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OPTICAL VEILING, DISK ACCRETION, AND THE EVOLUTION OF T TAURI STARS[1]

LEE W. HARTMANN AND SCOTT J. KENYON
Harvard-Smithsonian Center for Astrophysics
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ABSTRACT

High-resolution spectra of 31 K7–M1 T Tauri stars (TTS) in the Taurus-Auriga molecular cloud demonstrate that most of these objects exhibit substantial excess emission at 5200 Å. Extrapolations of these data consistent with low-resolution spectrophotometry indicate that the extra emission is comparable to the stellar luminosity in many cases. If this continuum emission arises in the boundary layers of accreting disks, $\gtrsim 30\%$ of all TTS may be accreting material at a rate which is sufficiently rapid to alter their evolution from standard Hayashi tracks. We estimate that roughly 10% of the final stellar mass is accreted in the TT phase. This amount of material is comparable to the minimum gravitationally unstable disk mass estimated by Larson and we speculate that the TT phase represents the final stages of disk accretion driven by gravitational instabilities.

Subject headings: stars: accretion — stars: evolution — stars: pre–main-sequence

I. INTRODUCTION

Circumstellar disks of appreciable mass may be responsible for the peculiar properties of the pre–main-sequence T Tauri stars (TTS). Extensive, opaque disks are required to explain the ubiquitous infrared excesses of TTS (Lynden-Bell and Pringle 1974; Rucinski 1985; Adams, Lada, and Shu 1987; Kenyon and Hartmann 1987). Disk *accretion* may provide enough energy to explain the extreme ultraviolet and optical emission of many TTS (Lynden-Bell and Pringle 1974; Bertout 1987; Kenyon and Hartmann 1987; Bertout, Basri, and Bouvier 1988; Strom *et al.* 1988; Basri and Bertout 1989), whereas the magnitude of the excess emission is difficult to understand in terms of enhanced solar-type activity (Calvet and Albarran 1984).

Disks can affect the interpretation of observed TT properties in two qualitatively different ways. First, disks can alter the *apparent* position of TTS in the H-R diagram by changing the estimated system luminosity. Disks may occult or obscure the central star and may provide extra emission, either by absorbing and then reradiating stellar radiation or by generating energy internally from accretion. Changes in the H-R diagram introduced by these phenomena are discussed in a companion paper (Kenyon and Hartmann 1990). Second, the accretion of disk material can change the *actual* position of the central star in the H-R diagram (Mercer-Smith, Cameron, and Epstein 1984). Whether TTS actually depart from conventional Hayashi track evolution in any substantial way depends upon the accretion rate, which must be inferred from observations (see Kenyon and Hartmann 1987; Bertout, Basri, and Bouvier 1988; Basri and Bertout 1989).

In this paper we make some preliminary estimates of the likely effects of circumstellar disks on the true positions of TTS in the H-R diagram. We use optical observations of a significant sample of TTS to estimate the distribution of excess optical continuum emission. Assuming that this excess emission arises from boundary layer radiation, we estimate accretion rates using the optical observations in conjunction with simple disk models. For many TTS, the derived rates seem to be sufficient to perturb their evolution away from a standard Hayashi track in the H-R diagram. Our estimates suggest that about 10% of the final stellar mass is accreted in the TT phase, comparable to the maximum fractional mass for a gravitationally stable disk estimated by Larson (1984). Thus, the TT phase may represent the final stages of disk accretion driven by gravitational instabilities.

Optical observations of excess TT emission and our estimates for accretion rates are described in § II. In § III we show that the higher accretion rates estimated are probably enough to perturb Hayashi track evolution significantly. Our conclusions are summarized in § IV.

II. OPTICAL VEILING OBSERVATIONS

We used the high dispersion spectroscopic survey data of Hartmann *et al.* (1986) and Hartmann and Stauffer (1989), originally obtained to measure rotational and radial velocities, to estimate the optical veiling of TTS in Taurus-Auriga. The spectra were taken at various times between 1984 and 1987 using the intensified Reticon detectors and echelle spectrographs on the MMT and on the 1.5 m telescope of the Fred L. Whipple observatory on Mount Hopkins. The data consist of one 50 Å echelle order centered at 5200 Å, and have a resolution of ~ 12 km s^{-1} (see Hartmann *et al.* 1986 for further details).

We restricted our study to stars with spectral types of K7–M1, producing a reasonably large sample of stars with modest differences in photospheric properties. Inspection of standard star spectra indicated that the depths of the strong Cr I and Fe I lines in the $\lambda\lambda$5205–5210 region (Fig. 1) were not very sensitive to spectral type in this range. Absorption lines are very "washed out" for rotational velocities exceeding 20 km s^{-1}, making the determination of veiling much more difficult. We eliminated V410 Tau in the Cohen and Kuhi (1979, hereafter CK) list from this study because of rapid rotation, and DQ Tau because of possible radial velocity variability. In all, we have estimated the amount of veiling for 31 of the 34 stars in the K7–M1 range with $V < 14.7$ listed by CK.

Figure 1 presents some sample spectra of program objects. The spectra have modest signal-to-noise ratio values and are

[1] Research reported herein used the Multiple Mirror Telescope, a joint facility of the Smithsonian Institution and the University of Arizona.

