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HAMILTON ECHELLE SPECTRA OF YOUNG STARS. I. OPTICAL VEILING

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ABSTRACT

We present a extensive set of veiling measurements of T Tauri stars covering almost the entire optical spectrum. These are based on Hamilton echelle spectra obtained during 1987–1989. We have studied a full range of T Tauri stars, from "weak" to "continuum" stars. In some cases we have several spectra of a given target in which the veiling has changed, occasionally dramatically. We determined the veilings using two new methods: one which concentrates on the residual intensities of selected spectral lines, and the other which compares the autocorrelation functions for a T Tauri star and a veiled standard. We discuss some of the difficulties associated with veiling determinations, particularly the choice of "appropriate" standards. We tried both field subgiants and Hyades dwarfs as standards; the latter proved preferable. A line-ratio method is employed for spectral type matching.

The general shape of the veiling is often as predicted by accretion disk models: almost flat in the red and increasing in the blue. Cooler stars have generally higher veiling, implying that the veiling power is relatively independent of stellar mass. The relation between veiling and the narrow and broad emission lines supports a nonstellar origin for the veiling and broad line components, and a stellar origin for the narrow lines. When the veiling changes, the variations in Hα suggest it is powered by the same source as the veiling continuum when the line is strong. This work leaves us satisfied that the disk accretion model for T Tauri stars is sensible, and that the strong line emission may be formed along with the continuum in the interface between star and accretion disk. The veilings found will serve as important constraints in refining further disk models.

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

I. INTRODUCTION

The T Tauri phase of a star represents its evolution from when it becomes visible at optical wavelengths until it reaches the main sequence. T Tauri stars (TTS) encompass (1) objects strongly resembling young embedded sources mainly observed at radio and infrared wavelengths, (2) the "classical" TTS with ultraviolet and infrared excess as well as strong emission lines, and (3) pre–main-sequence stars with the signature of magnetic activity stronger than usually found among late-type main-sequence stars. Combining all the present observations of TTS to establish an evolutionary picture for them has been a fascinating and controversial area of research.

Joy (1945, 1949) first recognized TTS as an independent class of emission-line variable stars. He noted the sometimes shallow appearance of the absorption lines, mainly at short wavelengths, and concluded that the photospheric spectrum is sometimes "veiled" by an external continuum emission. He also considered the weakening of the lines due to intrinsic emission. The spectroscopic properties of TTS were summarized by Herbig (1962). In this classic paper, he discussed the veiling noted by Joy and the strong ultraviolet continuum shortward of about 3800 Å. Later, as an explanation for this flux excess at short wavelengths, Herbig (1970) suggested that the region of minimum temperature in the photosphere of TTS was optically thicker than the analogous solar region. In his view, if the chromospheric temperature rise took place at continuum optical depths between 0.01 and 0.1, it might explain both the extra continuum flux and the observed emission line features. This proposal launched a series of semiempirical chromospheric models (e.g., Dumont *et al.* 1974).

Refinement of the deep chromospheric approach was made by Cram (1979) and Calvet, Basri, and Kuhi (1984). Their models reproduced most of the line emission features in TTS with the exception of the Balmer lines. The location and slope of the chromospheric temperature gradient are free parameters controlling the increase of the line over the continuum source functions. The continuum source function itself becomes partly chromospheric for sufficiently deep chromospheres, which can yield the optical continuum excess flux. The photospheric absorption lines are filled in by intrinsic emission resulting in a shallower profile or, for sufficiently extreme cases, an emission line. Because of its dependence on line strength, this is sometimes called differential veiling and has been seen in weak TTS (e.g., Finkenzeller and Basri 1986). The main drawback of the deep chromospheric approach is in explaining the energy mechanism which could supply the chromosphere with power sometimes higher than that of the underlying photosphere (as implied when the lines are all less than 50% of their usual depths).

Solar-type magnetic dynamos are usually invoked for chromospheric activity. In fact, correlations between rotation periods and X-ray flux are found for TTS (Bouvier 1990). Also Calvet *et al.* (1985) found that the K-line flux of the weaker TTS is consistent with magnetic activity in main-sequence stars, with slightly greater values of nonradiative flux. Likewise, Bouvier and Bertout (1988) found that starspots are a common feature on TTS, but their properties are not so different from active main-sequence dwarfs or RS CVn stars. Since none of these other active stars exhibit appreciable veiling, it is difficult to see how the chromosphere could actually be its source in TTS.

Rydgren, Strom, and Strom (1976) analysed the colors of some TTS spectra and concluded that the veiling could be free-bound and free-free hydrogen continuous emission from a hot ionized envelope surrounding the star ($T \sim 20{,}000$ K). This circumstellar gas might explain the emission-line features as well as the ultraviolet and blue excess; however, it might also create high optical extinctions which are not observed (Cohen and Kuhi 1979).

Another hypothesis for optical veiling is suggested by the evidence that circumstellar disks are important components in young stellar objects. Mendoza (1966) discovered that near-infrared flux excesses are also common features in TTS. His explanation was that they arise in an optically thick circumstellar envelope which reprocesses the photospheric visual light. *IRAS* observations of dense cores (Myers *et al.* 1987) favor circumstellar *disk* geometry since the amount of dust to explain the infrared data is in contradiction with the observed optical extinction. Lynden-Bell and Pringle (1974) were pioneers in proposing a viscous Keplerian disk accreting onto recently formed stars in order to account for the observed blue and near-infrared flux excess. Passive disks were shown to be consistent with some TTS infrared excesses by Adams, Lada, and Shu (1987), and strongly accreting disks were suggested for FU Ori objects by Hartmann and Kenyon (1985).

To explain UV excesses as well, the interface of the disk and the central star must be a thin region (boundary layer) in which the gas of the disk at hypersonic (orbital) velocities (~ 250 km s^{-1}) is slowed down to photospheric velocities (~ 20 km s^{-1}). This creates a turbulent high-temperature region whose luminosity could reach stellar values depending on the accretion rate and view angle. Disks were shown to be consistent with extreme TTS by Kenyon and Hartmann (1987), and this was extended to classical TTS by Bertout, Basri, and Bouvier (1988). In this view, the boundary layer is the major source of optical veiling, and the near infrared excess comes from the accretion and reprocessed stellar photons by the disk.

