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HIGH SPATIAL RESOLUTION IR OBSERVATIONS OF YOUNG STELLAR OBJECTS: A POSSIBLE DISK SURROUNDING HL TAURI

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ABSTRACT

High spatial resolution images of the T Tauri star HL Tau were obtained at 1.6 μm and 2.2 μm. The original images as well as maximum entropy image reconstructions reveal a circumstellar envelope structure, similar at both wavelengths, and extended along P.A. = 112°; the 10% width of the structure is 1″.9 (300 AU at 160 pc). The extended structure is interpreted as light scattered toward Earth by dust in a disk surrounding this young stellar object. Polarization measurements made at 2.2 μm support this hypothesis. The total solid particle mass is, at minimum, $5 \times 10^{-7}\ M_{\odot}$.

Subject headings: infrared: general — stars: circumstellar shells — stars: individual — stars: pre–main-sequence

I. INTRODUCTION

HL Tau is a T Tauri star located in the Lynds 1551 dark cloud; the cloud also contains Herbig-Haro objects 28, 29, and 30 (Herbig 1974) as well as a large HH complex, HH 102 (Strom, Grasdalen, and Strom 1974).

The optical appearance of HL Tau is peculiar. Images of the region (Strom, Grasdalen, and Strom 1974; Mundt and Fried 1983) suggest that this star and XZ Tau are surrounded by an extensive (~ 20″) cloud of ionized gas. The brightest portion of this emission region lies 2″ northwest of HL Tau at P.A. = 150°. Recently, Mundt and Fried (1983) discovered two ionized jets emanating from the HL Tau, XZ Tau region (see Fig. 3). The jet apparently arising from HL Tau extends northeastward at P.A. = 48° from the star and is blueshifted (Morgan *et al.* 1984). A redshifted jet most probably arises from XZ Tau and extends southward. Hence, each of these young stars appears to be the source of a highly collimated mass outflow.

The absorption line spectrum of HL Tau (Cohen and Kuhi 1979) suggests a K7 type, although the classification is complicated by strong "veiling." The forbidden emission lines are unusually strong for a T Tauri star. Jankovics, Appenzeller, and Krautter (1983) note that the systemic velocity of the forbidden emission lines is blueshifted by more than 100 km s^{-1} compared to the velocity of the L1551 cloud.

HL Tau also exhibits the largest linear polarization known for a T Tauri star, measured (at R) to be 13% at P.A. = 144° (Vrba, Strom, and Strom 1976). The e-vector is oriented at an angle of 60° with respect to the cloud magnetic field lines.

The infrared properties of HL Tau are unusual as well. Cohen (1975) and Rydgren, Strom, and Strom (1976) report the presence of 3.05 μm water ice and 10 μm silicate absorption; τ(ice) = 0.41 and τ(silicate) = 0.33. Cohen (1983) finds HL Tau to be unique among T Tau stars in exhibiting these features.

Cohen (1983) has observed HL Tau in the far-infrared and notes that it is unusual among T Tauri stars in exhibiting a large excess at far-infrared wavelengths; the ratio of infrared ($\lambda > 2\ \mu$m) to optical flux is 630. If the IR flux arises from re-radiation of ultraviolet and optical photons absorbed by circumstellar dust grains then τ(dust) ≈ 7 mag at V if the envelope surrounding HL Tau is spherical and > 7 mag if the envelope intercepts only a part of the radiation emanating from HL Tau.

II. OBSERVATIONS

We have begun a program aimed at inferring the structure of circumstellar material surrounding young stellar objects (YSOs). Our method involves near-IR mapping of small regions surrounding YSOs at high (sub-arcsecond) spatial resolution. If the structures surrounding YSOs are comparable in size with the present-day solar system (≈ 100 AU), then the angular size of such disks will be on the order of 1″ at 100 pc.

The nature of these structures is sought either from detection of scattered light from the structure itself or from the pattern of light scattered in the observer's direction by nearby

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dust grains in the associated dark cloud complex. The near-IR offers the advantage of permitting observations of optically obscured YSOs.