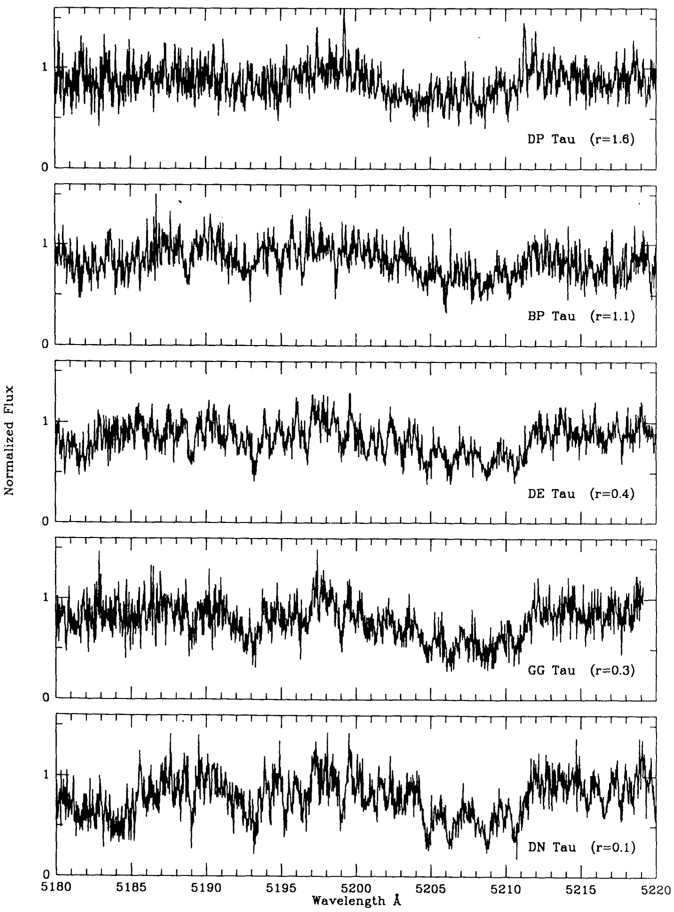

FIG. 1.—Mount Hopkins echelle spectra of selected T Tauri stars at 5200 Å. The objects are arranged in order of the veiling parameter, r, with DN Tau having the smallest veiling ($r \sim 0.26$) and DP Tau the largest ($r > 2$).

not competitive with recent CCD echelle spectra of the brighter objects (see Finkenzeller and Basri 1987; Hartigan *et al.* 1989). However, the survey contains fainter stars that are not customarily studied at high signal-to-noise ratios, so it is better suited for an analysis of the statistical properties of veiling.

The absorption lines in TTS usually are weaker than expected for a normal stellar photosphere. The weakening of the absorption lines has been attributed to a combination of additional continuum emission and varying amounts of chromospheric line emission (Cram 1979; Calvet, Basri, and Kuhi 1984). Hartigan *et al.* (1989) showed that the spectrum of BP Tau between 5100 Å and 6600 Å can be modeled accurately as a veiling continuum added to a normal stellar photosphere. Only a few of the very strongest lines are filled in by chromospheric emission (for example, the Mg I λ5183 *b* line, Fig. 1). The Mount Hopkins Reticon data generally are consistent with the continuum veiling interpretation, but they are not of sufficient quality to show that no emission line reversals are present. Thus, we simply *assume* that continuum veiling alone is responsible for weakening the blend between λ5204 and λ5212, consistent with the results of Hartigan *et al.* for BP Tau (see also the discussion in Herbig 1977).

The veiling was estimated by measuring the equivalent width of the absorption in the 5204–5212 Å band. This measurement should be independent of the stellar rotational velocity. The difference in residual intensities between TTS and the standard was interpreted to be a continuum veiling, expressed as the ratio r, of the veiling continuum to the stellar continuum level. The expected uncertainties in r are $\sim \pm 0.1$ to 0.2 for most stars; for $r > 1$, the errors are larger. The value of $r = 0.94 \pm 0.39$ determined for BP Tau from many spectra over several years agrees quite well with the single epoch result of $r \sim 1.1$ measured by Hartigan *et al.* (1989) in the same wavelength region from much higher signal-to-noise ratio data. For very strongly veiled stars, the weakness of the absorption features makes it very difficult to derive veiling ratios, and consequently the uncertainties in these measurements are larger. For a few objects (DP, DO, DD, and FM Tau), little or no absorption was seen, despite the normal spectral types assigned by CK; we estimate $r \gtrsim 2$ for these objects.

Our veiling results are summarized in Table 1 and in Figure 2. The dispersions quoted in Table 1 are the standard deviations of a single observation from the mean; dispersions much larger than 0.2 probably indicate real variability. Veiling emission at 5200 Å is important in most TTS and is *larger* than the stellar photospheric flux in roughly one-third of all TTS. These results demonstrate that attempts to estimate stellar luminosities from V magnitudes (e.g., Cohen, Emerson, and Beichman 1989) will systematically *overestimate* the observed stellar photospheric flux, in some cases by large factors.

The relation between r and various other TT properties is presented in Figure 3. It is apparent from Figure 3*a* that there is no correlation between stellar luminosity (estimated from J magnitudes; Kenyon and Hartmann 1990) and veiling for the K7–M1 stars in our sample. According to conventional stellar evolution calculations, the K7–M1 TTS in Taurus-Auriga are low-mass stars evolving down essentially vertical Hayashi tracks (CK). If this theory is correct, then the veiling emission might be expected to decay with decreasing stellar luminosity (increasing age). However, these stars exhibit a very small spread in luminosity. In a companion paper (Kenyon and Hartmann 1990) we show that much of the observed scatter in stellar luminosities could be a result of observational uncer-

