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CORRELATIONS OF OPTICAL AND INFRARED EXCESSES IN T TAURI STARS

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ABSTRACT

We report the results of a survey of excess optical continuum emission (veiling) in a sample of 35 K7–M1 pre–main-sequence stars in Taurus-Auriga. Stars with detectable veiling emission always show significant near-infrared $K-L$ excesses. This result agrees with the prediction of a simple accretion disk model, where a boundary layer produces the veiling and the infrared excess comes from the disk. The $K-N$ colors of T Tauri stars fall into two distinct groups: stars in the group with small or absent $K-N$ excesses have no detectable veiling emission, while objects with large $K-N$ excesses usually have detectable veiling. This result also agrees with the prediction of the disk model, where a large $K-N$ excess indicates an optically thick disk, and an optically thick disk is required to generate a mass accretion rate large enough to produce detectable veiling. Stars with strong Hα and [O I] emission also have veiling, suggesting a connection between accretion and outflow. These latter correlations are not strong, possibly the result of radiative transfer, cooling, and ionization effects in Hα and [O I].

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

I. INTRODUCTION

The spectra of many pre–main-sequence (T Tauri) stars show optical and infrared excesses, Balmer line emission, and both permitted and forbidden metallic line emission. These phenomena were once thought to arise from a dense chromosphere and an energetic wind in young stellar objects (Herbig 1970; Dumont *et al.* 1973; Cram 1979; Calvet, Basri, and Kuhi 1984). An alternative explanation for the emission characteristics of young stars, originally suggested by Lynden-Bell and Pringle (1974), is that a hot boundary layer between a slowly rotating star and an accretion disk produces the observed optical excesses (veiling). Disk models explain the infrared and optical excess emission of T Tauri stars in a natural way (Rucinski 1985; Adams, Lada, and Shu 1987; Kenyon and Hartmann 1987; Bertout, Basri, and Bouvier 1988), whereas chromospheric models do not produce substantial infrared excesses (Calvet, Basri, and Kuhi 1984; Hartmann *et al.* 1990) and cannot account for the large magnitude of the excess emission radiated by T Tauri stars (Calvet and Albarran 1984).

The accretion disk model makes a clear, testable prediction. If the excess optical emission of T Tauri stars is produced in a boundary layer, a disk must be present near the star. The disk should be optically thick for mass accretion rates sufficient to account for the observed continuum excesses and should therefore produce a substantial near-infrared excess (Kenyon and Hartmann 1987; Bertout, Basri, and Bouvier 1988). Thus, the disk model predicts that any T Tauri star with nonchromospheric excess optical emission must have a near-infrared excess above (weak) chromospheric levels. In what follows we combine new estimates of veiling in T Tauri stars with those published by Hartmann and Kenyon (1990) to test the accretion disk model.

II. OBSERVATIONS AND ANALYSIS

Spectra used to derive veiling estimates for a sample of 18 T Tauri stars in Taurus-Auriga were obtained using the echelle spectrograph and TI CCD on the KPNO 4 m telescope in the period 1988 November 30–December 2 (UT). We selected objects in the restricted spectral type range of K7–M1 from Cohen and Kuhi (1979), Herbig, Vrba, and Rydgren (1986), and Walter *et al.* (1988) and used the procedure described by Hartigan *et al.* (1989) to determine the ratio ($r = I_{\rm veil}/I_{\rm star}$) of veiling emission to the photospheric radiation. These r-values are calculated by comparing the depths of absorption lines in high-resolution echelle spectra of T Tauri stars with spectra of standard stars of comparable spectral types. For example, if the absorption lines in a T Tauri star are half as deep as those in the standard star, then the veiling emission in the T Tauri star is as bright as the photospheric flux at that wavelength ($r = 1$). The spectral energy distributions of the veiling, the effect of the veiling on determinations of reddening, and a discussion of observational constraints concerning the nature of the boundary layer will be presented in a forthcoming paper (Hartigan *et al.* 1990).