In this *Letter* we describe our observations of HL Tau carried out during 1983 October and 1984 January at the IRTF. A series of high spatial resolution pictures was obtained by programming the telescope motions to effect a raster scan across the star. Measurements were made in AC mode: a chopper throw of 90″ along a position angle of 45° was used for most of our observations. A chopping frequency of 14 Hz was selected. Typically, we measure the flux from the star through a 2″ diameter circular aperture and at intervals of 0″.4 to produce a map 32 × 32 pixels in size; the integration time per picture was 300 s. Immediately before and after each HL Tau map, we obtained a map of a nearby standard star in order to measure the response of the telescope and atmosphere to a point image.

Maps were made at H (1.6 μm) and K (2.2 μm) using an InSb detector mounted in Dewar RC 1. In addition, we imaged HL Tau at K through an IR polarizer.

III. REDUCTIONS

The brightness of HL Tau ($H = 8.7, K = 7.1$) and our strategy of sampling at high spatial frequencies allowed us to attempt maximum entropy reconstructions using the method of Willingale (1981) as outlined by Grasdalen, Hackwell, and Gehrz (1983).

In Figure 1, we present unprocessed images of HL Tau at K along with images of a nearby unresolved star observed both before and after HL Tau. It is already plain from these images that HL Tau exhibits distinct flattening. In Figure 2, we present the maximum entropy reconstructions from these observations. In Figure 3 (Plate L3), we present our H band reconstructions. At both H and K, the image of HL Tau is elongated. In Figure 4 (Plate L4), we present the processed images of HL Tau obtained at K through a polarizer; the position angle of the polarizer is given above each panel. Note that in each case, an unpolarized standard star was observed through the polarizer at the indicated position angle both before and after an HL Tau observation. We can see that at