An improvement of this model was made by Basri and Bertout (1989, hereafter BB) to allow for an optically thin boundary layer in order to explain the observed Balmer continuum jump. Their main results concerning veiling are (1) its direct dependence on the accretion rate implying (2) close relation with near-infrared excess and (3) its importance in controlling blue colors and the size of the Balmer jump. They conclude the amount and wavelength dependence of the veiling is one key to constraining TTS disk models and that the means to measure this is through high-resolution echelle observations. A similar analysis was also made by Kenyon and Hartmann (1990), who discuss in more detail the effects of disk accretion on the placement of TTS in the H-R diagram.

Strom (1983) and Finkenzeller and Basri (1986) have reported differential veiling for weak TTS by comparing them with standards of the same spectral type. Recently Hartigan *et al.* (1989, hereafter HHKHS) compared echelle spectra of main-sequence Hyades dwarfs to BP Tau and quantitatively measured the continuum emission veiling in the range 5100–6800 Å. They find that the continuum veiling is almost flat and nearly as luminous as the underlying photosphere. Hartmann and Kenyon (1990) use equivalent widths of lines around 5210 Å to extend the analysis of veiling to a larger group of TTS. Assuming the veiling is caused by accretion of a circumstellar disk onto TTS, they discuss possible changes in the standard Hayashi tracks of TTS, since the accretion rates implied by the veiling might mean that 10% of the final stellar mass is accreted in the TTS phase. This work makes it clear that a study of the optical veiling is important to the overall understanding of TTS.

In this paper we present an extensive set of veiling measurements obtained from high-resolution echelle spectra. In most cases we present veiling for almost the entire optical spectrum, obtained through nearly simultaneous observations of the red (5100–8700 Å) and blue (3800–5100 Å) spectral regions. The veiling is determined by two new independent methods. Some stars were observed at different epochs and sometimes show striking changes in veiling. Because the observations were made with a two-dimensional echelle, we simultaneously obtained emission lines whose relation to the veiling is of interest. In § II the observations are described as well as the methods of reduction and analysis. The results are presented and discussed in § III, and § IV is a summary.

II. OBSERVATIONS AND ANALYSIS

a) Observations

The observations were gathered using the Hamilton Echelle Spectrometer at Lick Observatory, between 1986 October and 1989 October. This instrument has been described by Vogt (1987). The targets are a sampling of the brighter TTS in the Taurus-Auriga region, with a few objects from the summer sky as well. The sample is not selected for any particular characteristic of TTS and is biased against fainter objects. The primary goal of the observations was a study of the strong emission lines, so the exposures were generally not optimal for a veiling study. The data were reduced in a standard way, which has been described briefly by Basri, Wilcots, and Stout (1989). In addition to the TTS, a number of spectral standards were observed, as described in the next subsection.

Typically, each star was observed in each of two echelle grating settings: red and blue. Because the instrument is designed for the eventuality of 2048 × 2048 CCD chips, the current TI 800 × 800 chip does not fully cover the spectral format, especially in the red. The chip placement was made to cover many of the important emission lines. In the red setting the 53 orders of spectral coverage include the Ca II infrared triplet, Hα, Na D, and the Mg I *b* lines. In the blue the 38 orders include the next three Balmer lines, and the Ca II H and K lines. Exposure times are typically 2000 s in the red and 4000 s in the blue. The spectral range per order is variable but averages about 35 Å. A concerted effort was made to obtain the red and blue spectra within a day of each other, though this was not always possible. A number of the stars were observed on several occasions to allow a study of the variability of interesting spectral features.

One problem encountered in the reduced spectra of relevance to the veiling analysis is that the continuum was not particularly flat, especially in the red where chip fringing produces 20% variations in the raw spectrum. Flat-fielding should remove these (and mostly does), but if the background subtraction is not perfect, residual fringes remain. Furthermore, the blaze function is not completely removed by the flat-field lamp which is much cooler than stars. Finally the level of continuum exposure is certainly less than optimum, and low level ripples appear in long exposures which are not present in the flat fields. We developed a continuum-fitting procedure which divides the spectrum from each order into a chosen number of bins (typically 10), sorts the points in each bin, and assigns the continuum to the top chosen fraction (typically 10%). Obvious emission features are excluded from the points considered. A fit is then made to these points; usually a third-order polynomial was adequate. The choice of the continuum is of importance in the veiling measurements, since the program and standard star continua must both be normalized to unity. The line depth is obviously quite dependent on the chosen continuum as well. In very noisy spectra, the continuum is increasingly unreliable.

b) *Methods of Determining Veiling*

All the calculations carried out to extract veiling from a TTS spectrum are based on the assumption that atmospheres of TTS are similar to the atmospheres of the associated standard. General support for this comes from the study of Finkenzeller and Basri (1986), who found that medium to weak lines divided out well between young and older stars. Abundances are a complication, since the metallicity of the adopted standards is not guaranteed to be the same as the metallicity of a recently formed star in a young cloud. If the TTS has higher metallicity than the associated standard, the calculated veiling will be underestimated, since the TTS absorption lines are intrinsically stronger. On the other hand, chromospheres tend to reduce the contrast of the stronger absorption lines. Thus, chromospheric filling-in will tend to increase the total inferred veiling over that from accretion alone. Another potential source of error is the spectral type matching between TTS and standard; spectral types are particularly uncertain (or even appear to change!) in the extreme TTS. All these effects will increase the scatter in the calculated veiling to the extent they are present. Our data include a large spectral range which permits an averaging over many lines, reducing the global random (but not systematic) errors in derived veilings.

When normalizing the continuum stellar flux to unity, the effect on an absorption profile (P) of adding an external continuum flux which is a fraction V of the stellar continuum is to change the residual profile to

$$P' = \frac{P + V}{1 + V} ,$$

where P' is the veiled profile. We refer to V as the "veiling"; a veiling of 1 means an equal contribution from the star and external continuum (equivalent to r in HHKHS).