A compilation of the new veiling results and those of Hartmann and Kenyon (1990), infrared colors, and Hα and [O I] emission equivalent widths appears in Tables 1 and 2. For purposes of correlation we averaged the new (CCD) r-values over the wavelength range of 5400–5630 Å. We restricted the long-wavelength end of the bandpass to permit direct comparisons with the veiling results of Hartmann and Kenyon, who measured veiling at 5200 Å for a larger sample of stars over a period of years with lower quality reticon (IRet) data obtained with the FLWO 60 inch (2.5 m) telescope. At shorter wavelengths, strong Fe II emission lines sometimes complicate

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TABLE 1

OBJECTS WITH VEILING MEASUREMENTS

Object	Veiling (r)	$K-L$	$K-N$	W_λ (Å) Hα	[O I]
		CCD Veiling Measurements			
AA Tau	0.39	0.93	3.77	26	0.59
	0.77	0.93	3.77	60	2.1
BP Tau	0.52	0.53	3.84	47	0.06
CI Tau	0.54	0.90	4.09	55	0.08
DG Tau	4.6	1.60	5.02	60	9.4
DI Tau	0.04	0.33	2.32	0.8	<0.02
DK Tau	0.67	1.19	4.33	13	0.57
DL Tau	2.6	1.08	3.64	89	0.58
	2.0	1.08	3.64	86	0.53
DN Tau	0.17	0.68	3.40	23	0.29
DQ Tau	0.34	0.89	4.17	69	2.7
DR Tau	8.8	1.40	3.70	85	0.39
GG Tau	0.35	0.87	4.01	42	0.12
	0.18	0.87	4.01	38	0.14
GI Tau	0.36	1.00	4.20	14	0.26
GM Aur	0.05	0.37	...	...	...
LkCa7	0.00	0.31	0.28	1.6	<0.02
LkCa8 (IP Tau)	0.26	0.90	2.70	10	0.40
RW Aur	1.7	1.02	3.64	45	0.9
	2.2	1.02	3.64	56	1.2
UY Aur	0.42	1.13	4.94	64	1.0
	0.30	1.13	4.94	45	1.2
	0.50	1.13	4.94	49	1.1
V819 Tau	−0.04	0.21	0.61	2.4	<0.02
V836 Tau	−0.02	0.42	2.67	4.8	0.12
		IRet Veiling Measurements			
CY Tau	0.94	0.65	3.42	...	...
DE Tau	1.08	0.77	3.33	...	...
DM Tau	1.4	0.56	...	...	...
DP Tau	1.6	1.07	4.55	...	...
FX Tau	0.39	0.65	3.71	...	...
GK Tau	0.21	0.84	3.97	...	...
HK Tau	1.16	0.69	3.52	...	...
HK Tau/G2	0.04	0.20	...	...	...
HP Tau/G3	0.06	0.07	...	...	...
Hubble 4	0.10	0.14	0.26	...	...
IQ Tau	1.18	0.89	3.71	...	...
LkHα 332	0.22	0.80	4.17	...	...
LkHα 332/G2	0.15	0.63	...	...	...
UX Tau B	0.22	0.04	...	...	...
UZ Tau W	0.77	...	...	...	...
VY Tau	0.01	0.41	3.44	...	...

TABLE 2

OBJECTS WITH $K-N$ DATA BUT NO VEILING MEASUREMENTS

Object	$K-N$
CW Tau	3.44
DD Tau	2.80
DF Tau	3.39
DH Tau	2.83
DO Tau	4.69
FM Tau	2.53
GH Tau (Haro 6-20)	3.81
Haro 6-37	3.85
HD 283447	2.92
HD 283572	0.20
HL Tau	5.22
HN Tau	4.39
HP Tau	3.84
IS Tau	3.27
IW Tau	−0.35
LkCa 1	0.51
LkCa 3	0.17
LkCa 4	0.07
NTTS 042417+1744	0.09
NTTS 045251+3016	0.54
RY Tau	4.68
SU Aur	3.29
T Tau	4.15
UZ Tau-E	3.89
V410 Tau	0.61
V827 Tau (FK-2)	0.25
XZ Tau	4.91

veiling measurements. The new r-values fall within the range of variability for all stars observed in common with Hartmann and Kenyon.

