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The young Herbig Ae/Be star LkHα 349

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Abstract. We present observations of the unique pre-main sequence object LkHα 349, the central star of the cometary nebula IC 1396A. The optical spectrum is dominated by strong P Cygni Balmer and Na D lines and the broad and shallow absorption lines of a rapidly rotating F8 star. The blue-shifted P Cygni absorption wings extend to $500-700$ km s^{-1} and are indicative of a very strong stellar wind. The spectral energy distribution from the optical through the far-infrared is that of a single F star with moderate extinction, a radius of 8.4 $R_\odot$ (L=84 $L_\odot$), and no obvious contribution from a circumstellar disk. The deconvolved absorption line broadening function shows a $v \sin i$ of 193 $\pm$ 12 km s^{-1}, suggesting that LkHα 349 is rotating at near break-up. LkHα 349 sits in the middle of a substantial circumstellar "hole" which it may have blown out of IC 1396A. All of these characteristics can be understood if LkHα 349 is a pre-main sequence star of intermediate mass ($\gtrsim$ 3 $M_\odot$) on its way towards becoming a Herbig Be star. The wind must be the star's response to the problem of rotating so quickly while rapidly contracting down to the main sequence. Due to the very short contraction times expected for intermediate-mass stars, LkHα 349 gives us a rare glimpse of a young star during a very short but important period in its pre-main sequence life.

Key words: ISM: dust – stars: pre-main sequence – stars: Herbig Ae/Be – stars: individual : LkHα 349

1. Introduction

LkHα 349 ($\alpha_{2000} = 21^h36^m51^s, \delta_{2000} = +57°31'11''$; HBC 308 in Herbig & Bell 1988) is a nebulous Hα emission-line star at the center of a cometary nebula within the HII region IC 1396 (= Trumper 37, the center of the Cep OB2 association) (Dibai & Esipov 1968). A fainter T Tauri star, LkHα 349c (V = 14.9 mag. versus 13.3 mag. for LkHα 349; HBC 729), is located 16" to the northwest. Both stars are embedded in a faint reflection nebula. The exciting star of IC 1396, the O6.5 dwarf HD 206267, not only excites the prominent bright rim of the surrounding globule but also enables one to determine a spectroscopic distance of 750 pc to LkHα 349 (Wootten et al. 1983).

There have been no published reports of major photometric activity of LkHα 349. The survey for variable stars in IC 1396 by Gieseking (1976) went to a limiting visual magnitude of more than 17 but did not include LkHα 349, suggesting that there were no changes by more than about 0.5 magnitudes from June 1969 to October 1971. Dibai (1969) gives a V magnitude of 13.3 whereas Cohen & Kuhi (1979) report 13.0, indicating that LkHα 349 shows a small amount of variability like many other Young Stellar Objects (hereafter YSO's).

The first detailed description of the optical spectrum of LkHα 349 is from Dibai (1969; for "Anon IC 1396"), who reported seeing an F6-F8 absorption line spectrum in the blue, Hβ in absorption, and an Hα emission line with an equivalent width of 10 Å. LkHα 349 is not in Kun's list of Hα emission-line stars found in an objective-prism survey of IC 1396 (Kun 1986). From the observed spectral type and colors (B-V=1.79, U-B=1.55), she estimated a visual extinction of 3.90 magnitudes. Spectra taken by Cohen & Kuhi (1979) clearly show a strong P Cygni profile at Hα ($W_\lambda \approx 9.1$ Å) with an absorption component stronger than that in emission. Using the approximate spectra type of dF8, they derived an A_V of 3.65 $\pm$ 0.10. Herbig (1988) reports seeing "strong, double P Cyg-type absorption components ... on a Lick Coudé plate."

The dark globule around LkHα 349, labelled IC 1396A by Pottasch (1956), has been the object of many detailed studies. Large-scale images of IC 1396A can be found in Osterbrock (1974; Figs. 7.3 and 7.4) and in Birkle (1991). The "bright rim" has an electron density of about 10^3 cm^{-3} (Schmidt 1974) and can be clearly seen at 6 cm (Baars & Wendker 1976; Schwartz 1985). The observed brightness at 6 and 11 cm is consistent with that expected due to the back illumination of the globule

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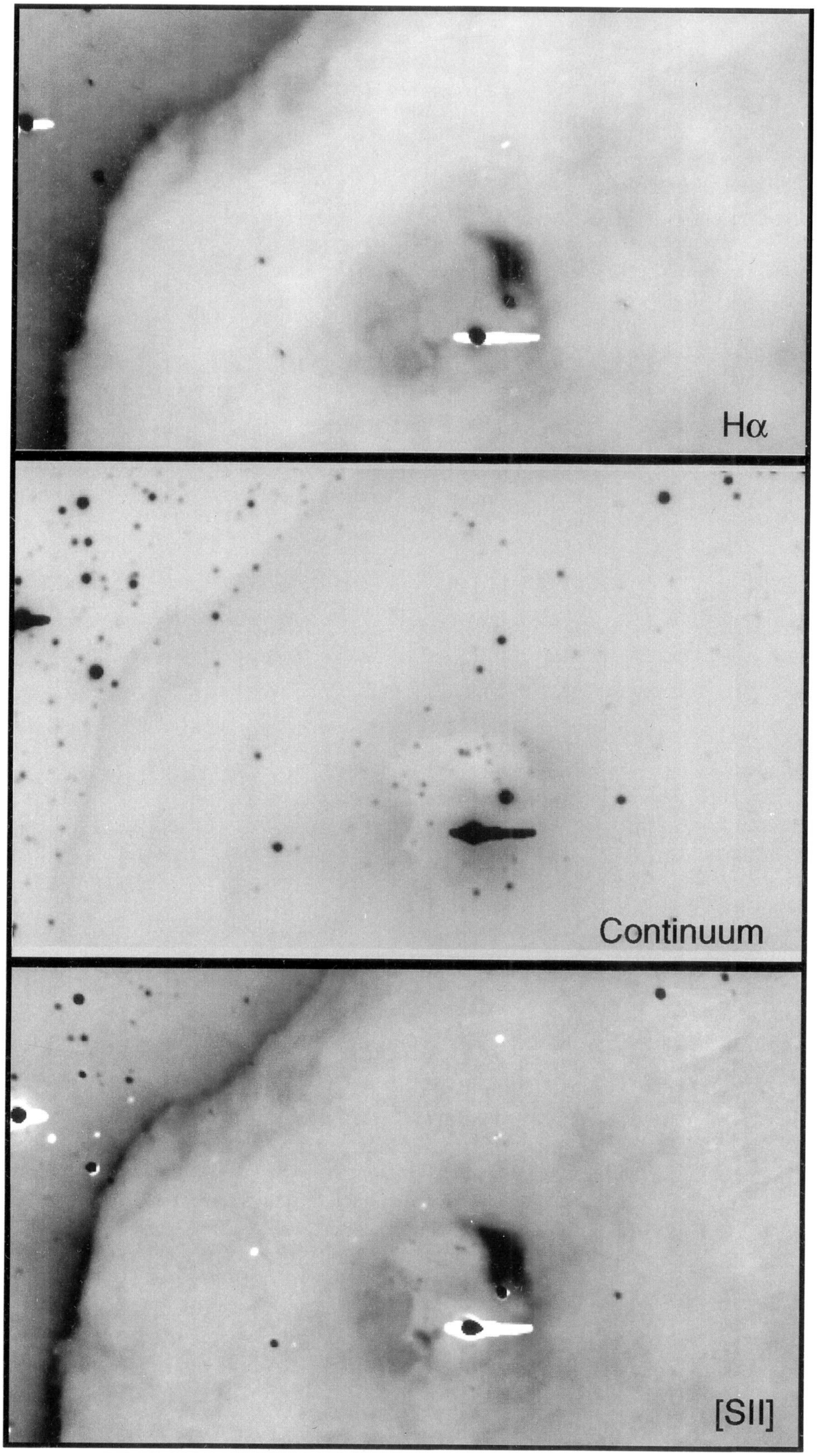