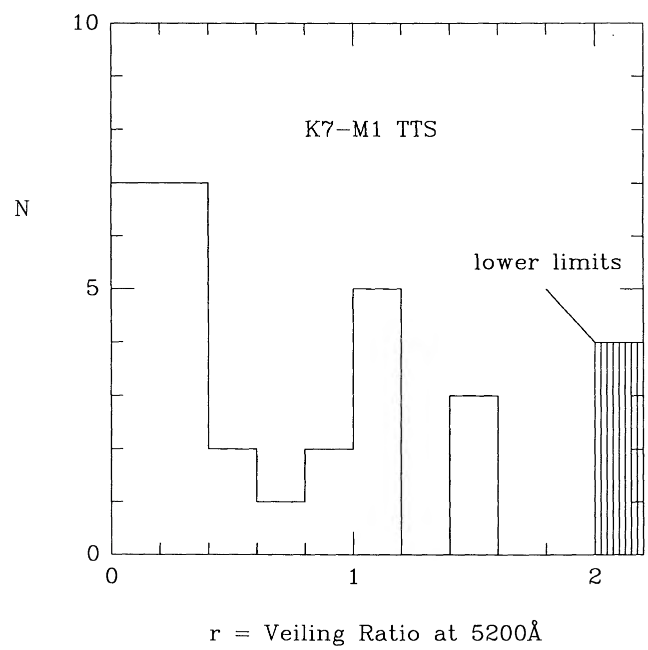

FIG. 2.—Distribution of veiling ratios (excess emission relative to the stellar photospheric continuum) for K7–M1 TTS in Taurus-Auriga.

TABLE 1

VEILING PARAMETERS FOR K7–M1 T TAURI STARS

Object (1)	N (2)	r (3)	$\log L/L_\odot$ (4)	$K-L$ (5)	W_λ(Hα) (6)	ΔL (7)	W_λ([O I]) (8)
AA Tau	7	0.48 ± 0.50	0.11	0.93	37.1	−0.04	0.5
BP Tau	10	0.89 ± 0.51	0.23	0.53	40.1	−0.03	0.0
CI Tau	6	1.03 ± 0.29	0.23	0.90	102.1	0.12	0.0
CY Tau	3	0.94 ± 0.47	−0.10	0.65	69.5	0.01	0.0
DD Tau	2	>2	0.08	1.1	181.8	0.16	2.7
DE Tau	5	1.08 ± 0.68	0.18	0.77	54.0	0.02	0.0
DH Tau	4	>2	0.00	0.66	53.4	0.07	0.0
DI Tau	4	0.28 ± 0.43	0.04	0.33	2.0	0.01	0.0
DK Tau	6	1.06 ± 0.97	0.30	1.19	19.4	0.12	0.5
DM Tau	3	1.44 ± 0.67	−0.40	0.56	138.7	0.21	0.0
DN Tau	6	0.19 ± 0.20	0.18	0.68	11.9	−0.05	0.0
DO Tau	5	>2	0.26	1.24	108.9	0.17	4.3
DP Tau	3	1.55 ± 0.63	−0.15	1.07	85.4	0.24	6.4
FM Tau	4	>2	−0.22	0.70	70.9	0.01	1.0
FX Tau	4	0.39 ± 0.09	0.11	0.65	9.6	0.06	0.0
GG Tau	5	0.39 ± 0.22	0.38	0.87	54.5	0.00	0.0
GI Tau	6	0.34 ± 0.15	0.20	1.0	18.8	0.08	0.0
GK Tau	6	0.21 ± 0.18	0.30	0.84	16.1	0.03	0.0
HK Tau	2	1.16 ± 0.73	−0.05	0.69	29.3	0.13	0.0
HK Tau/G2	4	0.04 ± 0.05	0.12	0.20	1.2	...	0.0
HP Tau/G3	2	0.06 ± 0.22	0.05	0.07	2.0	...	0.0
Hubble 4	7	0.10 ± 0.23	0.46	0.14	3.0	−0.18	0.0
IQ Tau	4	1.18 ± 1.04	0.08	0.89	7.8	0.08	0.4
LkHa 266N	4	0.11 ± 0.17	−0.13	...	48.3	...	0.3
LkHa 332	3	0.22 ± 0.10	0.31	0.80	12.7	0.05	0.0
LkHa 332/G2	3	0.15 ± 0.25	0.21	0.63	3.1	...	0.0
UX Tau B	4	0.22 ± 0.25	−0.28	...	4.0	...	0.0
UZ Tau W	5	0.77 ± 0.09	0.03	...	98.1	...	7.4
VY Tau	5	0.01 ± 0.06	−0.10	0.41	4.9	−0.01	0.0
GM Aur	12	0.53 ± 0.67	−0.03	0.37	96.5	0.01	0.0
UY Aur	10	1.45 ± 1.07	0.38	1.13	72.8	0.17	3.6

Col. (1). Object name.

Col. (2). Number of spectra.

Col. (3). Ratio of veiling flux to stellar continuum at 5200 Å. The quoted uncertainties in r are the standard deviations of the mean; expected measurement errors are ~0.1 to 0.2, for $r \lesssim 1$.

Col. (4). log (10) of the luminosity in solar units, measured from the J magnitudes (see Kenyon and Hartmann 1990); except for LkHa 266N, UX Tau B, and UZ Tau W, where we have adopted luminosities from Cohen and Kuhi 1979.

Col. (5). Average $K-L$ colors taken from Rydgren *et al.* 1984, Cohen and Kuhi 1979 for HK Tau G2, HP Tau G3, and LkHa 332 G2, and Elias 1978 for Hubble 4.

Col. (6). Hα equivalent widths in Å, taken from Cohen and Kuhi 1979.

Col. (7). ΔL, logarithmic excess luminosity, from Strom *et al.* 1988.

