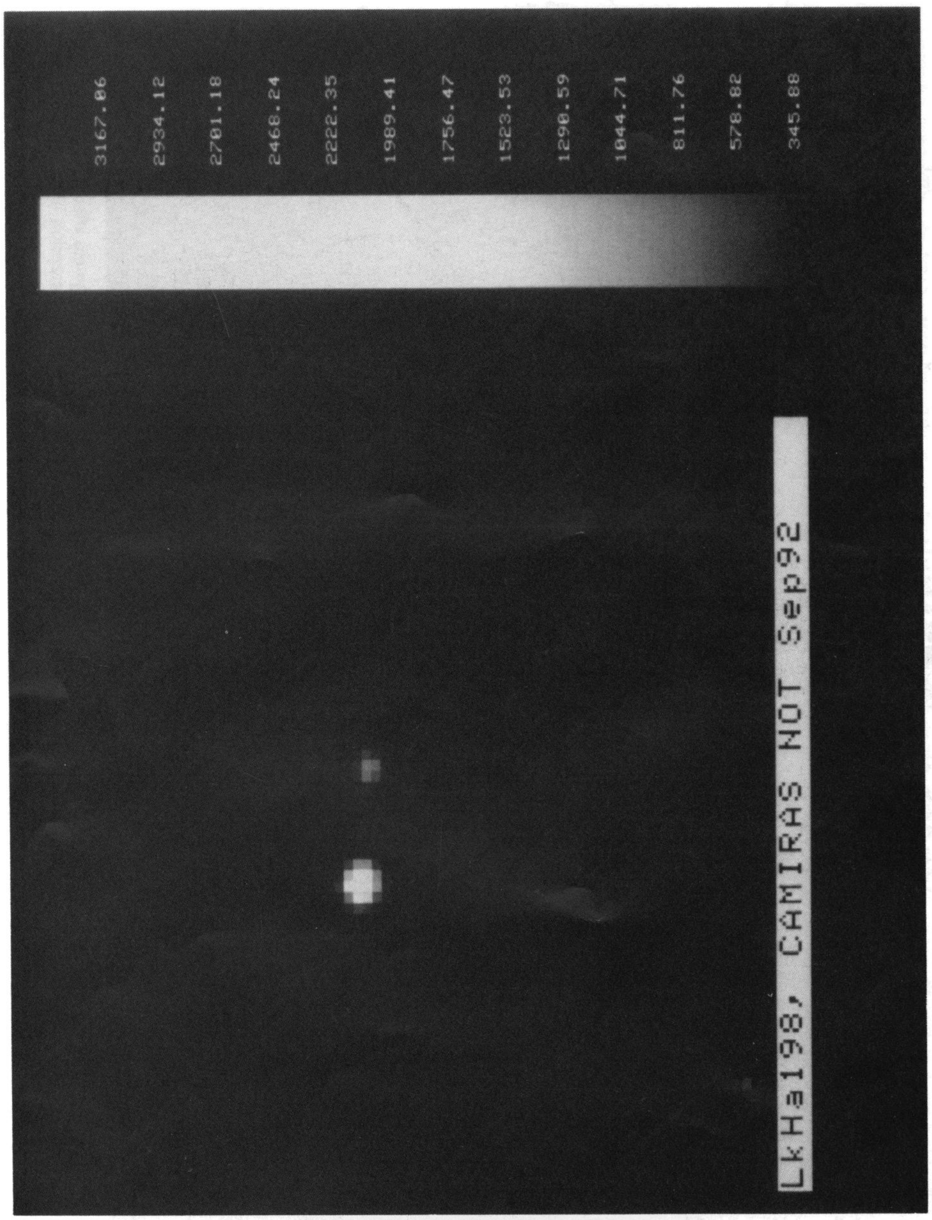

FIG. 1.—Image of the LkHα 198 region obtained with the Saclay CAMIRAS 10 μm camera mounted on the Nordic Optical Telescope. A companion clearly appears 6″ north of LkHα 198 (the brightest source). East is to the right; north is at the top; the pixel size was 0″.55 and the 10–13 μm filter was used. Integration time: 10 minutes on-source.