Fig. 1. Hα (top), red continuum (middle) and [SII] (bottom) images of IC 1396A. The emission line images have been corrected for contaminating continuum emission by the scaled subtraction of the middle image. The images cover a field of roughly 2.7×4.3 arcminutes. North is up and East is to the left

by HD 206267. In ^{12}CO and ^{13}CO, a cavity roughly centered around LkHα 349 can be seen (Wootten et al. 1983; Nakano et al. 1989) with a diameter of about 0.3 pc. Whereas the region outside the cavity is very optically thick ($A_V \sim 15$ mag.), the "hole" in the cloud has a total optical depth in the visual along the line-of-sight of only 3-6 (Nakano et al. 1989; the latter estimate was made using the $A_V(N(^{13}CO))$ relation of Frerking et al. 1982). Noting that the density of stars within the cavity is not much less than that outside of IC 1396A and that the reflection nebulae around LkHα 349 are distributed in a manner similar to the CO cavity, Nakano et al. (1989) argued that the molecular "hole" is due to a depletion of about 20-40 $M_\odot$ of material relative to the surrounding globule rather than to photodissociation. The only sign of a residual molecular flow is a hint of blue-shifted emission in the Nakano et al. ^{12}CO data just east of LkHα 349, suggesting that the clearing out of the cavity has almost been completed.

LkHα 349 is within the IRAS PSC confusion limit of the source IRAS 21353+5717C, the object seen at even lower spatial resolution by de Muizon et al. (1980). The "ADDSCAN" measurements of Schwartz et al. (1991) show that LkHα 349 appears as additional "small peaks at 12 and 25 μm at the position of the star" superimposed upon the emission from the globule, suggesting that there is "a minor contribution from LkHα 349" (p. 270).

After being alerted to this object by Lee Hartmann, we added this object to our list of potential FU Orionis objects – YSO's with strong P Cygni absorption in the Balmer lines, an optical spectral type of gF, and broad absorption lines due to high accretion rates in an accretion disk (Hartmann & Kenyon 1990). As it turns out, LkHα 349 is instead an intermediate-mass YSO related to the pre-main sequence B, A, and F stars with visible circumstellar material: the so-called Herbig Ae/Be stars (see Catala 1989 for a review).

In the following sections, we present CCD images, long-slit spectra, infrared photometry, and a historical lightcurve of LkHα 349. Finally, we pull together all of the available information and construct a model for the circumstellar environment and evolutionary state of LkHα 349.

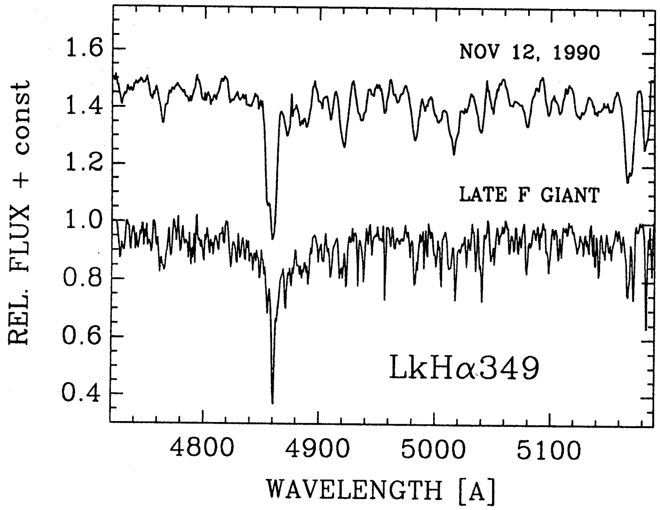

Fig. 2. "Blue" spectrum of LkHα 349 (top) and a field gF6-8 star (bottom). The many stellar absorption lines are considerably broadened in LkHα 349

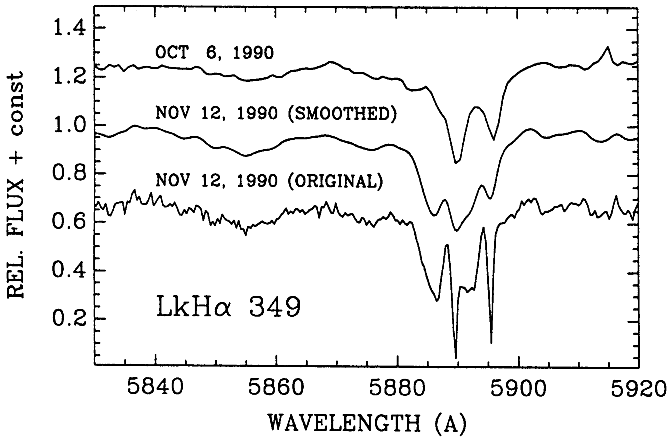

Fig. 3. Spectra of LkHα 349 around the Na D line (bottom). The middle spectrum is the same spectrum broadened to match the resolution of Hartmann's MMT spectrum (top) taken about a year earlier. Notice the absence of the blue-shifted absorption component in the latter

2. The observations

2.1. Direct imaging

Images of IC 1396A were obtained with a 15 μm RCA SID 501 EX CCD at the prime focus of the Calar Alto 3.5m on 1990 November 14 and 16. Exposures of 15, 30, and 30 minutes were obtained with red continuum, Hα, and [SII] filters, respectively. The CCD images were read out using 2×2-pixel binning, resulting in an effective pixel size of 30 μm and plate scale of 0.5 arcsec/pixel.

The images were reduced (bias subtraction, flat-fielding, cosmic-ray removal) using standard MIDAS reduction routines. The continuum contribution in the Hα and [SII] images was removed by rebinning, scaling and subtracting the red continuum image such that the field stars disappeared. Given the number of emission line objects in the field, this algorithm only resulted in a rough correction of the contamination. The resulting images are shown in Fig. 1. along with the unaltered continuum frame.

There are a few notable differences between the emission line and continuum images: there is a diffuse emission line background beyond the dark cloud (upper left) not visible in the red continuum image; the Hα image shows a distinct and bright emission line rim along the edge of the dark cloud (the boundary of the HII region); and there is a prominent emission line region just north of LkHα 349c.