Col. (8). [O I] equivalent widths from Cohen and Kuhi.

tainties. We also show in § III that conventional Hayashi track evolutionary calculations may not be appropriate for accreting systems.

Figure 3*b* shows the relation between log r and $\Delta[L]$, the logarithmic excess luminosity estimated by Strom *et al.* (1988) assuming that stellar photospheric emission dominates the H bandpass. After eliminating stars with $\log r \leq -1.0$ and lower limits, the correlation coefficient is 0.64, with a probability of being drawn from a random distribution of 3.1×10^{-3}. The Spearman rank correlation is 0.67 with a probability of 1.8×10^{-3} of being drawn from a random distribution. The relation does not exhibit the unit proportionality that might be expected, but Strom *et al.* point out that their technique is not a very sensitive measure of excess luminosity for $\Delta[L] < 0.2$, and only two of 31 stars in our sample have $\Delta[L] > 0.2$.

In Figure 3*c* we show the relation between optical veiling and Hα emission equivalent widths in logarithmic units. Again eliminating stars with $\log r \leq -1.0$ and lower limits, the correlation coefficient is 0.61 (probability of a random distribution $= 1.6 \times 10^{-3}$) while the Spearman rank correlation is 0.59 (probability of a random distribution $= 2.5 \times 10^{-3}$). The known variability of TTS may be responsible for some of the spread in the relation, and it is clear that the veiling of several program objects is intrinsically variable at the factor of 2 level (see dispersions in Table 1). Alternatively, the Hα and continuum emission may arise in physically different regions. It seems likely that Hα emission originates in an extended envelope (e.g., Hartmann, Edwards, and Avrett 1982), while the veiling continuum may well originate in relatively dense layers close to the star (see Cram 1979; Calvet, Basri, and Kuhi 1984; Bertout, Basri, and Bouvier 1988; Kenyon and Hartmann 1987). Still, Figure 3*c* indicates some correlation between Hα and r, suggesting a common energy source for the veiling and line emission.

Figure 3*d* suggests that strongly-veiled stars tend to have larger [O I] emission equivalent widths than TTS which are not veiled. This result is consistent with CK (see also Strom *et al.* 1988; Cohen, Emerson, and Beichman 1989), who found [O I] emission in all Taurus-Auriga TTS identified as "continuum" emission stars. These objects are not included in our study, because their spectral types are not known.

The $K-L$ color index is a useful measure of infrared excess

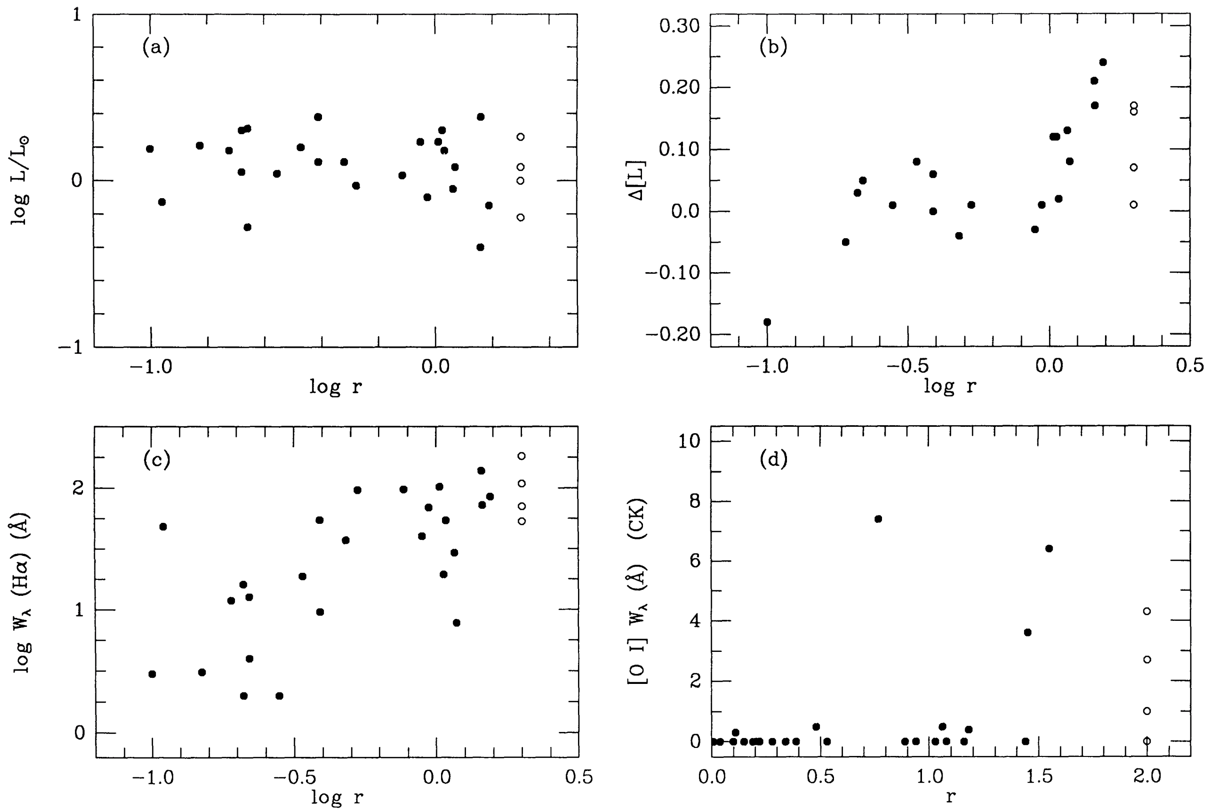

FIG. 3.—(*a*) Plot of stellar luminosities for program K7–M1 stars in Taurus vs. optical veiling ratio *r*. Luminosities are taken from Kenyon and Hartmann (1990) or from Cohen and Kuhi (1979). (*b*) Scatter plot of logarithmic infrared excesses $\Delta[L]$ from Strom *et al.* (1988) as a function of the veiling ratio *r* at 5200 Å for K7–M1 T Tauri stars in Taurus-Auriga. Open circles denote lower limits to *r*. (*c*) Hα equivalent widths from CK as a function of *r*. (*d*) [O I] equivalent widths from CK as a function of *r*.