LAGAGE et al. (see 417, L80)

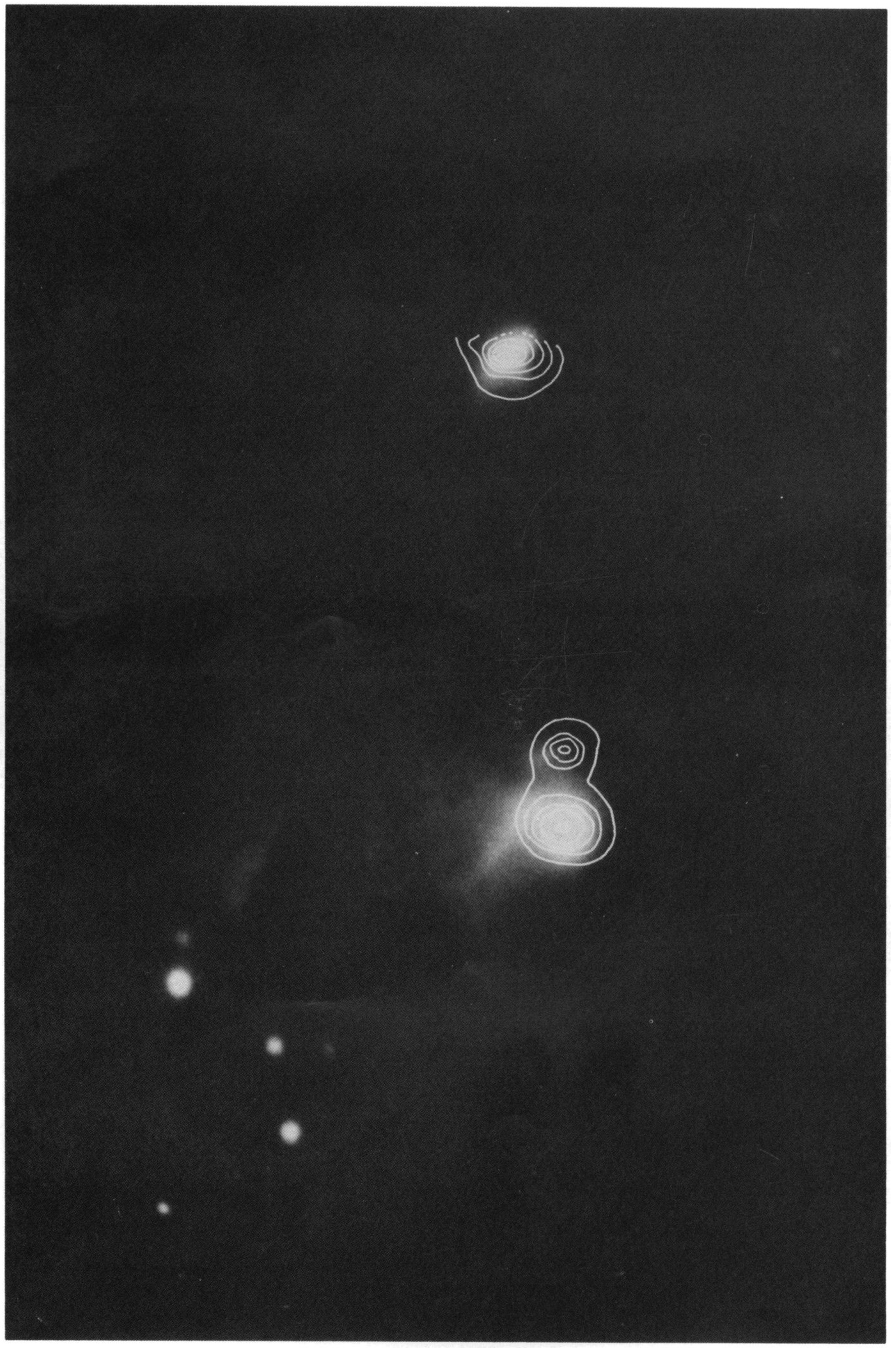

FIG. 2.—IR contours of the three sources LkHα 198, V376 Cas, and LkHα 198-IR superposed on an *I*-band CCD image obtained on the same nights as the IR images. The CCD exposure time was 2 minutes and the pixel size of the camera was 0″2; the seeing was good (0″6); as the observations were made during full Moon and as the sky-baffle around the secondary mirror was removed (to decrease the thermal emission seen by the IR camera), the image is not as deep as the image obtained by Piirola et al. (1992) with the same instrument. An optical jetlike structure aligned with the new IR source is clearly visible. The contours of V376 Cas appear elongated because it is on the edge of the field of the 10 μm camera.