2.2. Spectroscopy

We observed LkHα 349 with the Twin Spectrograph on the Calar Alto 3.5m telescope on 1990 November 19, 23, and 29. In the blue channel, a 1200 l/mm grating blazed at 5000 Å and a

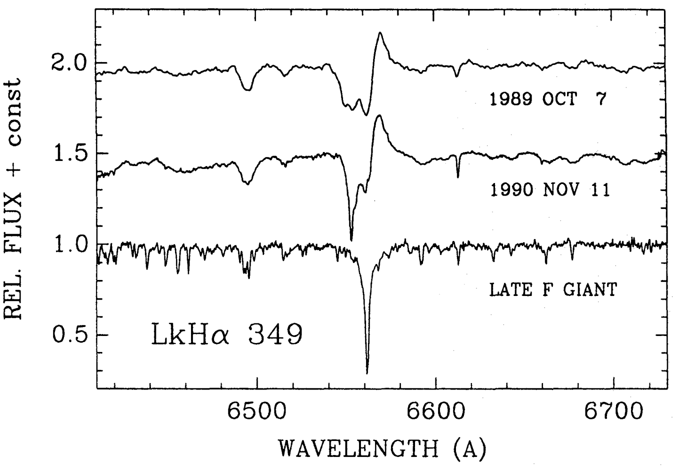

Fig. 4. Spectra of LkHα 349 around the Hα line. Bottom: a field gF6-8 star. Middle: our spectrum of LkHα 349. Top: Hartmann's MMT spectrum taken about a year earlier. Notice the absence of the strongly blue-shifted P Cygni absorption component in the latter

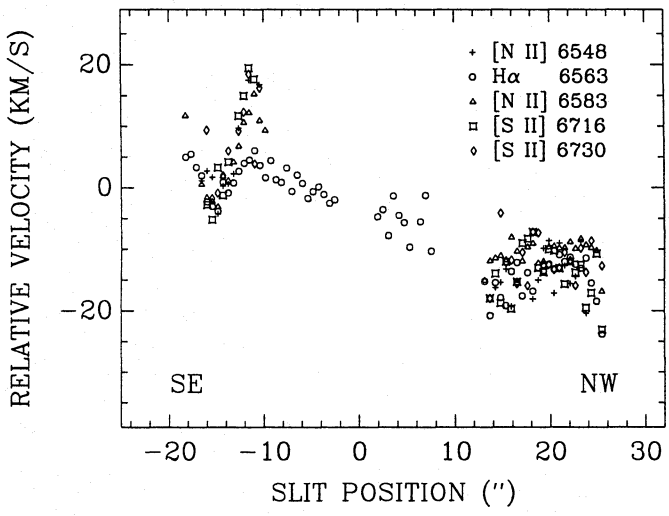

Fig. 5. Nebular radial velocities measured for several emission lines relative to that of LkHα 349 from the long-slit spectrum at P.A. 104°

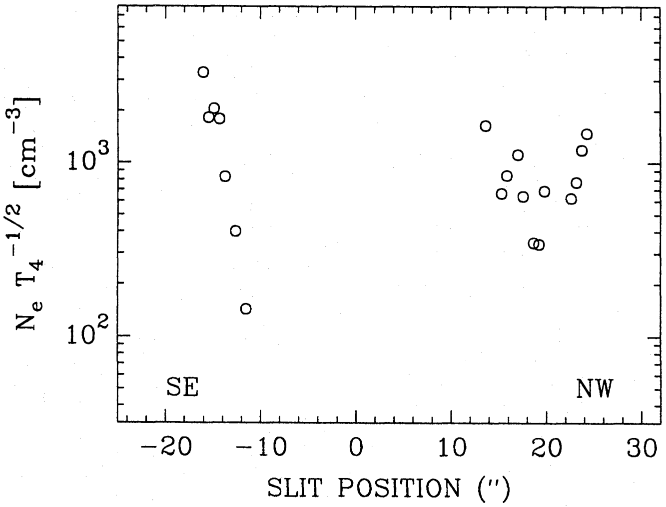

Fig. 6. Same as Fig. 5, but for the electron density derived from the [SII] $\lambda\lambda$6716,6730 lines. T_4 is the temperature of the gas in units of 10^4 K. There are fewer points than in Fig. 5 due to averaging performed in order to improve the S/N

GEC 8603A CCD (22 μm pixels) resulted in a resolution at Hβ of 90 km s^{-1}. The same resolution around Hα in the red channel was obtained by using an 830 l/mm grating blazed at 1.2 μm in second order with the RCA SID 501 EX CCD (unbinned). The Hα long-slit spectra were taken at a P.A. of 104°, permitting us to obtain simultaneous spectra of the "bright rim" of IC 1396A and a nearby field star. The Na D $\lambda\lambda$5890,5896 doublet was observed using a slit oriented at P.A. 137° so that spectra of both LkHα 349 and LkHα 349c (16" to the NE) could be obtained. The exposure times were 4800 and 5400 s for the Hα and Na D spectra, respectively.

The Hβ, Na D, and Hα spectra of LkHα 349 are shown in Figs. 2, 3, and 4, along with convenient comparison spectra of about the same spectral type (gF6-8) which happened to be the star at the end of our long slit for the Hβ and Hα exposures. The most obvious features are the highly broadened stellar absorption lines in both channels and the very strong P Cygni line in Hα. There are so many lines in the "blue" spectrum, that it is difficult to estimate how much and what kind of broadening is present, but the few strong absorption lines red-ward of Hα like LiI λ6707 clearly show very broad and dish-shaped profiles with half-widths at the continuum of $150 - 200$ km s^{-1}. This parabolic shape is exactly that expected for a rotating star (e.g. Gray 1976). Note that the Li line is not present – nor expected – in the field star spectrum, and that all spectra show the diffuse interstellar line at λ6614 (Krelowski & Walker 1987).

2.3. Infrared photometry

We obtained infrared photometry of LkHα 349 using the InSb single-element photometer on the Palomar 5m on 1991 January 2. The calibrator stars were HD 3029, HD 203856, and BS 8775 (the latter for the M band only: see Beckwith et al. 1976). The infrared JHKL' and M magnitudes for LkHα 349 were 9.58, 8.99, 8.65, 8.44, and 8.60, respectively. JHKLN observations made by B. Wilking at the IRTF in 1983 (9.76, 8.93, 8.64, 8.45, > 5.8 magnitudes, respectively), suggest LkHα 349 was then 0.2 magnitudes fainter at 1.2 μm (Schwartz 1993).

3. The circumstellar environment

In order to probe the nebular conditions in the emission nebulae around LkHα 349, we measured both the radial velocities and electron densities of the gas along the P.A. 104° slit.

The radial velocities of the Hα, [NII] $\lambda\lambda$6548,6583, and [SII] $\lambda\lambda$6716,6731 lines relative to that of LkHα 349 are shown in Fig. 5. Only the Hα emission line is measurable in the immediate vicinity of LkHα 349. Note that there is a slow gradient of about 20 km s^{-1} across the nebula immediately surrounding LkHα 349 in the sense that the gas to the SE/NW is mov-