emission (presumably arising in the circumstellar disk) that is not very sensitive to reddening corrections in our K7–M1 sample. We have taken means of the magnitudes reported by Rydgren *et al.* (1984), or otherwise used single measurements from Cohen and Kuhi (1979) and Elias (1978). Twenty-eight of our program objects that are not close visual pairs have measured $K-L$ indices; most are redder than the expected $K-L \sim 0.2$ for M0—M1 main-sequence stars. If the boundary layer model for the optical veiling is correct, then *r* should be small if no near-infrared excess is visible (the inner disk is optically thin or absent). Our data are consistent with this possibility; of the three objects without any evidence for $K-L$ excess, HK Tau G2, Hubble 4, and HP Tau G3, none show significant evidence for veiling ($r \leq 0.1$).

We find a modest correlation between the $K-L$ color index and log *r*, as shown in Figure 4. Eliminating lower limits, the correlation coefficient is 0.63 (probability of being drawn from a random distribution $\sim 1 \times 10^{-3}$) while the Spearman rank correlation is 0.59 (probability of being drawn from a random distribution $= 2.5 \times 10^{-3}$). It is not surprising that the correlation is not strong because a purely reprocessing, optically thick disk has essentially the same spectral shape at infrared wavelengths as a steady accretion disk (Adams, Lada, and Shu 1987). Simple disk models using the assumption of blackbody radiation (e.g., Kenyon and Hartmann 1987; Bertout, Basri, and Bouvier 1988) predict $K-L$ differences of only $\sim$0.2 mag between very low and very high accretion rates, with a similar range for inclination effects at a constant accretion rate.

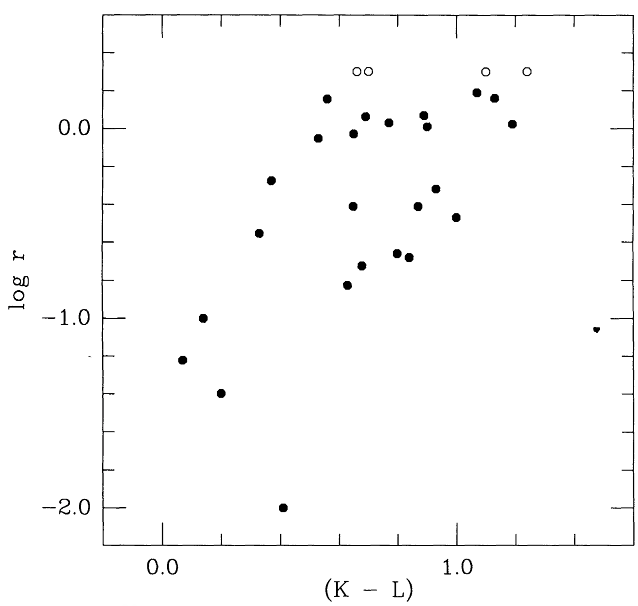

FIG. 4.—Scatter plot of $K-L$ magnitudes vs. veiling ratio log *r*. Open circles denote lower limits to *r*.

III. ACCRETION RATES AND STELLAR EVOLUTION

a) Optical Veiling and Disk Accretion

The results of the previous section suggest that many TTS have substantial optical veiling, a result consistent with low-resolution spectral analyses (Cohen and Kuhi 1979; Keynon and Hartmann 1987; Bertout, Basri, and Bouvier 1988; Basri and Bertout 1989). The excess optical radiation often is a large fraction of the stellar luminosity and has been difficult to explain as enhanced solar-type magnetic activity (Calvet and Albarran 1984). Instead, it has been proposed that the optical-ultraviolet excess emission is produced in the boundary layer (Lynden-Bell and Pringle 1974), a geometrically thin region where accreting disk material initially rotating in Keplerian orbits loses sufficient kinetic energy to come to rest on the (slowly rotating) star (Kenyon and Hartmann 1987; Bertout, Basri, and Bouvier 1988; Basri and Bertout 1989). As shown in Figure 4, all of our program stars with veiling exhibit infrared excesses, predicted to arise in the inner regions of accreting disks (Lynden-Bell and Pringle 1974; Adams, Lada, and Shu 1987; Kenyon and Hartmann 1987; Bertout, Basri, and Bouvier 1988).

The luminosity of a disk can be attributed to two components,

$$L_{\rm disk} = \frac{GM_* \dot{M}}{2R_*} + L_{\rm rep} \,, \tag{1}$$

where $\dot{M}$ is the accretion rate onto a star of mass M_* and radius R_*, and $L_{\rm rep}$ is the luminosity due to absorption and reradiation of light from the central star. Calculations of plausible disk models predict $L_{\rm rep} \sim 0.25$–$0.5\ L_*$, where L_* is the stellar luminosity (Adams, Lada, and Shu 1987; Kenyon and Hartmann 1987). Thus is is difficult to identify infrared excess emission as disk *accretion* luminosity unless $L_{\rm disk} \gtrsim L_*$, particularly since the spectral energy distributions of steady accretion disks are similar in form to the spectra of disks which simply reradiate absorbed starlight (Adams, Lada, and Shu 1987). Typically, $L_{\rm disk} \sim 0.5\ L_*$ is inferred from observations (Kenyon and Hartmann 1987; Strom *et al.* 1988), making the case for actual accretion ambiguous.