The infrared colors were compiled from Skrutskie *et al.* (1990) and Rydgren *et al.* (1984). Our choices of the $K-L$ and $K-N$ color indices as measures of infrared excesses in T Tauri stars were motivated by several factors. These indices are not sensitive to uncertainties in spectral type because the infrared colors are dominated by the Rayleigh-Jeans distribution of the photospheric flux. For the stars in our study, the photospheric values of $K-L$ and $K-N$ should be nearly constant ($\sim$0.20 and 0.40, respectively). Extinction corrections should be small ($A_V \sim$ 1–2 for a typical T Tauri star, with $E_{K-L} \sim E_{K-N} \sim 0.05$ A_V; Rieke and Lebofsky 1985). Reasonably good K, L, and N photometry exists for most T Tauri stars, and these colors do not vary significantly in time (Rydgren *et al.* 1984). Uncertainties and variability in the $K-L$ color indices are typically $\lesssim$0.1 mag, and $\sim$0.2 for $K-N$. We measured the Hα and [O I] 6300 Å equivalent widths in Figure 2 from the same CCD spectra used to determine the veiling. These spectra have terrestrial [O I] subtracted.

III. DISCUSSION

The relationship of veiling emission to near- and mid-infrared excess is displayed in Figures 1*a* and 1*b*. Stars with veiling emission *must* have near-infrared excesses according to the accretion disk model. A disk that simply absorbs stellar photons and radiates infared light will have $K-L$ colors between 0.4 and 0.7, depending on the viewing angle, and an accretion disk should have $K-L$ colors between 0.4 and 0.9 depending on the inclination and mass accretion rate (Bertout, Basri, and Bouvier 1988; Kenyon and Hartmann 1990). Every T Tauri star in Figure 1*a* with detectable veiling ($r \gtrsim 0.15$ for the IRet data; $r \gtrsim 0.07$ for the CCD data) has a $K-L$ excess $\gtrsim$0.4, in agreement with the most basic prediction of the accretion disk model. Figure 1*a* shows a cutoff value of $K-L \sim 0.5$ below which stars have no detectable veiling. There are apparently objects with $K-L \sim 0.4$ that are at least occasionally veiled, however. Hartmann and Kenyon (1990) found the veiling in GM Aur ($K-L = 0.37$) to vary between 0 and 1.2. GM Aur was not veiled when the object was observed in 1988 November.

There is a clear trend of increasing veiling with increasing $K-L$ (the Spearman rank correlation coefficient between $K-L$ and r is 0.75 in Figure 1*a*, with a probability of being drawn from a random distribution of 2.5×10^{-8}). One possible explanation for this trend is a geometrical effect caused by the disk. The stellar photosphere is hotter than the disk, so the star contributes a greater fraction of the total flux at shorter infrared wavelengths than it does at longer infrared wavelengths. Occultation of the star by the disk reduces the stellar flux by a factor $(1 + \cos i)/2$ for an inclined disk, but the flux