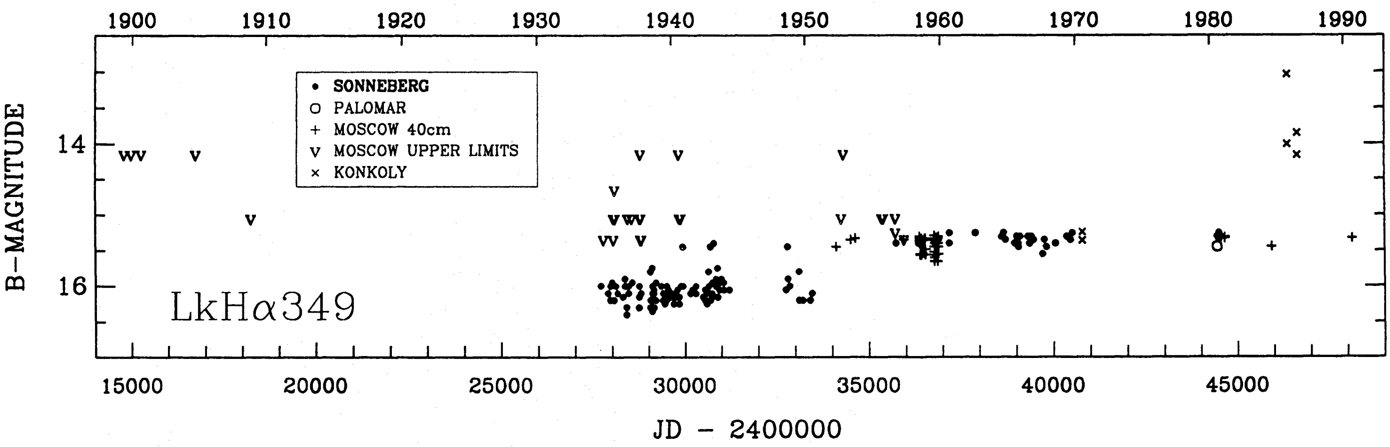

Fig. 7. Photographic B light curve of LkHα 349 obtained from measurements of plates in the plate archives in Moscow (pluses) and Sonneberg (filled circles), the Palomar Sky Survey (open circle), and measurements made at Konkoly Observatory (exes). The Moscow measurements have been crudely corrected using $m_{pg} - B \approx +0.45$ (see the text)

ing away from/towards us relative to LkHα 349. There are also signs of a large forbidden line velocity gradient in the nebula 15" to the SE (20 km s^{-1} over only 6").

The mean electron densities were obtained from the relative fluxes of the [SII] $\lambda\lambda$6716,6731 lines, and range from about 200 to 2000 cm^{-3} (Fig. 6). The density profile also shows a strong gradient in the nebula SE of LkHα 349, where there is an anti-correlation between the radial velocities and the electron densities (i.e. the lowest density regions are moving away from us relative to the large-scale trend across the nebula).

These properties are consistent with the hypothesis that the circumstellar environment around LkHα 349 consists of a large "hole" in the dense globule. The rim of the hole has a density of about 10^3 cm^{-3} – similar to that of the outer rim (Schmidt 1974). To the SE, a drop-off to about 10^2 cm^{-3} can be seen towards LkHα 349, accompanied by velocity structure of uncertain origin.

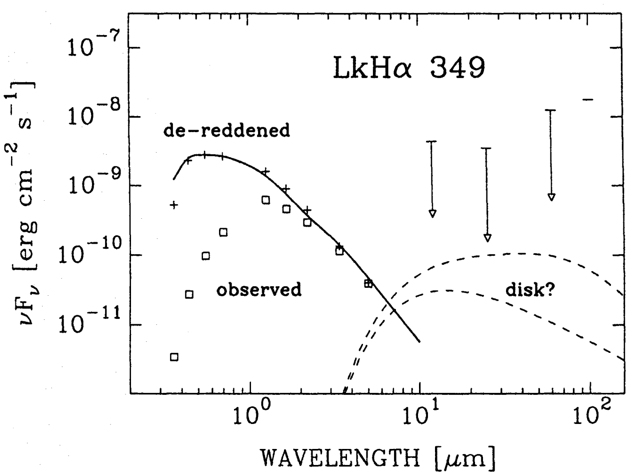

Fig. 8. The spectral energy distribution of LkHα 349. The observed fluxes (boxes) have been de-reddened by A_V=3.65 (pluses) and match the gF8 spectrum (solid line). The far-infrared upper limits are given by the total IRAS emission from the dark cloud: the bottoms of the arrows indicate an estimate for the stellar contribution (see text for details). The dotted lines represent a flat, passive circumstellar disk reaching down to a radius of 20 R_* (lower curve) and a crude model for a concave disk (upper curve; see text for details)

4. The historical lightcurve

A photographic B light-curve of LkHα 349 from 1899 to the present extracted from plates taken at the Sonneberg, Moscow, and Konkoly Observatories is shown in Fig. 7.

The plate stacks at Sonneberg yielded measurements from 1933 to 1980 (the filled circles in Fig. 7). The photoelectric sequence constructed by De Lichtbuer (1982) and the known reddening of LkHα 349 was used to transform the measured m_{pg} to B magnitudes as well as to correct for an emulsion change in the late 1950's. A.Y. Pogosyants (Moscow) very kindly obtained upper limits to the brightness of LkHα 349 from plates taken with the Steinheil 9.7/64 cm and Tessar 16/82 cm astrographs from 1899 to 1956, and measured the 40 cm astrograph plates taken from 1952 to 1990 (shown as the pluses in Fig. 7). Although Pogosyants used the same comparison stars, no color corrections were made, so we have simply shifted the Moscow data by $m_{pg} - B \approx +0.45$ in order to align the light curves between J.D. 2436000 and 2437000. M. Kun (Konkoly) measured LkHα 349 on a set of UBVRI Schmidt plates taken of IC 1396 at Konkoly Observatory between 1965 and 1986; her B measurements (103aO with a GG13) are shown as x's. Finally, a measurement was extracted from the Palomar Sky Survey blue plate (the open circle).

Up to about 1950, LkHα 349 had a mean B brightness of 16.2 with a few noticeable excursions to about 15.5. After 1952, the star appears to have remained at about 15.4 (as seen on the POSS B) for extended periods of time. Some excursions to 15.4 apparently took place before 1950 as well, suggesting that LkHα 349 may have had two distinct photometric states, separated by less than 1 magnitude in B. The measurements from the Moscow plates (only crudely corrected) are consistent with

$B \geq 15.5$. Small-scale variations are typical of a wide range of YSO's and are thought to be due to phenomena like modulation due to starspots, flare events, variable obscuration, and/or small changes in the accretion rate from a circumstellar disk. However, the suggested step-wise small change in brightness is unusual and needs to be confirmed by monitoring LkHα 349. Possible mechanisms for producing this behavior will be discussed in a later section.

The most dramatic variation occurred in 1985-86: the Konkoly observations show a 2-mag "outburst" not seen earlier during which B-V dropped from its usual value of about +1.8 to +0.9 (Kun, private communication). Since this fairly extincted star became very much bluer as it brightened, this change is probably due to a very short reduction in the reddening along the line-of-sight (from 3.6 to 2.5).

5. The spectral energy distribution

Using the value for A_V obtained by Cohen & Kuhi (1979), the UBV magnitudes from Dibai (1969), our own measurements, and the standard ISM extinction curve (Savage & Mathis 1979), one obtains the observed and de-reddened continuum flux distribution for LkHα 349 from 0.3 to 10 μm shown in Fig. 8. For comparison, an F8 III star with about the same luminosity (90 $L_\odot$ assuming a temperature of 6150 K: Schmidt-Kaler 1982) taken from Johnson (1966) has been scaled to fit the dereddened data, corresponding to a single, bare star with a radius of 8.4 $R_\odot$.