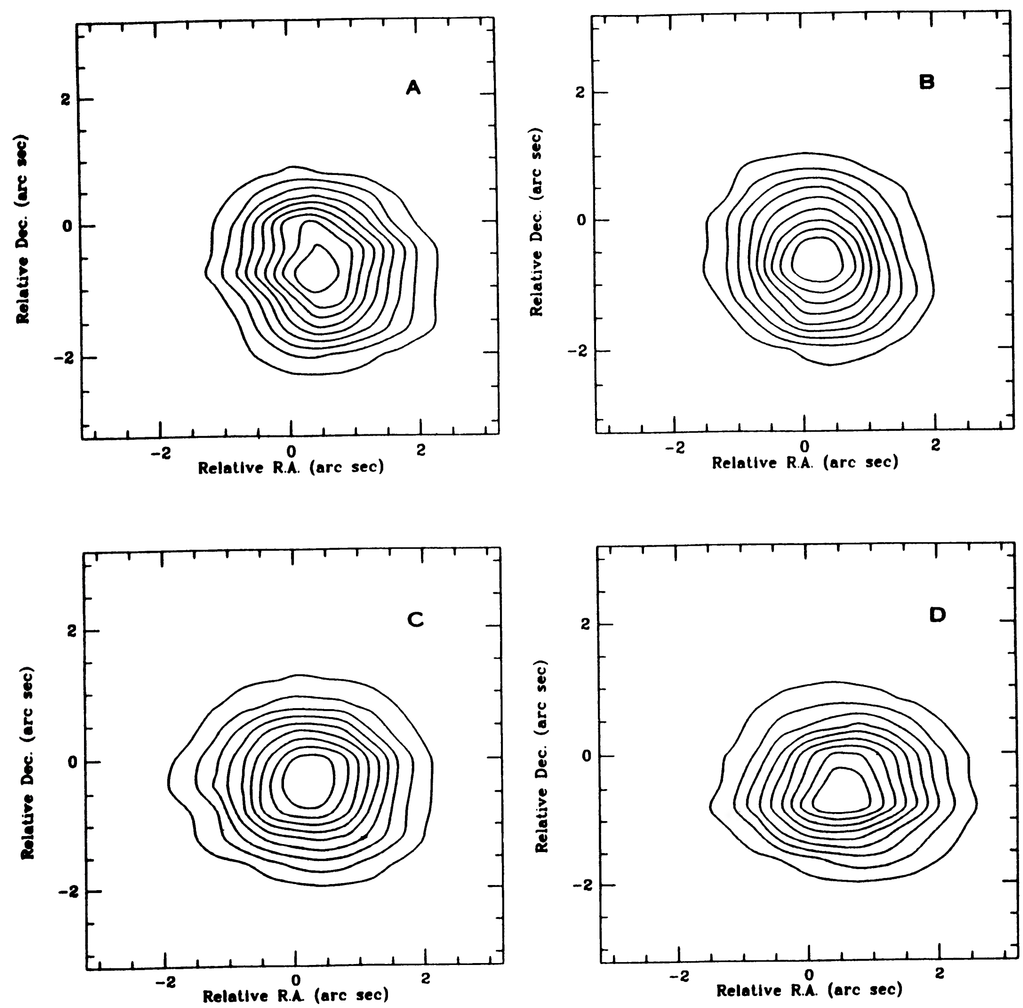

FIG. 1.—Unprocessed 2.2 μm (K) data. The two upper panels are observations of the unresolved star HR 1140. The lower two panels are observations of HL Tau. The temporal sequence of observations was a, c, d, b. The contour levels begin at 10% of the peak intensity and increase by 10% for each successive level.