For accretion onto a slowly rotating star, the simple theory predicts boundary layer emission up to a limit,

$$L_{\rm bl} \le \frac{GM_* \dot{M}}{2R_*} \,, \tag{2}$$

given by assuming that all of the kinetic energy of disk material in the inner Keplerian orbit is dissipated and released as radiation (Lynden-Bell and Pringle 1974). The measurement of boundary layer luminosity is extremely important, because it is a direct measure of the amount of material actually falling onto the star from the disk.

Unfortunately, measurements of boundary layer luminosities are also difficult. It is necessary to separate the stellar photospheric emission from potential boundary layer continuum and emission lines over a large baseline in wavelength, and to make the appropriate (large) extinction corrections. The data required for this decomposition are not yet available for a statistically significant sample of TTS. In the following section we use theoretical boundary layer models to estimate boundary layer luminosities. These models are consistent with presently available low-resolution spectrophotometry and help illustrate the uncertainties and difficulties involved in establishing boundary layer energy losses.

b) *Boundary Layer and Accretion Luminosities*

We approximate the boundary layer as a flat, narrow ring located between the disk and the stellar photosphere (Lynden-Bell and Pringle 1974). The boundary layer flux received at earth integrated over all wavelengths is

$$f_{\rm bl} = \frac{L_{\rm bl} \cos i}{2\pi d^2}\, g_{\rm occ}(i) \,, \tag{3}$$

where $L_{\rm bl}$ is the true boundary layer luminosity, i is the inclination angle of the disk's rotation axis to the line of sight, d is the distance to the object, and $g_{\rm occ}(i)$ is the fraction of boundary layer surface area which is not occulted by the central star ($1 \ge g_{\rm occ} \ge 0.5$). The stellar bolometric flux is

$$f_* = \frac{L_*}{4\pi d^2} \frac{(1+\cos i)}{2} \,, \tag{4}$$

where the factor involving cos i accounts for the occultation of the star by the disk. We let $f_{\lambda,*}$ and $f_{\lambda,{\rm bl}}$ represent the monochromatic fluxes at wavelength λ of the star and boundary layer, respectively. The luminosity of the boundary layer relative to the star can be written in terms of the veiling ratio, r, observed at a wavelength $\lambda(=5200$ Å):

$$\begin{aligned} \frac{L_{\rm bl}}{L_*} &= \left(\frac{f_{\lambda,{\rm bl}}}{f_{\lambda,*}}\right)\left(\frac{f_{\rm bl}}{\lambda f_{\lambda,{\rm bl}}}\right)\left(\frac{\lambda f_{\lambda,*}}{f_*}\right)\frac{(1+\cos i)}{4g_{\rm occ}\cos i} \\ &= r\beta_{\rm bl}\beta_*^{-1}\frac{(1+\cos i)}{4g_{\rm occ}\cos i} \,, \end{aligned} \tag{5}$$

where $\beta_{\rm bl}$ and β_* are the bolometric corrections needed to convert the monochromatic flux ratio, r, to a total radiative luminosity. The value of β_* is fixed by the spectral type of the underlying star.

It is clear from equation (5) that for a given true ratio of boundary layer luminosity to stellar luminosity, the observed ratio of boundary layer flux to stellar flux depends sensitively on the inclination. For example, at $i = 0$, the final term in equation (5) is equal to $\frac{1}{2}$ ($g_{\rm occ} = 1$), while at $i = 70°$, the same term is ~ 2 ($g_{\rm occ} \sim 0.5$). As shown in our companion paper (Kenyon and Hartmann 1990), inferring inclinations from energy distributions is very difficult, so the inclination uncertainty is likely to remain a problem. Furthermore, it is not clear that boundary layers are actually flat as assumed above (Patterson and Raymond 1985*a*, *b*) (although a "thick" boundary layer would reduce the dependence on inclination implied by eq. [5]).

Hartigan *et al.* (1989) found the veiling continuum in BP Tau was flat in f_λ over the range 5100–6600 Å, and Basri and Bertout (1989) have shown that low-resolution spectrophotometry of TTS in the 3200–8000 Å range can be fitted by relatively flat Paschen continua and modest Balmer emission jumps. These results indicate $\int f_\lambda\, d\lambda \gtrsim \lambda f_\lambda$ at $\lambda = 5200$ Å, and $\beta_{\rm bl} \gtrsim 1$. In our companion paper (Kenyon and Hartmann 1990) we apply a simple boundary layer model to low-resolution spectrophotometry of BP Tau, DN Tau, and GG Tau, finding $\beta_{\rm bl} \sim 1.5$–2.5 at $\lambda = 5200$ Å. Much of the uncertainty comes from estimating the ultraviolet continuum, which is substantial in many TTS (Herbig and Goodrich 1986), and for which the reddening corrections are substantial (typically 1.5–2 mag of extinction).