The limits on the IRAS fluxes were crudely estimated from "ADDSCAN's" of LkHα 349 kindly provided by C. Gabriel and IPAC. As mentioned by Schwartz et al. (1991), the complex nature of the emission makes it very difficult to know just what part can be attributed to LkHα 349 itself. The total flux from the entire complex at 12, 25, 60, and 100 μm is 18, 30, 250, and 580 Jy, respectively (the upper limits in Fig. 8): these are unreasonably high upper limits on the stellar contribution especially at 60 and 100 μm (where the spatial resolution is poorest). It is clear that the infrared emission cannot be due to dust at a single temperature: a range of $40 \lesssim T_{dust} \lesssim 270$ K is suggested by the relatively flat spectral energy distribution. In order to estimate the minimum flux contribution from LkHα 349, we assumed that the small "peaks" superimposed upon the larger-scale emission represent the stellar (or at least immediately circumstellar) contribution, yielding 1.4, 1.3, 12, and < 580 Jy (at 100 μm, no "peak" is visible, due to the lack of sufficient spatial resolution). These fluxes are shown as the bottoms of the arrows in Fig. 8 and are likewise too similar to be produced by a single dust population. Either the peak has nothing to do with the star itself (e.g. it is simply due to structures in the dark cloud), or this is a sign of some very minor disk emission.

6. The rotation speed

In order to obtain $v \sin i$ more precisely, one must deconvolve the observed spectrum with a star of the same spectral type. Given the signal-to-noise of our spectra and the very large magnitude of the broadening relative to the instrumental profile, this task is much easier than usually the case for YSO's of later type, which typically have $v \sin i \lesssim 50$ km s^{-1} (Stauffer & Hartmann 1987) and so normally require echelle spectra with much higher spectral resolutions.

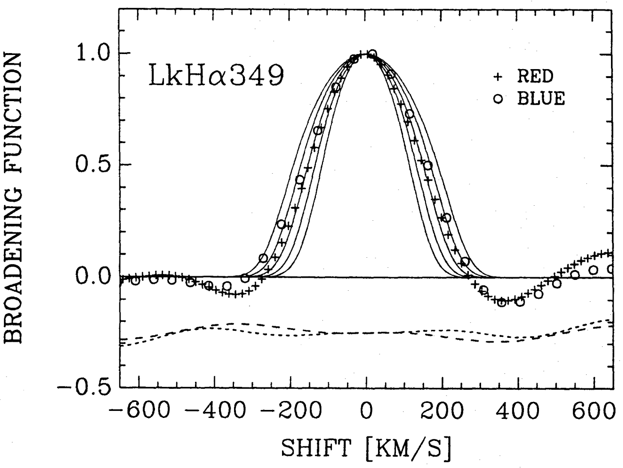

Fig. 9. The deconvolved rotational broadening function for LkHα 349 obtained for the "blue" and "red" spectra. The systematic "noise" in the measurements can best be derived from the deviations from zero in the wings (due to mismatching and noise in the template) and from the asymmetries of the profiles (the two dashed lines below). Also shown are model profiles for a classical rotating star (ϵ = 0.6, $v \sin i$=150,175,200,225,250 km s^{-1}) convolved with a Gaussian to give the same resolution as the observations

The rotation profiles of the stellar absorption lines in both spectra of LkHα 349 were extracted using spectra from the late F giant star fortuitously placed by nature at the end of our long-slit spectrogram and the correlation-function algorithm of Bender (1990): the results are shown in Fig. 9. The advantage of this method over more straightforward Fourier techniques is that it is less sensitive to differences in the spectral type of the program and template star. After removal of the continuum, substantial portions of the spectra had to be discarded due to the contamination by various emission lines, narrow circumstellar absorption lines (e.g. λ6614), and the equally broad LiI λ6707 absorption line (not present in the giant template star), leaving only about 60% of the blue and 50% of the red spectra for the analysis. Because both the observed and the classical model profiles (assuming a limb-darkening parameter ϵ = 0.6 and a resolution of 100 km s^{-1}; the solid lines in Fig. 9) resemble Gauss functions, the final value of $v \sin i$ was simply determined by fitting Gaussians to both, then calibrating the result by relating the fitted FWHM.

The resulting profiles for the red and blue spectra are both consistent with the classic profile expected from simple, solid-body rotation of a sphere with a $v \sin i = 198 \pm 10$ and 180 ± 16 km s^{-1} for the "blue" and "red" spectra, respectively. Taking the results of the two spectra regions together, we obtain a weighted average of $v \sin i = 193 \pm 12$ km s^{-1}.

By placing LkHα 349 on the Hertzsprung-Russel diagram and using standard stellar evolution tracks (e.g. Cohen & Kuhi 1980; Gilliland 1986; Strom et al. 1992; Fig. 10), we can place a lower limit of about 3 $M_\odot$ on the mass of LkHα 349. Rotating stars have lower effective temperatures and luminosities than non-rotating stars, so the probable mass is higher (Sackmann 1970). With an estimated radius of 8.4 $R_\odot$, a Keplerian velocity at the surface of the star of about 273 km s^{-1} is implied. Thus, LkHα 349 must be rotating *at least* at 70% of the break up speed (the maximum limit is reached for an inclination of 45°) if the mass is as low as 3 $M_\odot$. This rotation rate is so large, that the star should assume a non-spherical shape, may rotate strongly differentially, and will have an inclination-dependent apparent temperature and brightness. All of these effects would make it difficult to pin down any stellar properties. The classical parabolic shape of the deconvolved profile suggests, however, that the assumption of a near-spherical, uniformly-rotating body cannot be too bad, implying that the actual mass of LkHα 349 is higher than the 3 $M_\odot$ obtained from placement on classical evolutionary tracks. For simplicity in the discussion that follows, we will use a working value of 4 $M_\odot$ (corresponding to a minimum rotation rate of 64% of break-up).

7. The stellar wind

What makes LkHα 349 much more interesting that just any other pre-main sequence F star is the presence of an extremely strong stellar wind. While stellar winds are not uncommon among the Herbig Ae/Be stars (Finkenzeller & Mundt 1984) and there are several known ultra-fast rotators with similar spectral types and projected rotation speeds (e.g. HE 394N, 721, and 865 in the α Per cluster: Prosser 1992), there are no other known pre-main sequence late F or early G stars which show the same wind behavior. In the dozens of stellar spectra shown by Cohen & Kuhi (1979), only LkHα 349 and Z CMa (the latter more an accretion disk than a pre-main sequence star) have clear P Cygni profiles. The latest known Herbig Ae/Be star with P Cygni profiles is an A2 star (HD 150193: Finkenzeller & Mundt).

The differences between, e.g., the Na D (Fig. 3) and Hα (Fig. 4) lines are dramatic: the former have absorption troughs at -165 km s^{-1} and extend to about -500 km s^{-1} whereas the latter have troughs at -85 and -455 km s^{-1} and extend out to -740 km s^{-1}. The Na D lines show no signs of emission cores like those found in some Ae/Be stars (Finkenzeller & Mundt 1983) and most T Tauri stars (hereafter TTS). Felenbok et al. (1983) argue that the weak P Cygni absorption in the Ae/Be star AB Aur is due to material decelerated at large distances since neutral Na cannot survive closer to the central A star. This is not necessarily the case in LkHα 349, since the photospheric temperature is lower (6150 K versus 10^4 K in AB Aur). Alternatively, if the wind does not decelerate, it must start out rather cool (at or below the photospheric temperature of 6150 K) and later become hot enough to ionize Na I, thereby cutting off the high-velocity wings in the Na D profiles.