We first considered using the method of HHKHS to derive veilings. It did not work as well for us as for them, because our data were less ideal for the reasons described in § II*a* above. In particular, a large part of the residuals can come from the continuum between the lines if there are uncorrelated continuum wiggles in the two spectra being compared. Unless the continuum has good S/N and is quite flat, its residuals can significantly mask the veiling signal from the lines in the χ^2 method. We found results similar to those of HHKHS in the same spectral region of a high-quality BP Tau spectrum we had (although the veiling seemed to be lower at our epochs). For our overall sample, however, we developed two other approaches which complement each other and tend to reduce the above problems. One is based on the autocorrelation functions for a program star and a veiled standard, and the other on a detailed matching of chosen absorption lines. We discuss the autocorelation method first, since it is much easier to implement. All three methods converge on the same answer when the data are of high quality, and we found general agreement between our two methods on lower quality data.

The autocorrelation method (AC henceforth) relies on the fact that the autocorrelation function of a given spectral order yields, in essence, the average line profile in that order. When normalized so its peak is unity, the level of the "continuum" of the autocorrelation function gives a measure of the average line depth in the order, while the peak width can be used to compare the average broadening of the lines. The method is thus quite straightforward. The peak widths are compared to check whether the rotational broadening applied to the standard is appropriate, and the autocorrelation functions for various values of veiling on the standard area found. We assessed the "continuum" level by a simple averaging of the function on both sides of the peak at a distance selected to be outside the peak itself. An even better method of accomplishing both of these tasks is to fit a Gaussian plus continuum to each autocorrelation function and compare the widths and continuum levels (however, particularly at high veiling and with noise, it is not always possible to fit a sensible Gaussian).

This method works best if an entire echelle order is treated, and of course orders with strong emission lines or very strong absorption lines should be excluded. It does not matter if there is a mix of reasonable lines of different strengths since the same mix is present in both spectra. Because one essentially averages over the whole order, the noise in an individual measurement is less than with either the χ^2 or line-depth methods (though these can be averaged afterward). The method becomes less reliable as the number of absorption lines in an order diminishes (as happens in the near-infrared), and when the noise in the continuum becomes comparable to the line depths (as happens more easily in heavily veiled spectra). With our data set, we found it difficult to get reliable results for most spectra redward of 7000 Å or for the lowest quality spectra. The method could be improved by using selected bins within an order, concentrating on segments with good absorption lines.

Several points about the AC method are made in Figure 1. Figure 1*a* contains one echelle order studies of two stars. The inner traces in the upper panel are from DF Tau (*upper*) and CI Tau, while the outer traces are from the associated M0 and K5 Hyades standards. The M0 standard has been spun up to 20 km s^{-1} and veiled to 2.2, while the lower K5 standard is spun to 11 km s^{-1} and veiled to 0.2. Figure 1*b* shows the autocorrelation functions associated with the above observations, with Gaussian fits. This method is less sensitive than the other two to detailed matching between the program star and the standard insofar as the precision of the veiling is concerned, but obviously the choice of standard affects the accuracy in all three methods.

In Figure 1*c* is shown a test of the errors associated with the AC method. Here we use the K0 spectral standard shown in the upper panel and add noise to it to produce S/N ratios of 10, 20, 40, and 80. We then add a continuum to each of these to produce veilings of 0.5, 1.0, 1.5, 2.0, and 4.0. The AC method is applied to each mock "observation" to see what veiling it deduces. Each case was tested 10 times to assess internal consistency; the internal errors were always 0.1 or less in veiling for the 10 trials. It is obvious from the figure that very noisy spectra are poorly analysed by the AC method, always resulting in low veilings (because the noise is interpreted as signal). At high S/N, the method works fairly well up to veilings of 4. It tends to underestimate large veilings if the spectrum has too much noise. Not shown here is the fact that if there are very few absorption lines in the spectral order, the performance becomes worse. We conclude that for spectra bluer than 6500 Å and S/N above 40, this is a good (and easy) method for measuring veilings up to 2 or 3.

To avoid some of the potential problems above, we developed another method to find veiling. This is based on direct comparison of the residual intensities of selected lines in the standard and the TTS. While the AC method provides an