Despite the geometric and bolometric uncertainties of a factor of 2–3, it is interesting to estimate accretion rates implied by the veiling emission. We are motivated to use crude estimates, because disk inclinations probably will be uncertain for some time to come. Adopting mean values for cos $i = \frac{1}{2}$ and

$g_{\rm occ}(i) = 0.57$ and setting $\beta_*^{-1} = 0.27$ for an M0 star at $\lambda = 5200$ Å, and $\beta_{\rm bl} = 2$,

$$L_{\rm bl} \sim 0.35\ r\beta_{\rm bl} L_* \sim 0.7\ rL_* \ . \tag{6}$$

With this calibration, the distribution of veiling shown in Figure 2 indicates that the median boundary layer luminosity in TTS (median $r \sim 0.5$) is $L_{\rm bl} \sim L_*/3$, and $L_{\rm bl}$ may actually exceed L_* in $\sim$20% of TTS. The accretion disk luminosity is equal to the boundary layer luminosity in most disk models, so equation (4) suggests that the median disk luminosity derived from accretion in TTS should also be $\sim L_*/3$.

The average luminosity of the K7–M1 stars in our sample is $L \sim 1\ L_\odot$, with $R \sim 2\ R_\odot$ and $M_* \sim 0.8\ M_\odot$ (Kenyon and Hartmann 1990). For these parameters, a total accretion luminosity of $L_{\rm acc} = 1.4\ rL_*$ corresponds to an accretion rate of $\dot{M} = 1.4r \times 8 \times 10^{-8}\ M_\odot\ {\rm yr}^{-1}$. In particular, applying this formula to BP Tau ($r = 0.89$) results in $\dot{M} = 1 \times 10^{-7}\ M_\odot\ {\rm yr}^{-1}$, in good agreement with detailed models using low-resolution spectrophotometry, which yield $\dot{M} \sim 0.5$–$1 \times 10^{-7}\ M_\odot\ {\rm yr}^{-1}$ (Basri and Bertout 1989; Kenyon and Hartmann 1990). In general, our median $\langle r \rangle \sim 0.5$ indicates a median accretion rate of $5 \times 10^{-8}\ M_\odot\ {\rm yr}^{-1}$, consistent with the model of Basri and Bertout (1989). These accretion rates may well modify evolutionary tracks significantly, as we show in the following section.

IV. DISK ACCRETION AND EVOLUTIONARY TRACKS IN THE H-R DIAGRAM

If T Tauri stars accrete from disks at the rates suggested in the previous section, the evolution of the central stars may be affected. The mass accretion problem is complicated in a spherically symmetric geometry (see Stahler, Shu, and Taam 1980*a*, *b*; Stahler 1988); disk accretion is more complicated still, because material is added only in a narrow ring at the stellar equator and the diffusion of matter and energy into the stellar interior is latitude-dependent.

The observational estimates of mass accretion are necessarily crude, so for present purposes we adopt approximate arguments to see if the derived accretion rates can possibly have any effect on Hayashi track evolution. We assume that the central low-mass star remains essentially fully convective and can be represented as a polytrope of index 1.5. The adoption of a fixed polytropic structure amounts to assuming that the internal structure of the star globally adjusts to the addition of mass on a sufficiently short time scale. If the accretion rate becomes too large, the interior may become radiative (see Stahler, Shu, and Taam 1980*a*). For cases of interest here ($L_{\rm acc} \lesssim L_*$) we argue that since most of the star radiates freely into space when material is added at the equator, the star will remain convective. Our treatment also assumes that time variations in the mass accretion rate are slow compared with time scales (probably $\sim$ months) for energy transfer within a convective star.

We assume that the luminosity of the central pre–main-sequence star is derived entirely from the release of gravitational energy. Deuterium burning is neglected, so the energy equation has the simple form for an $n = 1.5$ polytrope

$$L = \frac{d}{dt}\frac{3GM_*^2}{7R_*} \tag{7}$$

(Stahler, Shu, and Taam 1989*a*, eq. [A3]). If the stellar mass is constant, evolution at constant surface temperature down the Hayashi track results in a luminosity that decays with time as $L \propto t^{-2/3}$, which is in reasonable agreement with detailed stellar evolutionary calculations (VandenBerg and Laskarides 1987; also CK). We make the further assumption that the mass accreted by the TTS has little kinetic or thermal energy. The addition of mass adds potential energy to the star, which may help balance the radiative energy losses,

$$L \sim \frac{3GM_*}{7R_*}\left(2\dot{M} - \frac{M_*\dot{R}_*}{R_*}\right) \tag{8}$$

(von Sengbusch and Temesváry 1966). Equation (8) can be rearranged to solve for $\dot{R}_*$:

$$\frac{\dot{R}_*}{R_*} = 2\frac{\dot{M}}{M_*} - \frac{L}{(3GM_*^2/7R_*)} \,. \tag{9}$$

Equation (9) implies that the gravitational contraction of a pre–main-sequence star along its Hayashi track can be halted ($\dot{R}_* = 0$) at a steady accretion rate

$$\frac{\dot{M}_c}{M_*} \sim \frac{1}{2}\frac{7R_* L}{3GM_*^2} = \frac{1}{2\tau_{\rm KH}} \,, \tag{10}$$

where

$$\tau_{\rm KH} \equiv \frac{3GM_*^2}{7R_* L}$$

is the Kelvin-Helmholtz time scale. The result (10) is intuitively reasonable; it says that the star's Hayashi track evolution is altered when mass is accreted at a rate such that the mass of the star would change appreciably on the gravitational contraction (Kelvin-Helmholtz) time scale. At the critical accretion rate, $\dot{M}_c$, the accretion luminosity is

$$L_{{\rm acc},c} = \frac{GM_*\dot{M}_c}{R_*} \sim \frac{7}{6}L_* \,, \tag{11}$$

where L_* is the luminosity that the star would have due to gravitational contraction in the absence of accretion.