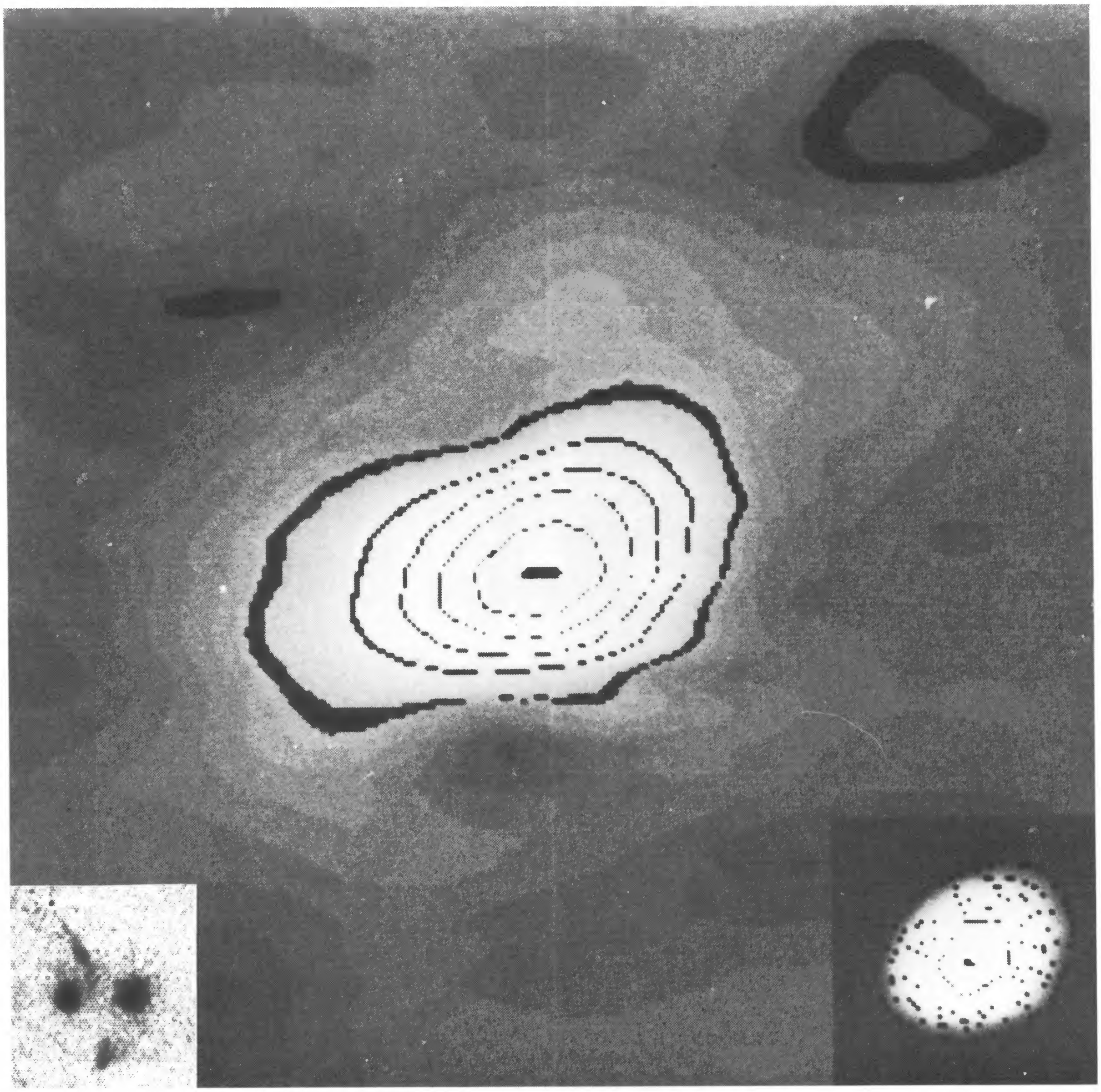

FIG. 3.—A reconstruction of a 1.6 μm (H) image of HL Tau. This is the most successful (as judged by a χ^2 test) reconstruction from a set of eight. Several others in the set are nearly as successful and show the same general features. The exterior dimensions of the figure are 12".8 × 12".8. The reconstructed image of an unresolved star is shown (to the same scale) in the lower right. Note that the gray scale intensities are proportional to the log of the intensity. The contour levels have a constant (logarithmic) spacing of 0.5 dex. North is at the top, and east is to the left. In the lower left insert, we illustrate the objects in a larger field surrounding HL Tau. XZ Tau lies 30" to the east. The northeastern and southern "jets" (see text) are also illustrated.

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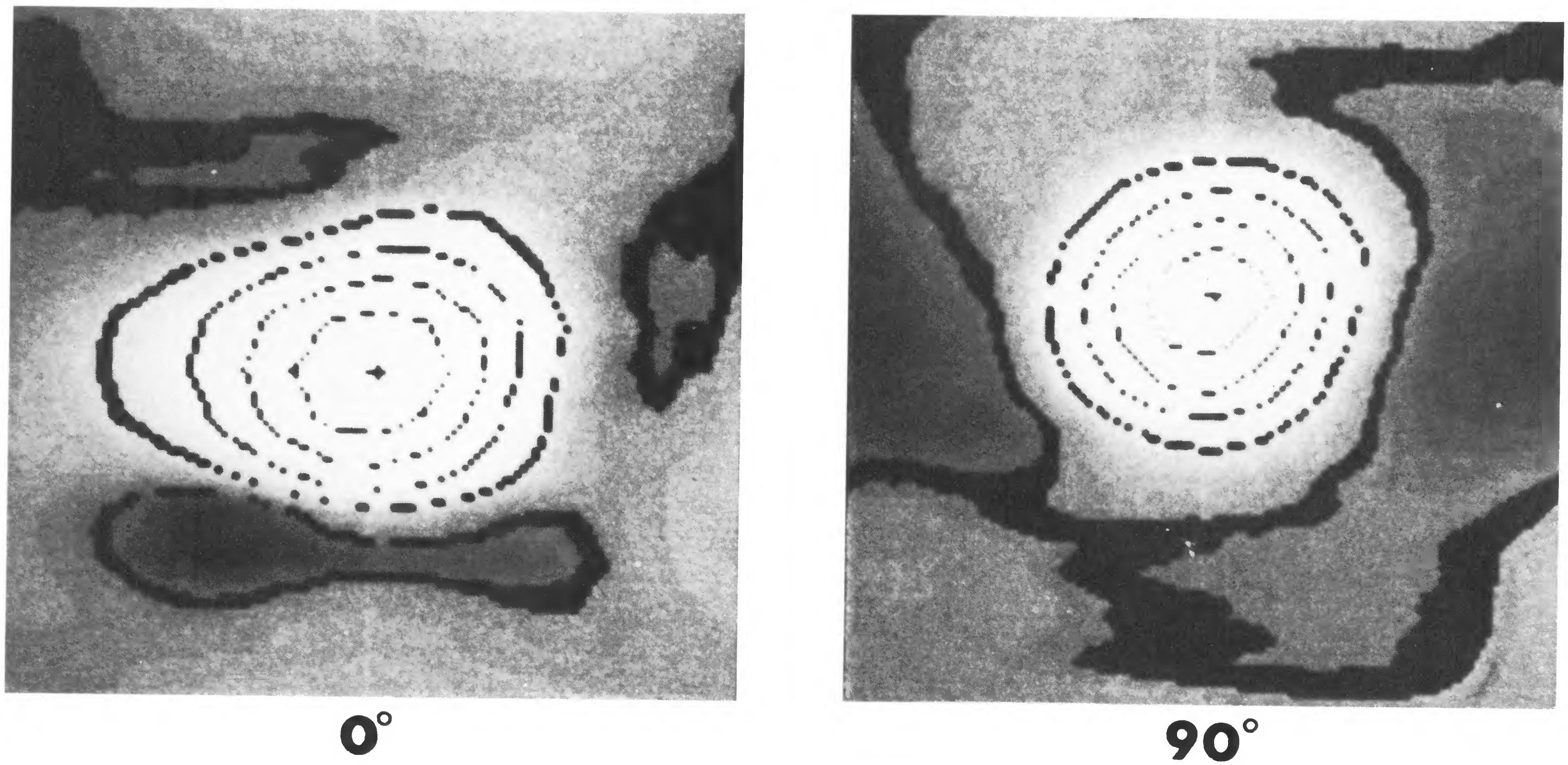