The mass-loss rate present in the wind can be very crudely estimated by comparing the observed P Cygni profiles with those calculated in spherical symmetry and for similar conditions by Croswell et al. (1987), scaling their results by $R_* v_\infty^2$ to account for a smaller stellar radius and a larger wind velocity in LkHα 349. A comparison of their Fig. 9 (p. 237) with the Hα profile in Fig. 4 suggests a mass-loss rate in LkHα 349 of roughly $10^{-9} - 10^{-8}$ $M_\odot$ yr^{-1}. The Balmer profiles are highly dependent upon the assumed temperature in the wind: the corresponding rates for hotter winds ($T > 6000$ K) could be much higher.

Since we do not know whether LkHα 349 has always had such a strong wind, it is impossible to prove that the wind is responsible for the clearing of the dark cloud IC 1396 A seen in the CO maps (e.g. Nakano et al. 1989). One can, however, reverse the argument and estimate the properties by asking what wind must have been responsible for the clearing of the hole. Nakano et al. find practically no trace of high-velocity CO emission centered on LkHα 349, implying that the wind is roughly in pressure equilibrium with the surrounding medium. By equating the ram-pressure of the hypothetical wind with the internal pressure at the inner surface of the hole, we can crudely estimate the mass-loss rate:

$$\dot{M} \approx \frac{4\pi R^2}{v_{wind}} \cdot \frac{N_{H_2}}{l_{cloud}}\, k\, T_{cloud} \approx 4 \cdot 10^{-7}\ M_\odot\, \mathrm{yr}^{-1} \qquad (1)$$

for a typical stellar wind speed of 300 km s^{-1} and the observed size $l_{cloud} \approx 0.2$ pc, a CO excitation temperature $T_{cloud} \approx 22$ K, and the molecular hydrogen column density of the dark cloud, $N_{H_2} \approx 3 \cdot 10^{22}$ cm^{-2}, measured by Nakano et al. (1989). This rate is not untypical of that estimated for many other pre-main sequence objects with observable molecular flows (e.g. Levreault 1988). If we use the parameters of the present wind (i.e. 700 versus the canonical 300 km s^{-1}), the comparisons with calculated P Cygni profiles suggest that a mass-loss rate of $\sim 10^{-7}$ $M_\odot$ yr^{-1} might be attainable if the wind temperature is significantly higher than that of the stellar photosphere (the effects of a denser wind on the line profiles might be compensated for by invoking a higher ionisation fraction).

That the strong wind revealed by the Na D and Hα P Cygni profiles is even inconstent is shown in Figs. 3 and 4. In order to better compare the wind features, we have smoothed our Na D data to match the resolution of spectra taken by L. Hartmann with the MMT about a year earlier. While there are no obvious changes in the stellar absorption lines, Hartmann's spectra have much less blue-shifted absorption. Neither set of spectra have smooth absorption profiles, so the wind appears to have "shell" components superimposed, presumably, upon an underlying flow. Alternatively, the wind might be non-axisymmetric, and we are seeing the result of the $\lesssim 50$ hr rotational period.

Assuming a mass-loss rate of 10^{-7} $M_\odot$ yr^{-1} and a terminal velocity of 700 km s^{-1}, the kinetic luminosity of the wind is roughly 8 $L_\odot$. With the uncertainties in the actual rate (at least a factor of 10), it is conceivable that the wind luminosity is a major fraction of the total luminosity. Given the extremely large $v \sin i$, this is perhaps not too surprising: LkHα 349 may posess an efficient means of converting the substantial rotational energy of the star into the kinetic (and/or magnetic) energy of a stellar wind. Thus, variations in the wind structure like those visible in the P Cygni profiles could be accompanied by other major changes (e.g. brightness, color). Indeed, the apparent step-structure in the light curve (Fig. 7) may have been produced by thermal structure-transitions in the wind qualitatively similar to those seen in hotter stars (e.g. Pauldrach & Puls 1990).

8. A circumstellar disk?

Although we only have upper limits for the amount of possible disk contribution to the infrared flux from LkHα 349, we can use models for such disks like those constructed by Beckwith et al. (1990) for TTS and, e.g., Hillenbrand et al. (1992) for Herbig Ae/Be stars to constrain the properties.

Because the central star is larger and much more luminous than is the case for low-mass TTS, the contribution of direct irradiation of the possible disk by the star is much greater:

$$T_{irr} \approx 350\ \mathrm{K} \left(\frac{R}{1\ \mathrm{A.U.}}\right)^{-3/4} \left(\frac{T_*}{6150\ \mathrm{K}}\right) \left(\frac{R_*}{8.4\ \mathrm{R}_\odot}\right)^{3/4} \quad (2)$$

for a geometrically flat, "passive" disk (e.g. Adams et al. 1987). If the disk is concave, it would intercept even more light and become even hotter. The above temperatures would make the disk around LkHα 349 on the average much hotter than those observed in TTS (Beckwith et al. 1990), though the latter are admittedly much older and perhaps more evolved (due to the shorter collapse time of the more massive star in LkHα 349).

Were a "passive" disk to extend all the way down to the star, the inner disk temperatures would be of the order of 3000 K ($T_{flat} \propto R^{-3/4}$) and would show up as a very noticeable contribution to the spectral energy distribution for any reasonable inclination angle. Since any additional mass-accretion through or onto the disk would only serve to increase the local effective temperature of the disk, this is a very serious constraint.

The simplest way of avoiding this situation is to place the inner edge of the disk far enough away that the optical and near-infrared contributions are removed: an example of a passive flat disk spectrum with an inner radius of 20 R_* (i.e. 168 $R_\odot$) and an assumed inclination of 45° is shown as the lower dashed line in Fig. 8. This solution is plausible for several reasons: given the strength of its stellar wind, LkHα 349 could probably blow away the inner parts of a circumstellar disk; if the star and wind are magnetic, the disk can be held off by magnetic forces as well; and it is conceivable that the disk has not had enough time to form completely.

Passive flat disks – even with holes – are unable to explain the simultaneous absence of disk flux at wavelengths less than 10 μm and the estimated far-infrared fluxes. However, by invoking a concave disk shape, one can increase the contributions to the latter (Kenyon & Hartmann 1987). Since the outer parts of concave disks are relatively hotter (more irradiating flux is intercepted), this can be crudely modelled by using the same geometrically thin disk as before, but with a flatter temperature distribution than that expected : a geometrically thin disk with $T_{disk} \propto R^{-1/2}$ is shown as the upper dotted line in Fig. 8. In either case, a "hole" in the center of the disk with a radius of the order of 10-20 R_* is necessary.