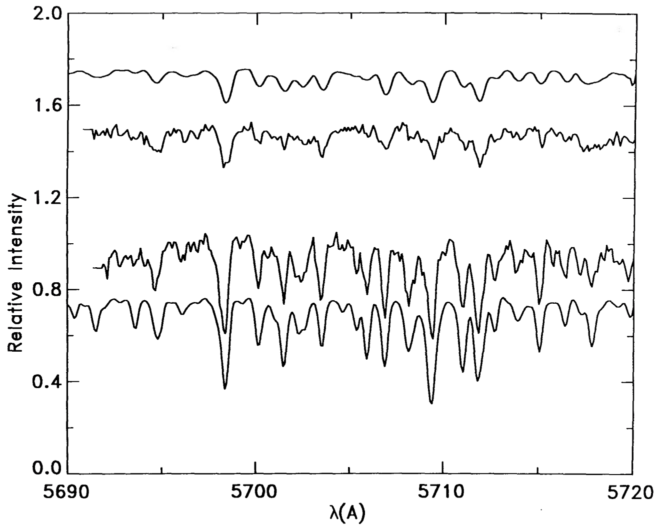

FIG. 1*a*

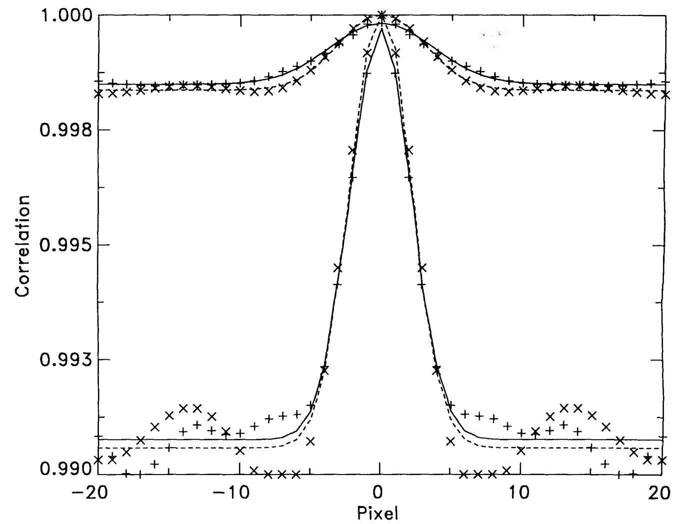

FIG. 1*b*

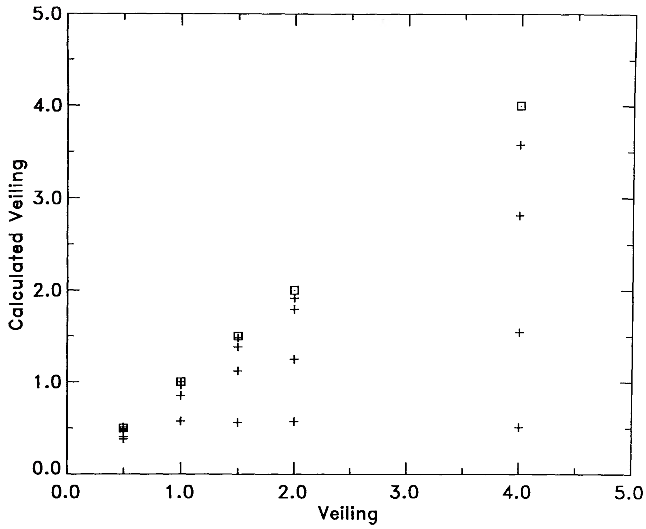

FIG. 1*c*

FIG. 1.—The autocorrelation method for determining veiling. In Fig. 1*a* are sample spectra of program and standard stars. The upper and lower traces are spectral standard stars, and the middle traces are observations of DF Tau (*upper*) and CI Tau (*lower*). The upper standard is M0 V and has been spun up to 22 km s^{-1} and veiled by 2.2. The lower standard is K5 V spun up to 11 km s^{-1} and veiled by 0.2. The spectra are all normalized to unity and arbitrarily shifted vertically. Fig. 1*b* shows the autocorrelation functions for the two program spectra (*plus signs*) and for the standard (*crosses*) stars. Also shown with solid and dashed lines are Gaussian fits to the program and standard autocorrelation functions. Fig. 1*c* shows a test of the AC method for a set of different assumed veilings and S/N ratios. The boxes are the correct values, and the plusses are the computed values. The lowest computed values at a given veiling are the lowest S/N, and they are in order up to the highest (see text).

average veiling for a whole echelle order (~30 Å), the line-depth method (LD henceforth) works with individual lines in a window of about 5 Å. Ideally, weak lines should be chosen since they are formed deeper in the atmosphere and therefore less subject to filling in by chromospheric activity. However, weak lines suffer most from noise and are difficult to use even in moderately veiled TTS. Thus, a selection of Fe, Ti, Ca, Ni, Cr, Al, K, Si, and Mg neutral lines with equivalent widths around 100 mÅ were selected from the solar spectrum (Moore, Minnaert, and Houtgast 1966). Only few iron and calcium lines with equivalent width greater than 200 mÅ were considered. We do not fit the lines, since we are making comparison with their depths directly.

We eliminated lines near telluric H_2O or in strong blends since the line depth is affected by those features. We checked the lines to see that they were still suitable in the later type spectra typical of TTS. The set of metal lines was further refined by eliminating those suspected of chromospheric filling-in. This was done by comparing their specific veiling with the average veiling nearby using a weak TTS and a classical TTS with very good data and moderate veiling. Lines which gave values above the expected scatter were assumed to be filled in. A total of 33 lines (primarily Fe I) were eliminated, including the iron lines 5227.4 Å, 5328.2 Å, and 5429.8 Å previously reported to be filled in by HHKHS.

A final sample of 170 lines in the red setting and 44 in the blue was chosen and an individual veiling calculated for each one of them. Assuming the standard is already corrected for radial and rotational velocity differences, the continuum in the standard as well as in the TTS spectra is normalized to unity in a range of 2.0 Å about the line center of each individual line. The derived veiling for a given line is that which brings the absorption core of the standard profile to the same percentage of the continuum as found in the TTS. Figure 2*a* shows how this method works with the Fe line λ5709.40 in a moderately and strongly veiled TTS. The calculated veiling for the spectral region is the average of all the individual veilings found separately within it, which then does not force agreement for every line (e.g., Fig. 2*b*).

The drawback of this method is its sensitivity to noise. In a very noisy spectrum, this procedure tends to overestimate the line depth, since there is a tendency to select high points for the continuum and low points for the line core. The calculated veiling for those cases are underestimated. A Gaussian fit to both profiles might help this problem but would have its own problems in weak or noisy lines, or those which do not really have a Gaussian profile. Only veiling for lines whose depth was greater than 15% were considered (7% in "continuum" TTS) as a compromise between the need for many lines and the need to minimize the scatter. The intrinsic scatter depends on the quality of the spectra and on the spectral type determination.