FIG. 4.—Reconstructions of 2.2 μm (K) images of HL Tau taken with a linear polarization analyzer in the beam. These are the most successful (as judged by a χ^2 test) reconstructions from a set of 16 reconstructions at each analyzer setting. The images are 6″.4 on a side. The gray scale intensities are proportional to the log of the intensity. The contours have a constant (logarithmic) spacing of 0.5 dex. North is at the top, and east is to the left.

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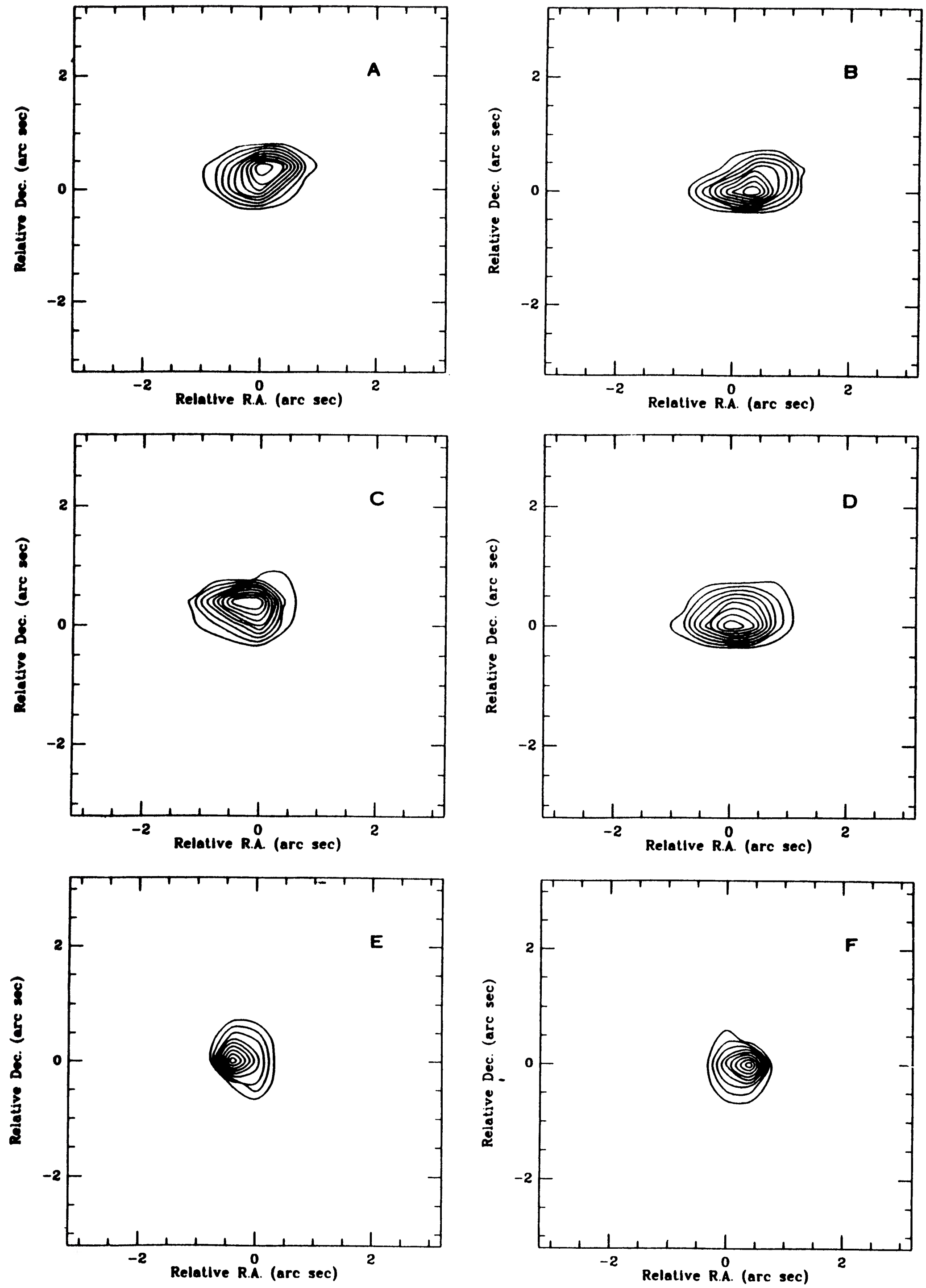