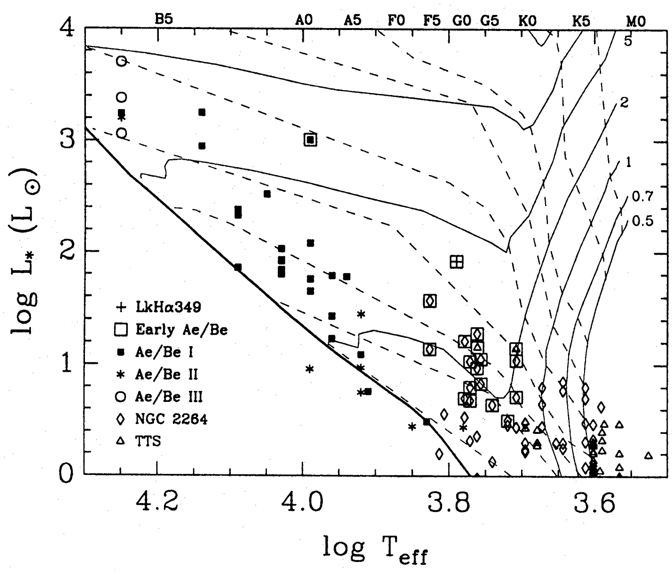

Fig. 10. The HR diagram showing the stellar temperatures and luminosities of LkHα 349 and other early Herbig Ae/Be stars (see text for an explanation), three classes of classical Ae/Be stars (as in Fig. 13 of Hillenbrand et al. 1992), pre-main sequence F, G, and K stars in NGC 2284 (Vogel & Kuhi 1981), and T Tauri stars (from Beckwith et al. 1990). The solid line is the ZAMS from Vandenberg & Bridges (1984). The pre-main sequence tracks (solid lines labelled with stellar masses in $M_\odot$) and isochrones (dashed lines; 100, 10^3, 10^4, $3 \cdot 10^4$, 10^5, $3 \cdot 10^5$ yr, etc.) are those of Hillenbrand et al. (1992)

The absence of a clear near- to far-IR excess directly associated with LkHα 349 means that a circumstellar disk – if present at all – cannot be invoked to explain the properties and behavior of LkHα 349. For example, Shu et al. (1988) proposed driving a stellar wind via the interaction of a very rapidly rotating star with a circumstellar disk. This model for the production of YSO winds cannot hold for this system (although it may still be true that the rapid rotation of the star is conducive to wind formation).

If associated with the star, the observed far-IR excess is probably due to more randomly distributed circumstellar material like that seen in many Herbig Ae/Be stars (Hillenbrand et al.'s group II objects).

9. The evolutionary state

Our original interest in LkHα 349 was awakened by the hope that it might turn out to be a FU Orionis variable (e.g. Hartmann 1991): luminous objects with F-G spectra in the visual, optical outbursts of 3-8 magnitudes, strong winds indicated by P Cygni profiles in the Balmer lines, flat spectral energy distributions in the infrared due to the broad range of temperatures in a disk, and, sometimes, broad absorption line profiles (the signatures of Keplerian orbital velocities in a rotating disk). Though LkHα 349 shares many of the important defining features, it is clearly not a member of this pre-main sequence class of objects:

there is no indication of a wavelength dependent spectral type in LkHα 349; the photometric variations have been small; there is no sign of any significant infrared emission, and the absorption line profiles have a parabolic shape more characteristic of a rotating star than a rotating disk.

9.1. The angular momentum

The further evolution of LkHα 349 towards the zero-age main sequence (hereafter ZAMS) depends not only upon the present mass, luminosity, and radius of the star – all quantities which have been discussed in previous sections – but also its angular momentum. The present total angular momentum of LkHα 349 is roughly

$$\begin{aligned} \mathrm{J} &\approx kMR\,v_{rot} \\ &\approx 1.8\cdot 10^{52}\,\mathrm{g\,cm^2\,s^{-1}}\ /\ \sin i \left(\frac{k}{0.2}\right)\left(\frac{M_\star}{4\,\mathrm{M_\odot}}\right) \\ &\quad\times\left(\frac{R_\star}{8.3\,\mathrm{R_\odot}}\right)\left(\frac{v\sin i}{193\ \mathrm{km\,s^{-1}}}\right) \end{aligned} \tag{3}$$

where $k \equiv I/MR^2$ is a dimensionless moment of inertia factor with a value between about 0.04 (lower limit for radiative main-sequence stars) and 0.5 (fully convective stars). We have arbitrarily used a value of 0.2, since LkHα 349 has apparently left the Hayashi tracks shown in Fig. 10, suggesting that a radiative core has quite plausibly started to form. In any case, this is only a rough estimate for the total angular momentum since the star is undoubtably differentially rotating (it may not even necessarily be true that the radiative core rotates faster than the convective envelope: see Fig. 3 in Soderblom et al. 1993).

Kawaller (1987) has shown that the observed distribution of $v\sin i$ for ZAMS stars more massive than about 1.7 M$_\odot$ (i.e. O,B, and A stars) is consistent with the assumption that the stars are rotating (at their surfaces) at a constant fraction (37%) of their break-up speeds, resulting in a total apparent angular momentum (assuming solid-body rotation):

$$J_{ZAMS} \approx 2\cdot 10^{51}\,\mathrm{g\,cm^2\,s^{-1}}\left(\frac{M_\star}{4\,\mathrm{M_\odot}}\right)^{2.02} \tag{4}$$

where $k_{ZAMS}(4\ \mathrm{M_\odot}) \approx 0.05$, and the expected ZAMS rotational speed is 513 km s^{-1}. Thus, LkHα 349 (or at least the outer, convective envelope of LkHα 349) presently has *roughly* 10 times the amount of angular momentum appropriate for a ZAMS B star. Most of this angular momentum must be removed in a time-scale of less than 10^6 yr in order for LkHα 349 to evolve to the main sequence, requiring an angular momentum loss-rate of 10^{52} g cm^{2}s^{-1}Myr^{-1}.

The only means for LkHα 349 to lose its angular momentum is through the production of a stellar wind. A spherical hydrodynamic wind would result in a angular momentum loss-rate

$$\begin{aligned} \dot{\mathrm{J}} &\approx \frac{2}{3}\,\dot{\mathrm{M}}\,\omega_*\,R_*^{\,2} \\ &\approx 10^{52}\sin i\ \ \mathrm{g\,cm^2s^{-1}Myr^{-1}}\left(\frac{\dot{\mathrm{M}}}{10^{-6}\ \mathrm{M_\odot\,yr^{-1}}}\right) \\ &\quad\times\left(\frac{v\sin i}{193\ \mathrm{km\,s^{-1}}}\right)^{-1}\left(\frac{R_*}{8.3\ \mathrm{R_\odot}}\right) \end{aligned} \tag{5}$$

Interestingly, the required mass-loss rate of such a wind needed to permit the unhindered evolution of LkHα 349 is of the order of that needed to create the large cavity in the dark cloud (Eqn. 1). We showed earlier that this extremely high mass-loss rate is compatible with the present appearance of the P Cygni profiles only if the wind is much hotter than the star.

A much more reasonable solution is to invoke a magnetic wind: it could have a substantially larger lever arm, and so would require a smaller mass-loss rate:

$$\begin{aligned} \dot{\mathrm{M}} &\approx \frac{3}{2}\,\dot{\mathrm{J}}\,\omega_*^{\,-1}\,R_*^{\,-2}\left[\left(\frac{R_A}{R_*}\right)\right]^{-2} \\ &\approx 10^{-8}\ \frac{\mathrm{M_\odot\,yr^{-1}}}{\sin i}\left(\frac{\dot{\mathrm{J}}}{10^{52}\ \mathrm{g\,cm^2s^{-1}Myr^{-1}}}\right) \\ &\quad\times\left(\frac{v\sin i}{193\ \mathrm{km\,s^{-1}}}\right)\left(\frac{R_*}{8.3\ \mathrm{R_\odot}}\right)^{-1}\left(\frac{R_A/R_*}{10}\right)^{-2} \end{aligned} \tag{6}$$

using the same parameters as before but for a dipole field geometry and an Alfven radius $R_A > R_*$ (Mestel 1984; Kawaller 1988).