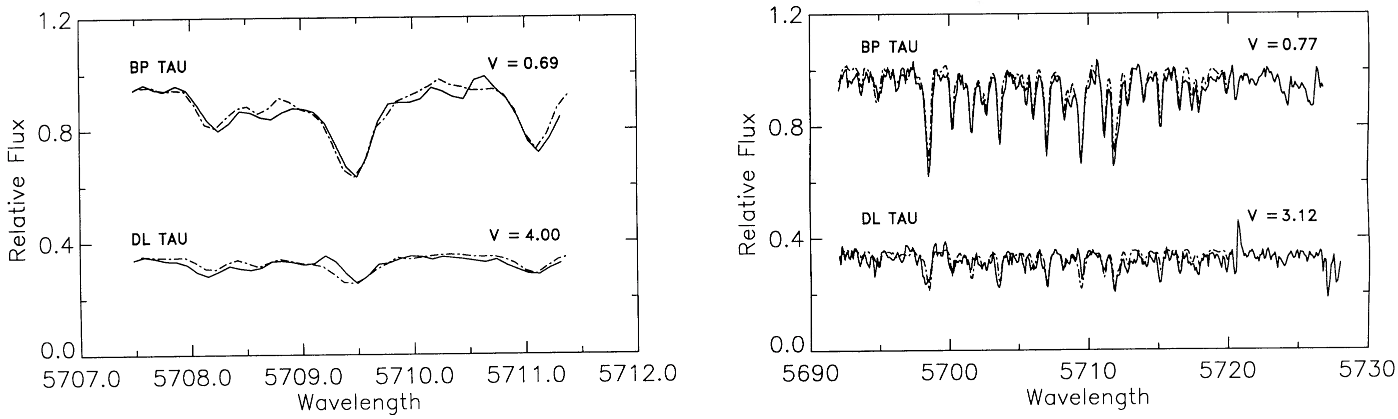

FIG. 2*a* FIG. 2*b*

FIG. 2.—The line depth method for determining veiling. Fig. 2*a* (veiling at 5709.40 Å) shows two examples of line fittings, for BP Tau and DL Tau. In all cases the spectral standard (rotated and veiled) is shown with the dash-dot line. Fig. 2*b* shows a full order with the veiling found from the average veiling nearby, illustrating that the fit is not perfect for all lines.

Usually an error of ± 0.2 in V was obtained for cases with veiling lower than 1.0. This error tends to increase as the veiling goes up (where the line contrast is increasingly low).

This method is able to reliably determine veilings up to 5 in spite of high scatter and low number of useful lines. Although the implementation of this method is rather lengthy, we found it the most reliable and useful, and our results are largely based on it. The AC method served as a confirmation for spectral orders in which it was able to operate well, and almost always agreed with the LD method for these. The χ^2 method of HHKHS lies between these two in the sense that it requires a detailed selection of bins also but is more automatic than the LD method. It provides an internal assessment of measurement uncertainty; we prefer to obtain that from the order-to-order scatter of our final veiling measurements.

c) Choice of Comparison Standards

A good determination of veiling in TTS relies to a large extent on the standard spectrum employed, since the final step in any method is to compare an "appropriate" standard with the TTS. The published spectral types of TTS are not necessarily accurate, since they have typically been derived from colors or low-resolution spectra without accounting for the presence of an accretion disk. For the continuum stars these problems are particularly acute. As discussed below, metallicity is another potential problem, since the chemical composition of both the TTS in a young molecular cloud and a standard chosen randomly from the field may not be the same, or even known.

We chose standards first with the philosophy that single late-type field subgiants would be most directly comparable to the TTS, which are typically classified as luminosity class IV. This proved somewhat problematic in practice, since such stars are not very numerous among the brighter stars. We used the Michigan Spectral Atlas of Buscombe (1980) and the Bright Star Catalog (Hoffleit 1982) as sources for our standards. A second set of standards was selected from main-sequence stars; these were from the Bright Star Catalog and from the Hyades (following the suggestion of HHKHS). We wanted to check whether there was an advantage to having actual subgiants, outweighing the disadvantage of not knowing for sure about their metallicity. In practice we found that at high resolution, the spectral classifications are not sufficiently accurate for our purposes and that metallicity variations caused us to drop several of our standards (we relied on intercomparison of several stars of the same spectral type to eliminate these). In the end, we found that the Hyades dwarfs were the best match to the TTS, and we calibrated all spectral types carefully with well-studied main-sequence stars.

We first tried assigning spectral types for the program stars using a χ^2 method similar to HHKHS. We chose orders in the TTS spectra with a relatively high number of stellar absorption lines. These are divided into bins about 8 Å wide and properly normalized (meaning the continuum is flattened and set to unity). The same is likewise done for the set of standards, after correcting their spectra for radial and rotational velocity differences. The bins of each standard are then veiled (see above) and compared with the bins of the TTS. The standard yielding the minimum quadratic difference for the best veiling is considered to match the spectral type of the TTS. This method gave some difficulties when there were metallicity problems, for the subgiants, and for noisy data.

We therefore developed a method using the ratios of the equivalent widths of low and high excitation lines. We chose two pairs (in two different orders), based on their visibility throughout the TTS and their behavior among the calibrated main-sequence stars. One pair is in a series of four partially blended lines: the lines of interest are Fe I λ5706.01 (4.61 eV) and V I λ5706.98 (1.04 eV). The other pair are a slightly blended Fe I λ6200.32 (2.61 eV) which is relatively insensitive to temperature variations and an isolated Sc I λ6210.67 (0.00 eV) line. The lines were checked for chromospheric filling-in by the method mentioned above and also by the consistency of the spectra after ordering using the method. We are satisfied this was not a problem. Line blending was dealt with crudely by measuring the lines in a consistent fashion.

The first ratio was a little more discriminating at the cool (late K and M) end; the second was better near the hotter end (with the Sc I line virtually disappearing by G2). No doubt there are many other possible pairs to use with no blending and excellent temperature sensitivity (and more attention could be paid to line saturation); these two were chosen for ease and range of usefulness in our data. A check against both the colors and published spectral types of a number of bright