FIG. 2.—Maximum entropy reconstructions of the data in Fig. 1. (*a*) Fig. 1*c* using Fig. 1*a* as a beam profile. (*b*) Fig. 1*d* using Fig. 1*a* as a beam profile. (*c*) Fig. 1*c* using Fig. 1*b* as a beam profile. (*d*) Fig. 1*d* using Fig. 1*b* as a beam profile. (*e*) Fig. 1*a* using Fig. 1*b* as a beam profile. (*f*) Fig. 1*b* using Fig. 1*a* as a beam profile. Although the details of the various reconstructions are not identical, the widths and position angles of the resolved structure agree quite well. The contour level convention is identical to that of Fig. 1.

P.A. = 0°, HL Tau appears extended, while at P.A. = 90°, the extension is considerably less.

A large-aperture (4″) polarization measurement yields a value of 1.1% at P.A. = 134° for the integrated K band polarization of HL Tau. Instrumental polarization was assessed by observing several unpolarized stars. The transformation from instrumental to absolute position angle was determined by measuring the highly polarized BN source (Dyck and Beichman 1974).

IV. INTERPRETATION

The image of HL Tau is clearly extended at both H and K. If we approximate the shape of the extension by an ellipse of major axis a and minor axis b, we compute from Figure 3 the 10% intensity points along the principal axes as $a = 1''.2$ and $b = 0''.8$ at H and $a = 1''.9$ and $b = 1''.1$ at K. Speckle interferometric measurements of HL Tau, obtained contemporaneously by Beckwith *et al.* (1984), yield image sizes (at K) consistent with our maximum entropy results.

Molecular hydrogen or Brackett-γ emission might conceivably contribute to the observed K band flux; no comparably strong emission features are found within the H filter. The similarity of the H and K reconstructions thus suggests that the extension is produced by a dust-scattering envelope. The polarized reconstructions (Fig. 4) confirm this conclusion.

Until now, we have avoided interpreting our observations in terms of a specific geometry. However, it appears as if our images find most economical description if we imagine that HL Tau is surrounded by a disk viewed nearly edge-on. The approximate angular extent, $1''.9$, corresponds to a diameter of 300 AU for an estimated distance to HL Tau of 160 pc.

Such a model (as noted by Cohen 1983) accounts for the following:

1. The high ratio of IR to optical flux. Since the disk is optically thick at V and is edge-on, it obscures the optical radiation from HL Tau along the line of sight.
2. The ice and silicate absorption features. Since HL Tau is one of a very few T Tauri stars which we view through the plane of a circumstellar disk, its unique silicate and ice features must arise within the disk.
3. The observed polarization. We have demonstrated that the 2 μm light from the *resolved* component of the disk is highly polarized. The *net* polarization observed for HL Tau (1.1% at K and 13% at R) must arise from asymmetries in the disk. Because the observed position angles at K (134°) and R (144°) are nearly identical, we conclude that an increase in the ratio of unpolarized starlight to polarized disk light is responsible for the decrease in *net* polarization from R to K. An *a priori* prediction of the magnitude and direction of the *net* polarization is nearly impossible since it requires detailed knowledge of the phase function for the scattering grains as well as their distribution within the disk.
4. The negative radial velocities of the forbidden lines. Radiation from those parts of the mass outflow behind the disk will be attenuated. Hence, the flow directed toward the observer will provide the dominant contribution to the forbidden line profiles.