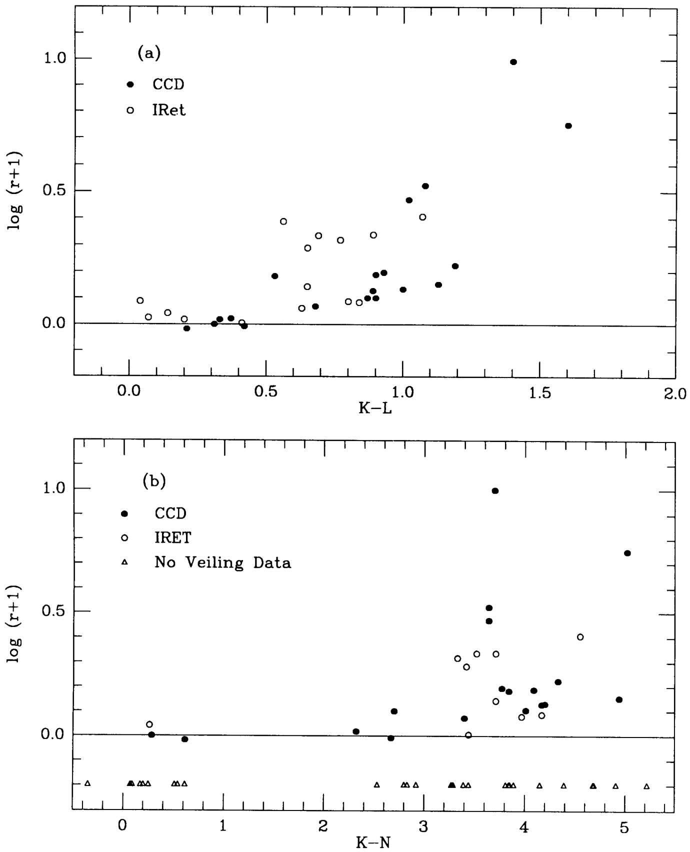

FIG. 1.—(*a*) Observed optical veilings at 5500 Å vs. $K-L$ color index for a sample of T Tauri stars. Filled circles are CCD data, and open circles are IRet data. Stars with $K-L \lesssim 0.5$ are not veiled, and those with $K-L \gtrsim 0.5$ have detectable veiling continuum emission. (*b*) Same as (*a*) but using $K-N$ as the color index. Triangles mark stars that have tabulated N magnitudes but not veiling measurements. No stars observed have $K-N$ colors between 1 and 2. Objects with $K-N \lesssim 0.6$ have no significant excesses.

from a flat surface such as a disk decreases more rapidly with inclination (as cos *i*). Hence, the $K-L$ colors of an inclined disk will be bluer than those of a face-on disk. Occultation of the boundary layer by the star and any geometrical flatness of the boundary layer reduce the observed boundary layer flux as the inclination increases, resulting in a correlation of $K-L$ color with optical veiling for a set of identical systems viewed from different angles. A quantitative analysis of these correlations depends on the details of the model used and is beyond the scope of this *Letter*.

Figure 1*b* shows the remarkable gap ($K-N$ = 1–2) devoid of objects reported by Skrutskie *et al.* (1990). To check the reality of this gap we added all the T Tauri stars in Skrutskie *et al.* and Rydgren *et al.* (1984) that have N magnitude measurements (no veiling estimates) as open triangles. The gap remains and has a probability of 2.3×10^{-5} of occurring from a uniform distribution in $K-N$. Objects to the left of the gap have essentially photospheric $K-N$ colors, and those to the right appear at least as red as a standard optically thick disk ($\lambda F_\lambda \sim \lambda^{-4/3}$; $K-N \sim 2.6$). The absence of intermediate cases between stars with $K-N$ colors consistent with photospheric emission and those with $K-N$ values indicative of optically thick disks suggests that the time for disks to evolve from optically thick to optically thin structures is short compared to the typical age of a T Tauri star ($\sim 3 \times 10^6$ yr; see also Skrutskie *et al.* 1990). Pre–main-sequence stars surrounded by optically thin disks will have colors intermediate between the photospheric colors and those for optically thick disks. All the veiled stars in the $K-L$ plot have $K-N$ colors redward of the gap in Figure 1*b*, a result expected from simple accretion disk theory. A few objects (such as V836 Tau and DI Tau) lie to the right of the gap in Figure 1*b* and have no veiling emission, so it is possible to have an optically thick disk without detectable veiling emission.

If accretion energy powers the molecular outflows from young stars as envisioned in some theoretical models (e.g., Pudritz and Norman 1983), then emission lines formed in the wind, such as Hα and [O I], should be brightest in stars with strong boundary layer emission (Strom *et al.* 1988; Cabrit *et al.* 1990). Figure 2*a* exhibits the correlation between the veiling continuum and the Hα equivalent width. The Hα emission equivalent width is measured relative to the total continuum (stellar photosphere plus veiling excess), so we display the veiling in terms of $r/(1 + r)$, which similarly normalizes the veiling emission to the total continuum. The veiling at Hα is generally slightly smaller than at 5500 Å, but this difference does not affect the results significantly. Because both Hα and r vary with time, we plot only the CCD data, where the measurements of these quantities were simultaneous. Dotted lines connect observations of the same star on adjacent nights. The