The K7–M1 stars in our sample exhibit a small spread in luminosity (see Kenyon and Hartmann 1990), and cluster around $L = 1\ L_\odot$, $R = 2.1\ R_\odot$. Standard Hayashi tracks indicate $M_* = 0.8\ M_\odot$. Then $\tau_{\rm KH} = 3.7 \times 10^6$ yr and $\dot{M}_c = 9 \times 10^{-8}\ M_\odot\ {\rm yr}^{-1}$. This accretion rate is comparable to that estimated for BP Tau, with $r = 0.9$. Twelve of the 31 program stars have $r \geq 1$, suggesting that the H-R diagram positions of one-third of the K7–M1 TTS in Taurus may be modified by disk accretion.

Equation (8) implies that the luminosity of the central star increases when $\dot{M}$ is above the critical accretion rate. Detailed evolutionary calculations are required to determine the actual trajectories of accreting objects in the H-R diagram. Nevertheless, it is apparent that significant departures from classical Hayashi contraction are possible. We also note that fusion of fresh deuterium as it accretes would produce an additional luminosity of $0.15\ (\dot{M}/10^{-7}\ M_\odot\ {\rm yr}^{-1})\ L_\odot$.

If the phase of disk accretion is sufficiently prolonged, some TTS may be substantially older than presently estimated using non-accreting stellar evolution calculations. By making the T Tauri phase last longer, disk accretion may reduce the expected number of "post–T Tauri stars" (Herbig, Vrba, and Rydgren 1986; Jones and Herbig 1979, and references therein).

c) *Mass Evolution of TTS*

With a median mass accretion rate of $\sim 5 \times 10^{-8}\ M_\odot\ \mathrm{yr}^{-1}$ (see also Basri and Bertout 1989) and an average age of $\sim 10^6$ yr (taking the undisturbed Hayashi track age for the appropriate stellar parameters), the amount of disk material accreted during the TT phase is

$$\langle \dot{M} \rangle t \sim 0.05\ M_\odot \sim 0.06\ M_* , \tag{12}$$

assuming $M_* = 0.8\ M_\odot$. Alternatively, the distribution of Figure 2 suggests that about one-fourth of all TTS accrete at a rate which produces a veiling, $r \gtrsim 1.4$. Our models can account for this amount of veiling when $\dot{M} \sim 1.5 \times 10^{-7}\ M_\odot\ \mathrm{yr}^{-1}$. If we suppose that this accretion is a relatively short phase in all TTS, lasting for about one-fourth of the total T Tauri lifetime, then

$$\dot{M}(\mathrm{high}) t(\mathrm{high}) \sim 0.05\ M_* . \tag{13}$$

Thus, $\sim 5\%$–10% *of the final stellar mass is accreted during the TT phase.* In this connection we note that Sargent and Beckwith (1987) have detected disks with $M_{\mathrm{disk}} \sim 0.1\ M_\odot$ around HL Tau and R Mon.

The reservoir of mass needed to power TTS for their estimated lifetimes is comparable to the maximum gravitationally stable disk mass predicted by Larson (1984; see also Cassen *et al.* 1981). Larson suggested that disks with masses $\gtrsim 0.1\ M_*$ would be gravitationally unstable and argued that torques generated by spiral density waves would be capable of efficient angular momentum transport and generate substantial disk accretion. The effect of gravitational instabilities has been considered further by Lin and Pringle (1987) and by Adams, Ruden, and Shu (1989). Lin and Pringle estimated a time scale for the infall of material,

$$t_\nu \sim \Omega^{-1} (M_*/M_{\mathrm{disk}})^2 , \tag{14}$$

where Ω is the orbital angular frequency at a radius, R. This estimate suggests that angular momentum transfer, and hence accretion, can in principle proceed quite rapidly. Adams, Ruden, and Shu (1989) have suggested that $m = 1$ gravitational instabilities are particularly important in massive disks, and may dominate the transfer of angular momentum.

For disk temperature distributions expected around a typical T Tauri star, Pringle (1988) estimated the critical mass for gravitational instabilities to be

$$M_{\mathrm{disk}} \sim 0.21 (R/100\ \mathrm{AU})^{1/8}\ M_* , \tag{15}$$

where we have used a typical disk radius estimate of 100 A.U. (cf. Edwards *et al.* 1987). We suggest that the T Tauri evolutionary phase corresponds to accretion in disks near the critical mass for gravitational instability, resulting in the accretion of approximately the critical disk mass onto the central star.

As mentioned above, disk accretion may cause Hayashi track ages to be *underestimates* of the true ages of some T Tauri stars. In this case, *the total amount of mass accreted during the T Tauri phase could be larger than 0.1 $M_\odot$.* These considerations underline the importance of improving observational estimates of $\dot{M}_{\mathrm{acc}}$ for TTS.

V. CONCLUSIONS

We have presented a survey of optical veiling in T Tauri stars which indicates that many pre–main-sequence objects exhibit large amounts of excess optical continuum emission. Combining these data with attempts to model the excess optical emission of TTS as boundary layer emission from an accretion disk, we find that one-third of K7–M1 TTS accrete sufficiently rapidly ($\gtrsim 1 \times 10^{-7}\ M_\odot\ \mathrm{yr}^{-1}$) to alter their evolution in the H-R diagram significantly.

The data suggest that $\sim 10\%$ of the final stellar mass is accreted in the TT phase, which is comparable to the minimum fractional mass for a gravitationally unstable disk. We suggest that the TT phase may represent the final stages of disk accretion driven by gravitational instabilities.

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LEE HARTMANN and SCOTT J. KENYON: Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138