LAGAGE et al. (see 417, L80)

TABLE 2

FLUXES IN JANSKYS AND MAGNITUDES FOR VARIOUS FILTERS;[a] (IN PARENTHESES: 1 σ STATISTICAL UNCERTAINTIES AND ESTIMATED PHOTOMETRIC ERROR IN MAGNITUDE)

Date	Filter λ (central) (μm)	Filter Δλ (μm)	LkHα 198 (Jy, mag)	LkHα 198-IR (Jy, mag)	V376 Cas (Jy, mag)
1992 Sep 9–10	8.5	1	7.7, 2.11 (0.01; 0.1)	1.3, 4.05 (0.1; 0.1)	17.7, 1.2 (0.01; 0.14)
1992 Sep 9–10, 10–11	9.7	0.5	10.3, 1.50 (0.04; 0.14)	<0.3, >5.4 (1 σ) (/; 0.14)	
1992 Sep 10–11	10.8	1.4	12.0, 1.10 (0.01; 0.1)	1.5, 3.35 (0.04; 0.1)	
1992 Sep 9–10	11.9	2.7	10.0, 1.09 (0.01; 0.1)	2.4, 2.62 (0.04; 0.1)	
1992 Sep 10–11	12.3	1.3	9.3, 1.10 (0.02; 0.1)	3.5, 2.17 (0.05; 0.1)	21.5, 0.19 (0.03; 0.14)

[a] The reference star was HD 34029 (α Aur), assumed to be a blackbody of magnitude −1.94. The correspondence between magnitude and Janskys is considered at the central wavelength of the filter; the 10.0 μm magnitude is taken equal to 38.7 Jy (Cohen et al. 1992, and references therein).

The fluxes found for LkHα 198 and V376 Cas are in agreement with existing values in the literature (Cohen & Schwartz 1976; Berrilli et al. 1987). LkHα 198-IR was not detected through the silicate filter and has a flux reaching almost 40% of the LkHα 198 flux at 12.3 μm. The total flux at 12.3 μm from LkHα 198, its infrared companion, and V376 Cas, 34 Jy, is compatible with the *IRAS* measurements (32 Jy from the Low Resolution Spectrum instrument on-board the *IRAS* satellite; *IRAS* Science Team 1986). Hence there is little room for additional embedded sources in the region or for a diffuse component at 12 μm.

3. DISCUSSION

3.1. *The Infrared Companion, LkHα 198-IR*

There are several indications that the newly discovered companion plays an important role in the region. The first indication comes from its luminosity as inferred from the observed energy spectrum. The upper limit in the silicate band proves that LkHα 198-IR is a deeply embedded source. A conservative lower limit to the silicate optical depth, τ_{si}, can be obtained by taking for the 9.7 μm continuum flux an interpolation between the fluxes observed at 8.5 μm and 12.3 μm. This method leads to $\tau_{si} > 2$, from which we can derive a visual extinction, A_V, of at least 35 (Rieke & Lebofsky 1985; Whittet 1988). Dereddening our spectrum with an A_V of 35, we find a new source "intrinsic" luminosity in the 8–13 μm region of the same order as that of LkHα 198. A tentative estimate of the total luminosity of LkHα 198-IR can be made by comparing it to other known sources. The silicate depth indicates that LkHα 198-IR is more deeply embedded than T Tau's companion, for which $\tau_{si} \sim 0.4$ (Ghez et al. 1991), and that it is more similar to cold objects like IRAS 04365+2535 in Taurus, which emit most of their luminosity at long wavelengths (Myers et al. 1987). If its spectral shape is close to that of IRAS 04365+2535, LkHα 198-IR would be at the origin of most of the observed KAO (Kuiper Airborne Observatory) fluxes toward LkHα 198 (Natta et al. 1992). By assuming a similar ratio of bolometric to *N*-band luminosity, we would then infer a luminosity around 100 $L_\odot$ for LkHα 198-IR, assuming a distance of 600 pc (Racine 1968; Chavarria-K 1985; Schevchenko & Yakubov 1989). Additional observations in the *L* and *M* bands (*K* observations already exist; (Ray T. private communication) and in the 20 μm atmospheric window would be useful to further explore the nature of this source.