V. PROPERTIES OF THE DISK

a) *Overall Size*

Since the surface brightness of a disk seen in scattered light should decrease at least as rapidly as the square of the distance from the illuminating star, our H and K band observations may not reveal the full extent of the disk. Direct detection of thermal radiation from the dust grains may be useful in diagnosing the extent of the disk. In Figure 5, we plot the spectral energy distribution of HL Tau. Included in this plot are both the far-infrared observations (beam size 45″) made by Cohen (1983) and shorter wavelength observations made at the Wyoming Infrared Observatory. The energy distribution is continuous throughout this wavelength interval despite the fact that the 19.5 μm and 23 μm points were obtained through a 7″ aperture. Hence, long wavelength emission from the disk is likely to arise from a region smaller than 7″ in size.

b) *Mass of Dust in the Disk*

Our data also permit an estimate of the minimum mass for grains contained in the HL Tau disk. If we call F the fraction of the observed 2 μm light scattered by disk grains, then

$$F = N\sigma V / 4\pi r^2,$$

where N is the number density of the grains, σ is the grain cross section, V is the disk volume, and r is the disk radius. For grains of radius a,

$$\sigma = Q\pi a^2.$$

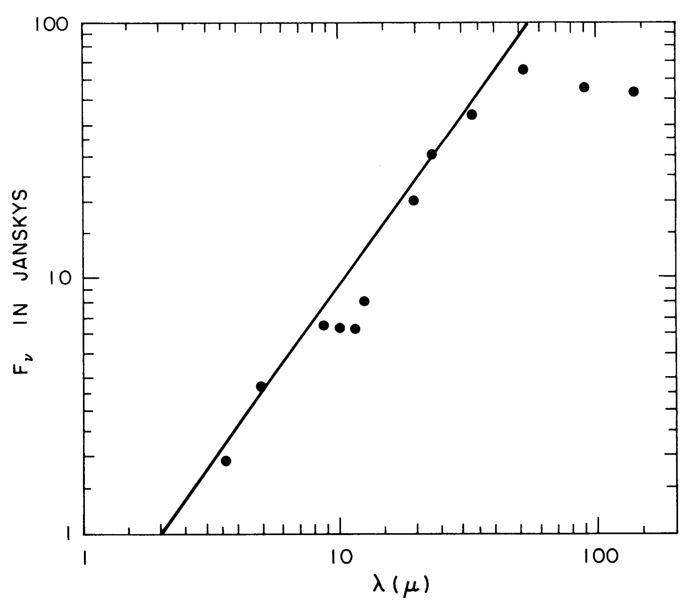

FIG. 5.—The infrared energy distribution of HL Tau. The data from 2.2 μm to 23 μm are averages of ground-based results (see text) taken with a 7″ beam. The points beyond 30 μm are from Cohen (1983) and were obtained with a 45″ beam.

If we assume "perfect" scatterers, $Q = 1$. For grains of density ρ, we compute

$$M(\text{grains}) = (16\pi/3)\rho a r^2 F.$$

With assumed values $\rho = 3$ g cm^{-3}, a = 0.35 μm, $r = 50$ AU, and $F = 0.5$, $M(\text{grains}) = 5 \times 10^{-7}\ M_{\odot}$. If the disk is optically thick at K, then this estimate represents a lower limit to the grain mass.

c) *Evolutionary State of the Disk*

Unfortunately, we cannot determine at present whether the HL Tau disk is (1) a remnant of the parent molecular cloud yet to be accreted by the star, (2) a signature of a solar system in the process of formation, or (3) the dust remaining after the formation of large solid bodies in a solar system and the removal of the gaseous material and small particles by a stellar wind. A crucial next step in addressing the evolutionary state of the HL Tau disk will be the determination of its gas content.

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