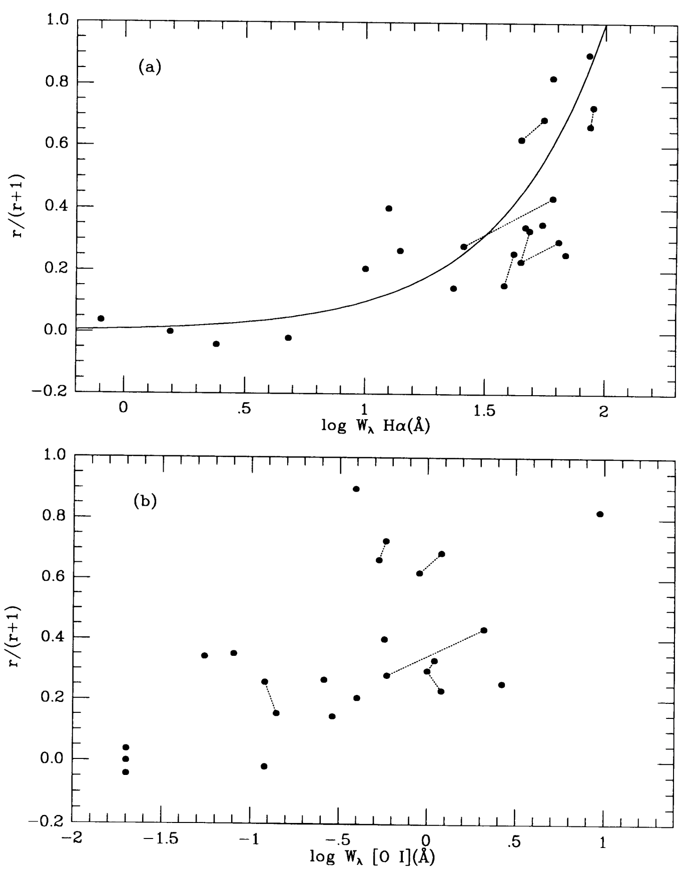

FIG. 2.—(*a*) Normalized veiling vs. Hα equivalent width plotted for the CCD data only, where veiling and Hα are measured simultaneously. Dotted lines connect observations of the same star on different nights. The veiling and Hα fluxes are correlated. The solid line through the points is discussed in the text. (*b*) Same as (*a*) except for [O I]. The three points at log W_λ[O I] = −1.7 are upper limits.

four stars with Hα equivalent widths $\lesssim 10$ Å are not veiled, and there is a correlation between the Hα equivalent width and the veiling (probability of this correlation from a random distribution is 3.7×10^{-7}).

Basri and Bertout (1989) have suggested that the broad component of Hα emission in T Tauri stars arises from a boundary layer, and since this component dominates in the spectra of veiled T Tauri stars, Figure 2*a* provides support for this idea. However, Hα must emit from a much larger surface area than Hβ to explain the large Balmer decrements in these objects (Hartmann *et al.* 1990), and it is not clear how to accomplish this if a boundary layer produces the Balmer emission lines in T Tauri stars. The solid line drawn in the figure represents the simplest case where the Hα intensity equals a constant (the same constant for each star) times the veiling intensity. The constant was chosen to make the Hα equivalent widths of the most heavily veiled stars 100 Å, in accord with the observations.

Three of the four stars with no veiling have no detectable [O I] ($\lesssim 0.02$ Å), and all the veiled stars have [O I] emission. A correlation between veiling and [O I] emission as positive as that observed in Figure 2*b* arises only 0.27% of the time from a random distribution, although among stars with detectable [O I] emission the correlation arises 7.6% of the time from a random distribution.

Several complicating factors must be considered when interpreting the correlations of the wind diagnostics Hα and [O I]. The Hα line is known to be optically thick (Hartmann, Edwards, and Avrett 1982), so radiative transfer effects influence the observed equivalent width. Although the [O I] line does not have this drawback, in a wind model it forms in a low-density region far from the star (Edwards *et al.* 1987), where the ionization state and previous cooling history of the gas determine the energy emitted in this line (Hartmann and Raymond 1989). All of these factors can vary between objects with identical mass accretion rates and could account for some of the scatter in Figures 2*a* and 2*b*.

IV. CONCLUSIONS

We have used new estimates of optical continuum veiling in 35 T Tauri stars to test the most basic prediction of the accretion disk model. Veiled stars always possess significant near- and mid-infrared excesses, in agreement with the model. A striking gap exists in the $K-N$ diagram for T Tauri stars, which could result from the coagulation of material in the disk into particles greater than a millimeter in size. Most, but not all, objects with large $K-N$ excesses have detectable optical veiling. Stars with strong Hα and [O I] emission are always veiled, suggesting a connection between accretion and outflow. These latter correlations are not strong, however, perhaps the result of radiative transfer, cooling, and ionization effects in the Hα and [O I] lines.

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