TABLE 1

SPECTRAL STANDARDS

Star	Published Spectral Type	λ5706/λ5707	λ6200/λ6210	Spectral Type[a]	$B-V$
		A.			
VA 495	G2	1.98	>11	G2 V	0.61
VA 587	...	1.24	3.4	K0.5 V	0.84
VA 459	...	1.09	2.5	K2 V	0.93
VA 135	...	0.82	1.29	K4 V	1.11
VA 276	...	0.70	0.87	K5 V	1.24
VA 404	K	0.56	0.54	K7 V	1.34
VA 622	K7	0.37	0.35	M0 V	1.44
SAO 80653	G2 IV	1.37	>12	G2 IV	...
HR 7689	K0 IV	1.18	4.0	K0 IV	0.85
HR 8166A	G8 IV	1.06	5.0	K1 IV?	1.08
HR 7948	K1 IV	0.80	1.8	K2 IV	1.04
SAO 79555	K5 V	0.85	1.8	K2 IV	...
BD +592667	K7 IV	0.72	...	K2 IV	...
HR 1703	M0 V	0.64	0.74	K5 IV?	1.46
SAO 76803	K5 V	0.68:	1.24	K5 IV	...
BD +461635	K7–M0	0.54	0.64	K7 V	...
		B.			
HR 1262	G5 V	1.81	10.25	G4 V	0.62
HR 159	G8 V	1.57	9.6	G8 V	0.72
HR 8	K0 V	1.41	8.3	G9 V	0.75
HR 493	K1 V	1.11	4.0	K1 V	0.84
HR 857	K2 V	1.18	4.2	K1 V	0.87
HR 222	K2 V	1.00	3.1	K1.5 V	0.88
HR 753	K1 V	0.93	1.56	K3 V	0.98
61 Cyg A	K5 V	0.64	0.95	K5 V	1.18
61 Cyg B	K7 V	0.35	0.52	K7–M0	1.37

NOTE.—Stars with SAO or BD numbers are from Buscombe 1980. Stars labeled VA are Hyades dwarfs. Stars in part B were not used in the analysis, but as checks on the spectral typing. The 61 Cyg stars have weak lines, and most stars listed as class IV have stronger lines than the dwarfs.

[a] A spectral type (approximate) based on the line ratios tabulated. These are the types used for matching with the TTS.

main-sequence stars confirmed that the line-ratio system was closely correlated with MK spectral type. The data for the standard stars are listed in Table 1.

This proved to be a sensitive and accurate means of assigning relative spectral types. Indeed, it was our impression that with some work a "high-resolution" spectral typing scheme can be devised that would be superior to the conventional low-dispersion approaches; we found some clear inconsistencies in published spectral types for a few "standards." The conversion to the usual spectral typing appeared to be reasonable, but we do not advertise our results as identical to the conventional low dispersion methods. In particular, we have not made a strong effort to differentiate M stars (molecular lines should be employed). Indeed, there are occasional surprises where we move stars whose classification suggest they have molecular bands to types where they should not. Without concurrent low-dispersion spectra, we cannot assess the source of these discrepancies and can only report that the overall spectral matches are better for the line-ratio inferred types in our high-dispersion spectra.

The line-ratio method is used to assign spectral types to both the Hyades standards (for which conventional spectral types were largely unavailable), and to the TTS. For TTS, we adopt the spectral types of Herbig and Bell (1988) whenever our classification agrees with theirs within ± 2 subclasses and adopt ours when more serious disagreement is found. We note that there are only a few cases where this happens, and we can generally demonstrate for those that there is a closer match with our (always hotter) standards. We urge caution for the present and that detailed analysis of high- and low-resolution spectral typing be pursued.

The results for the "continuum" TTS are of particular interest. Only high-resolution spectroscopy is adequate to measure extremely veiled photospheric lines. Appenzeller, Reitermann, and Stahl (1988) found the diluted observed photosphere of DR Tau to resemble Arcturus (K2 III). They rule out a spectral type later than K5 by the absence of TiO lines. We found Ti lines (low-excitation) generally deeper than our K5 standard and the strength of the Sc I line implies a later type for DR Tau (near M0). The same applies for the strongly veiled star DL Tau. The veiling of RW Aur is variable and the most lightly veiled spectrum reveals a mid-K star; values as early as late G have been reported earlier (Mundt and Giampapa 1982). DG Tau is probably similar, although our spectra are not of sufficient quality to make a precise determination. We adopt the unpublished determination of Strom that HL Tau is an early M star, as our spectrum is very noisy.

We can derive rotation velocities from our spectra but prefer to rely on previous determinations of $v \sin i$ except in cases of necessity or substantial disagreement. For the classical TTS we used the results of Hartmann *et al.* (1986) and Bouvier *et al.* (1986). For the continuum stars we convolved the standard spectra with a rotational function and looked for the best agreement between the rotated standard and the TTS. The accuracy of our determinations is ± 3 km s^{-1}. The highly veiled stars HL Tau, DR Tau, DG Tau, DF Tau, RW Aur, and DL Tau are all found to be slow rotators, in good agreement with the results of Hartmann and Stauffer (1989) except that we find a smaller value for DL Tau. This clearly eliminates any theory of solar-type magnetic dynamos to hyperactivate these stars and generate the veiling and emission lines. It also eliminates the Shu *et al.* (1988) centrifugal magnetic wind mechanism from playing a *direct* role in the strong activity observed in these systems, since the stars are clearly not rotating near breakup. The spectral types and rotation velocities we used are listed in Table 2.

III. RESULTS

a) Measured Optical Veilings

In Figure 3 we present the veiling for those stars in which both blue and red frames were obtained. Because the spectra are noisier than desirable, the individual veiling measurements show scatter; this becomes worse in lower quality spectra or for more heavily veiled stars. The AC method derives the average veiling in a whole echelle order of about 35 Å, while to unveil an absorption line the LD method is sensitive to noise within 4 Å of the line profile. Thus, the intrinsic scatter in the LD method is always higher than the AC method. We have averaged the individual points in the LD method over 100 Å in presenting our results. The veilings longward of 7000 Å suffer from the relative paucity of stellar absorption lines in that part of the spectrum, which renders the LD method more reliable than the AC or χ^2 methods (especially for noisy data). Since the AC method showed good agreement with the LD results when both were reliable, we only show the LD results. Table 2 lists the continuum veiling for all program stars averaged over 5000–7000 Å (thus including the region near Hα). The errors are standard deviation in V after a quadratic fitting is passed

TABLE 2

MEASURED VEILINGS (RED)