Another argument in favor of an important role of the IR source in the region is its position on the optical image. It is aligned with the optical jetlike structure seen in CCD images taken in the *R* and *I* bands (Leinert, Haas, & Lenzen 1991; Piirola, Scaltriti, & Coyne 1992; Asselin, Bastien, & Ménard 1993) (see also Fig. 2). It also lies closer than LkHα 198 to the axis of the elliptical optical reflection nebula (see Fig. 3), whose position angle (p.a.) is similar to the p.a. of the CO bipolar molecular outflow seen in the region (Bally & Lada 1983; Cantó et al. 1984; Levreault 1988; Nakano, Kogure, & Yoshida 1990).

Up to now LkHα 198 was considered as the driving source of the molecular outflow, mainly because of its position close to the center of the (mostly redshifted) outflowing gas. Additional arguments are that the dense molecular gas, as traced by HCO^+, HCN, and CS, is mostly distributed around LkHα 198 (Nakano et al. 1990) and that most of the far-infrared flux found by *IRAS* (source number 00087+5833) arises from the LkHα 198 region (Natta et al. 1992). However, the finding of a blueshifted optical flow extending from LkHα 198 at a p.a. of ~100°, led Strom et al. (1986) to recommend the search for additional embedded candidates to the driving of the molecular outflow. The observational arguments favoring LkHα 198 are also valid for LkHα 198-IR, because the angular resolution of the observations was not high enough to distinguish between the two objects. In fact, the Herbig & Bell (1988) position adopted by Nakano et al. (1990) for LkHα 198 is closer to the position of LkHα 198-IR (cf. Table 1). Furthermore a high extinction is a frequent characteristic of molecular outflow sources, and a luminosity of 100 $L_\odot$ would be more than sufficient to account for the energetics of the CO outflow, according to the correlation found between the energy content of outflows and the luminosity of the central star (Levreault 1988; Cabrit & Bertout 1992). Therefore it appears quite possible that it is the embedded companion, and not LkHα 198, which is driving the outflow. Spectroscopic observations of the linear optical feature, e.g., in the 2.12 μm H_2 line, would be useful to confirm its stellar jet nature and to compare its radial velocity with that of the molecular outflow.

3.2. *LkHα 198*

If the new source contributes significantly to the integrated fluxes, then the determination of the luminosity of LkHα 198 has to be revised and models of the dust environment of LkHα 198 (e.g., Natta et al. 1992) will have to be reexamined. Because it is so deeply embedded, we would not expect LkHα 198-IR to contribute significantly to the infrared excess of LkHα 198 shortward of 3.5 μm. However, it could dominate the flux at longer wavelengths around 60 μm. This would relax present constraints on the inner radius of the dust envelope around LkHα 198, based on size measurements at 100 μm (Natta et al. 1992), and thereby lessen the need for a disk with a very high accretion rate to explain the mid-IR excess (Natta et al. 1993a).

Another way to obtain information on the dust distribution around the object is by direct imaging. We have searched for a spatial extension of LkHα 198 in our data; no convincing evidence was found. The observed full width at half maximum (FWHM) of LkHα 198 was in the same range (1″.1 to 1″.3) as that of the reference stars (α Auri, μ Cep). It is slightly higher than expected from the diffraction (0″.8 at 10 μm) mainly because of our sampling (0″.55). These observations rule out the presence of a diffuse component with an intensity greater than about 10% of the central intensity. Therefore, the mid-IR excess from LkHα 198 cannot be due to an extended envelope with a large amount of transiently heated small dust grains. Our upper limit to the 10 μm size does not allow to distinguish between the remaining two alternatives: a hot accretion disk, or an envelope with a small inner radius (Natta et al. 1993b).

4. CONCLUSIONS

The observations of the LkHα 198 region presented here illustrate the potential of high angular resolution 10 μm imaging observations of star-forming regions to search for embedded sources. The new embedded source discovered near LkHα 198 may play an important role in the region and may contribute to the driving of the molecular outflow. Additional high angular resolution spectroscopic and imaging observations at various wavelengths (optical, near-infrared, 20 μm, ...) are required to clarify the properties of this source and to disentangle the effect of each of the two stars on the ambient medium.

A systematic 10 μm survey at high angular resolution of YSOs has been initiated in order to study the circumstellar environment of young stars and to search for other embedded companions. We will be able to determine whether LkHα 198 is a special case or whether embedded companions are sufficiently common to have an impact on the accretion disk problem for intermediate mass YSOs, as well as to influence the statistics of appearance of binary systems, which is another important parameter for theories of star formation.

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