9.2. The "young Herbig Ae/Be" stars

LkHα 349 occupies a region of the H-R diagram with few visible pre-main sequence stars (Fig. 10): the early collapse timescales for YSO's of intermediate mass are so short (only a few million years), that there is a low probability of catching a star like LkHα 349 in such a phase. There is only one other object in the literature with a comparable luminosity ($L_* > 25$ L$_\odot$) and spectral type (later than F0): VSB 114 ($L_* \approx 37$ L$_\odot$, F2) in NGC 2264 (Vogel & Kuhi 1981). Such objects are especially important, since they connect the nearly invisible luminous "embedded" sources – very young objects whose luminosities may be known, but for which it is usually impossible to determine masses, radii, and rotation rates – with the well-studied (if not well-understood) Herbig Ae/Be stars already quite near the ZAMS. Both are likely to turn into B stars. These stars have just finished their Hayashi phase and are forming their radiative cores – a process accompanied by a re-arrangement of the mass and angular momentum distributions.

We have seen, LkHα 349 has many similarities with the Herbig Ae/Be stars: a dense circumstellar environment; a high luminosity; an inferred mass higher than and a spectral type earlier than the TTS; and a strong wind found in many (if not most) Herbig Ae/Be stars. Given a mass of about 4 M$_\odot$ and barring any catastrophic events (fission!), LkHα 349 should briefly become a classical Herbig Ae/Be star before finally settling down on the ZAMS as a B star with a radius of about 3 R$_\odot$. The Herbig Ae/Be star label is somewhat confusing, however: as the name suggests, Herbig's original list of objects contained stars much hotter than LkHα 349. With time, several early F stars very near the main sequence but with similar properties were added to the list – mostly for the lack of any other useful label. Thus, this class of objects contains both stars near the end of their pre-main sequence evolution and younger stars with luminosities much larger than those of stars nearer to the main sequence. This inhomogeneity is one of the reasons that our referee complained about the use of the term "pre-Herbig Ae/Be star" in our original manuscript.

When the positions of a wide range of stars – classical Herbig Ae/Be stars, F, G, and K stars from young clusters, and the TTS – are plotted on the H-R diagram (Fig. 10), and if one uses the HR-diagram as a (crude) means of estimating stellar masses (Fig. 10), we can identify other late-type stars likely to go through a stage when they would normally be classified as Herbig Ae/Be stars, and which should end up on the main sequence as O, B, and A dwarfs. All such stars from NGC 2264 from the list of (Vogel & Kuhi 1981) and a few early TTS from the list of Beckwith et al. (1990) with estimated masses greater than about 1.7 $M_\odot$ are also plotted with boxes in the HR-diagram of Fig. 10. Thus, these young objects may be reasonably termed "young Herbig Ae/Be stars", although the class normally contains stars of much earlier spectral type. The lower cutoff-mass of about 1.7 $M_\odot$ appropriate for ZAMS A stars is the same limit found by Kawaller (1987) for rapidly rotating stars. Thus, these stars represent a group of very young, intermediate-mass stars whose mean rotation rates are at or approaching the critical rates. Of the stars mentioned before, LkHα 349 has the only reported P Cygni profiles, is the most luminous, and has the highest value of v_{rot}/v_{Kepler}. Thus, it is one of the most extreme young Herbig Ae/Be stars.

9.3. Circumstellar disk formation

There have been suggestions in the literature that many Ae/Be stars have circumstellar disks similar to those in TTS (Lada & Adams 1992; the "group I" stars in Hillenbrand et al. 1992 and Fig. 10). By fitting the infrared and mm spectral energy distributions in a manner similar to that used by Beckwith et al. (1990), disk masses of $0.01 - 6$ $M_\odot$ and inner disk radii of $3 - 25$ R_* have been inferred. Although it is not always clear how much of the observed infrared radiation may be due to dust in an extended shell (Natta 1994; Hartmann et al. 1994), most Ae/Be stars appear to have circumstellar disks.

Hillenbrand et al. compared the properties of the stars with the fitted disks and envelopes and found strong correlations with the inferred stellar masses: most sources had strong fitted disk emission ("group I"); the few sources with very strong envelope emission ("group II") had the lower mean masses; and the sources with neither disks nor envelopes ("group III") were hot, massive stars ($M_\star > 5$ $M_\odot$). The stars with disks had inferred disk accretion rates $\dot{M} \propto M_\star^{2.2}$: this strong dependence on mass might explain why some Ae/Be stars have disks despite the short times $\tau_{disk} < 0.3 Myr$ available for their formation compared with the lower-mass TTS.

Although LkHα 349 would seem to be classifiable as a "group III" Herbig Ae/Be star (i.e. one without a significant dust envelope or disk), this label would make it an extreme exception to the rule that group III stars are hot and more massive. Indeed, it appears to have much more in common with a few group I stars of similar mass: for example, HD 250550 and BD+61° 154 are rapidly rotating stars with disks and – interestingly – optical P Cygni profiles. If one can believe the isochrones in Fig. 10, these two stars are roughly τ_{disk} older than LkHα 349: does this mean that LkHα 349 is in the process of growing a disk despite the fact that a strong and perhaps long-lived wind is present?

By comparing and contrasting the young Herbig Ae/Be stars with their classical counterparts, we might hope to learn more about the processes responsible for disk-formation and how such processes are affected by or are responsible for stellar rotation rates and the formation of winds.

10. Conclusions

The pre-main sequence star LkHα 349 is an extremely interesting and unusual object for several reasons: it is one of the fastest-rotating F stars known, with a $v \sin i \approx 193$ km s^{-1} and a predicted rotational period of less than 50^h; a very fast (500-700 km s^{-1}) and strong stellar wind is present, which, like the star itself, is inconstent; and a comparison of the luminosity (84 $L_\odot$) and temperature (6150 K) of LkHα 349 to the results of standard evolutionary models as well the form of the observed rotational broadening function suggest that the star has a mass greater than 3 $M_\odot$. Thus, LkHα 349 appears to be an early Herbig Ae/Be star caught just after leaving its Hayashi phase.

There is no sign of a circumstellar disk, so all of the observed activity must be produced by the star itself. Due to the high luminosity of LkHα 349, even a passive disk reaching down to less than about 10-20 stellar radii would have been seen. The constraint on any concave disk is even more severe. Due to the relatively short dynamical time-scales of this intermediate-mass star, the evolution of LkHα 349 must not have been affected by a circumstellar disk. However, there are early Herbig Ae/Be stars with similar masses, stellar winds, and apparent disks which may now be in the state into which LkHα 349 will evolve during the next few hundred thousand years. Thus, by studing LkHα 349 in more detail, we may learn how circumstellar disks are formed in intermediate-mass YSO's.

The presence of strong Na D P Cygni absorption suggests the presence of a cool wind, but a much hotter wind may be necessary to account for the high mass-loss rates needed to drive the further evolution of the star. If so, the kinetic luminosity of the wind could be a substantial fraction of the total luminosity. Such a massive wind could have cleared out the conspicuous "hole" in the surrounding dark cloud. A less dense magnetic wind fed by dynamo-action in the rapidly rotating star would be a more efficient mechanism for removing excess angular momentum. If the wind is indeed the mechanism which controls the further evolution of LkHα 349, more detailed studies of the wind properties may reveal much about how intermediate-mass stars make their way to the main sequence.

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