Star	Date	Quality	λ5706 / λ5707	λ6200 / λ6210	Spectral Type	$v \sin i$	Veiling near Hα(±σ)
AA Tau	1986 Dec 21	2	0.33	0.40	M0	10	0.0 ± 0.08
	1986 Dec 22	2					0.15 ± 0.1
	1988 Jan 7	2					0.0 ± 0.1
	1988 Nov 30	1					0.2 ± 0.1
	1989 Jan 17	2					1.6 ± 0.65
	1989 Oct 13	1					0.13 ± 0.09
	1989 Dec 8	2					0.54 ± 0.19
AS 205	1986 Jul 25	3	0.90	2.08	K2	10	0.2 ± 0.2
	1987 Jun 10	2					0.25 ± 0.1
AS 209	1987 Jun 10	1	0.64	1.50	K5	10	0.4 ± 0.1
AS 353	1986 Jul 25	3	?	2.20	K2(C)	10	1.8 ± 1.0
	1987 Jun 9	3					1.45 ± 0.3
BP Tau	1986 Dec 21	1	0.42	0.57	K7	<10	0.6 ± 0.1
	1988 Nov 30	1					0.5 ± 0.1
	1989 Jan 17	1					0.75 ± 0.15
CI Tau	1987 Oct 12	1	0.67	1.11	K5	11	0.2 ± 0.1
CO Ori	1986 Oct 21	3	?	?	G2	48	0.00 ± 0.2
	1986 Dec 22	2					0.0 ± 0.1
	1987 Oct 12	2					0.0 ± 0.1
	1987 Nov 7	2					0.0 ± 0.4
DE Tau	1987 Oct 12	1	0.10:	0.1	M2	<10	0.9 ± 0.15
DF Tau	1986 Oct 22	1	0.15:	0.40	M2	20	1.0 ± 0.2
	1986 Dec 21	3					1.3 ± 0.6
	1988 Mar 8	2					0.9 ± 0.5
	1989 Jan 17	3					1.15 ± 0.4
	1989 Oct 14	2					1.24 ± 0.31
DG Tau	1986 Dec 21	3	?	<0.4:	K7?(C)	20:	0.77 ± 0.44
	1989 Dec 8	2					1.77 ± 0.58
DK Tau	1987 Oct 12	1	0.35:	0.55	M0	11.5	0.4 ± 01
	1988 Nov 30	3					1.15 ± 0.25
	1989 Jan 17	2					1.1 ± 0.3
DL Tau	1987 Oct 12	1	0.73	0.37	M0(C)	<10	3.1 ± 1.2
	1988 Nov 30	3					2.2 ± 0.9
	1989 Oct 13	1					2.42 ± 0.38
DN Tau	1986 Nov 12	1	0.38	0.40	M0	10	0.1 ± 0.05
DR Tau	1986 Nov 14	1	?	0.28	M0(C)	<10	3.9 ± 1.0
	1987 Oct 12	1					4.7 ± 1.6
	1988 Mar 8	2					2.8 ± 0.8
	1988 Nov 30	1					4.5 ± 1.1
	1989 Oct 14	1					4.82 ± 0.56
	1988 Nov 30	2					0.7 ± 0.2
GG Tau	1986 Nov 22	1	0.42	0.46	K7	<10	0.4 ± 0.05
	1988 Jan 7	1					0.2 ± 01
	1989 Jan 17	1					0.5 ± 0.05
	1988 Nov 30	1					0.4 ± 0.1
GM Aur	1987 Oct 11	1	0.46	1.16	K7	13	0.25 ± 0.1
GW Ori	1986 Oct 21	1	?	?	G8	43	0.2 ± 0.1
	1986 Oct 22	1					0.1 ± 0.1
	1986 Dec 22	1					0.2 ± 0.1
HL Tau	1986 Nov 12	3	0.50::	?	K7?(C)	15:	0.9 ± 0.4
IP Mon	1989 Jan 18	3	1.00	1.3:	K3	<10	1.2 ± 0.2
ROX 6	1987 Sep 6	1	0.52	0.52	K5	<10	0.25 ± 0.1
ROX 29	1987 Jun 9	1	0.59	0.94	K5	15.8	0.0 ± 0.1
	1987 Jun 10	1					0.0 ± 0.05
RY Tau	1986 Dec 21	1	0.67:	>3:	K0	48.7	0.05 ± 0.1
	1986 Dec 22	1					0.0 ± 0.05
	1989 Jan 17	1					0.10 ± 0.1
RW Aur	1986 Oct 21	2	1.00	1.10	K5(C)	15	0.2 ± 0.2
	1986 Dec 21	2					1.0 ± 0.8
	1988 Feb 4	2					3.5 ± 1.35
	1988 Nov 30	1					1.8 ± 0.6
	1989 Jan 17	2					2.0 ± 0.35
	1989 Oct 14	2					3.83 ± 1.05
SU Aur	1988 Nov 11	1	?	?	G2	66	0.0 ± 0.05
	1989 Jan 17	1					0.0 ± 0.1
T Tau	1987 Oct 11	1	0.93	2.28	K0	20	0.0 ± 0.1
	1989 Oct 13	1					0.01 ± 0.10
TAP 9	1988 Nov 30	1			K5(W)	20	0.2 ± 0.2
TAP 29	1988 Nov 29	1	0.18	0.53	K7(W)	17	0.0 ± 0.1
TAP 35	1988 Dec 22	1	1.1	?	K0(W)	15	0.0 ± 0.05

TABLE 2—*Continued*

Star	Date	Quality	λ5706/λ5707	λ6200/λ6210	Spectral Type	$v \sin i$	Veiling near Hα(±σ)
TAP 56	1988 Nov 29	1	1.0	2.66	K2(W)	22	0.0 ± 0.1
UX Tau	1986 Dec 22	1	0.13:	?	K0	20	0.05 ± 0.1
UY Aur	1987 Nov 7	1	0.50	0.75	K7	10	1.9 ± 0.3
UZ Tau E	1988 Nov 30	2	0.29	0.7:	M0	15	0.7 ± 0.25
UZ Tau W	1988 Nov 30	2	0.05	0.5:	M2	13.5	0.45 ± 0.3
V410 Tau	1986 Oct 21	3					0.0 ± 0.2
	1986 Nov 12	2	?	>3:	K2(W)	65	0.1 ± 0.3
	1986 Nov 13	2					0.05 ± 0.1
	1986 Dec 21	3			K4		0.15 ± 0.2
V830 Tau	1986 Nov 12	1	0.41:	0.55	K7(W)	25	0.1 ± 0.1

NOTES.—Quality indicates the level of S/N, with 1 being fairly reliable data, 2 meaning the data were noisy but useable, and 3 meaning the usefulness of the measurement is questionable. The (C) and (W) designations on the spectral type indicate whether the star has been considered a "continuum" or "weak (naked)" star previously. The veiling is the average between 6000 and 7000 Å (where it is fairly constant). The errors are standard deviations around a quadratic fit to the veilings in the entire spectral range.

on the points at this region. Veilings near Hβ and Hγ are presented in Table 3.

In a quarter of the cases—DK Tau, GG Tau, BP Tau, AA Tau, and perhaps UY Aur—a clear tendency for increasing veiling in the blue is found. For $\lambda \geq 5000$ Å a relatively flat continuum veiling is derived. These are primarily the cooler TTS. The stars not showing the blue rise tend to have either very strong (larger than 1) over very weak veiling. This general result is expected for a hot veiling continuum over a cool stellar photosphere, since the stellar flux distribution drops rapidly in the Wien part of the spectrum (blue), while the veiling continuum peaks in the ultraviolet. When the veiling continuum is very strong, its flatness will dominate the wavelength dependence in the optical, and if it is very weak then small values occur throughout dominated by noise in the measurement.

TABLE 3

MEASURED VEILINGS (BLUE)

Star	Date	Veiling near Hβ(±σ)	Veiling near Hγ(±σ)
AA Tau	1989 Oct 13	0.41 ± 0.12	0.72 ± 0.17
AS 205	1986 May 25	0.0 ± 0.3	0.0 ± 0.3
AS 209	1987 Jun 10	0.4 ± 0.1	0.5 ± 0.1
AS 353	1986 Jul 27	4.1 ± 2.0	4.9 ± 1.0
	1987 Jun 9	2.8 ± 0.7	2.4 ± 0.85
BP Tau	1986 Oct 23	0.85 ± 0.2	1.0 ± 0.3
	1986 Dec 21	0.9 ± 0.2	2.0 ± 0.3
CO Ori	1986 Oct 21	0.0 ± 0.2	0.0 ± 0.2
DE Tau	1988 Feb 4	1.0 ± 0.5	0.55 ± 0.6
DF Tau	1986 Oct 23	1.6 ± 0.15	1.3 ± 0.4
DG Tau	1986 Oct 23	2.7 ± 1.5	3.2 ± 0.8
DK Tau	1987 Oct 12	0.7 ± 0.25	0.7 ± 0.3
	1988 Feb 4	0.4 ± 0.3	0.3 ± 0.2
DL Tau	1989 Oct 13	2.64 ± 0.39	2.30 ± 0.49
DN Tau	1986 Nov 12	0.25 ± 0.2	0.2 ± 0.1
DR Tau	1987 Oct 12	4.3 ± 2.0	3.3 ± 0.75
DS Tau	1987 Oct 11	0.5 ± 0.15	0.6 ± 0.1
GG Tau	1989 Jan 18	1.55 ± 0.4	2.0 ± 0.4
GK Tau	1988 Feb 4	0.0 ± 0.1	0.05 ± 0.15
GM Aur	1987 Oct 11	0.15 ± 0.1	0.15 ± 0.1
GW Ori	1986 Oct 21	0.0 ± 0.1	0.0 ± 0.05
ROX 6	1987 Jun 9	0.15 ± 0.15	0.0 ± 0.15
ROX 29	1987 Jun 9	0.1 ± 0.1	0.0 ± 0.1
RY Tau	1986 Dec 21	0.0 ± 0.1	0.0 ± 0.2
	1989 Jan 18	0.0 ± 0.2	0.2 ± 0.2
RW Aur	1986 Dec 21	3.2 ± 0.5	3.6 ± 1.0
T Tau	1989 Oct 13	0.00 ± 0.11	0.16 ± 0.62
UY Aur	1988 Feb 4	0.8 ± 0.3	0.4 ± 0.3
V380 Tau	1986 Nov 12	0.2 ± 0.15	0.0 ± 0.1

According to BB, the cases with strong blue rises should also be those with strong Balmer continuum emission jumps, which are also intermediate veiling cases (and this is largely true). A few cases (AS 209, ROX 6) have substantial veiling which does not rise in the blue, but these are K5 stars in which the photosphere does not fall off as fast. There is a tendency to find higher veilings for later type TTS. This is not necessarily surprising, since the contrast between the stellar flux and a given external continuum flux weakens for hotter stars because they are brighter. It implies, however, that the power in the veiling continuum does not increase with the mass of the star.

We found that the veilings measured with subgiant standards were generally larger than those using the Hyades dwarfs, and even the WTTS had values of 0.4. This is because of the deeper lines in those standards, but is unlikely to be due to high metallicity, since several show the effect and the Hyades is already slightly metal-rich. We therefore suppose it is due to the lower gravity of the subgiant standards (perhaps in part because of NLTE effects). While it is difficult to be sure which values are better without detailed model atmospheres for the TTS and subgiants, the tendency of the weak TTS to have nonzero veilings by our measurements makes the lower veilings preferable from the standpoint of the disk hypothesis for the TTS phenomenon. It is interesting that the TTS photospheres are better matched by dwarfs and argues for the smaller radii which are predicted by disk models. A more appropriate luminosity classification for TTS is therefore V–IV.

Most of the program stars were observed more than once. Selected cases are presented in Figure 4 using quadratic fits to the red measurements. The slope changes seen should not be taken too seriously as they are typically driven by relatively few points on the red end. Moderate variability seems to be more common than constancy when significant veiling is present. As can be seen, large variations in veiling are generally found for the "continuum" TTS. Very striking variations were seen in AA Tau. AA Tau has veiling no larger than a fifth of the stellar flux during the four runs in 1986 and 1988. However, in early 1989 its veiling was nearly twice the stellar flux. This case is discussed further in the next subsection.

b) Relation to Emission Lines

We have examined the relation between Hα and veiling, considering only the spectra with high quality in K7–M0 TTS. All line measurements are being published in a separate paper (Basri 1990), but they refer to the same echelle frames as

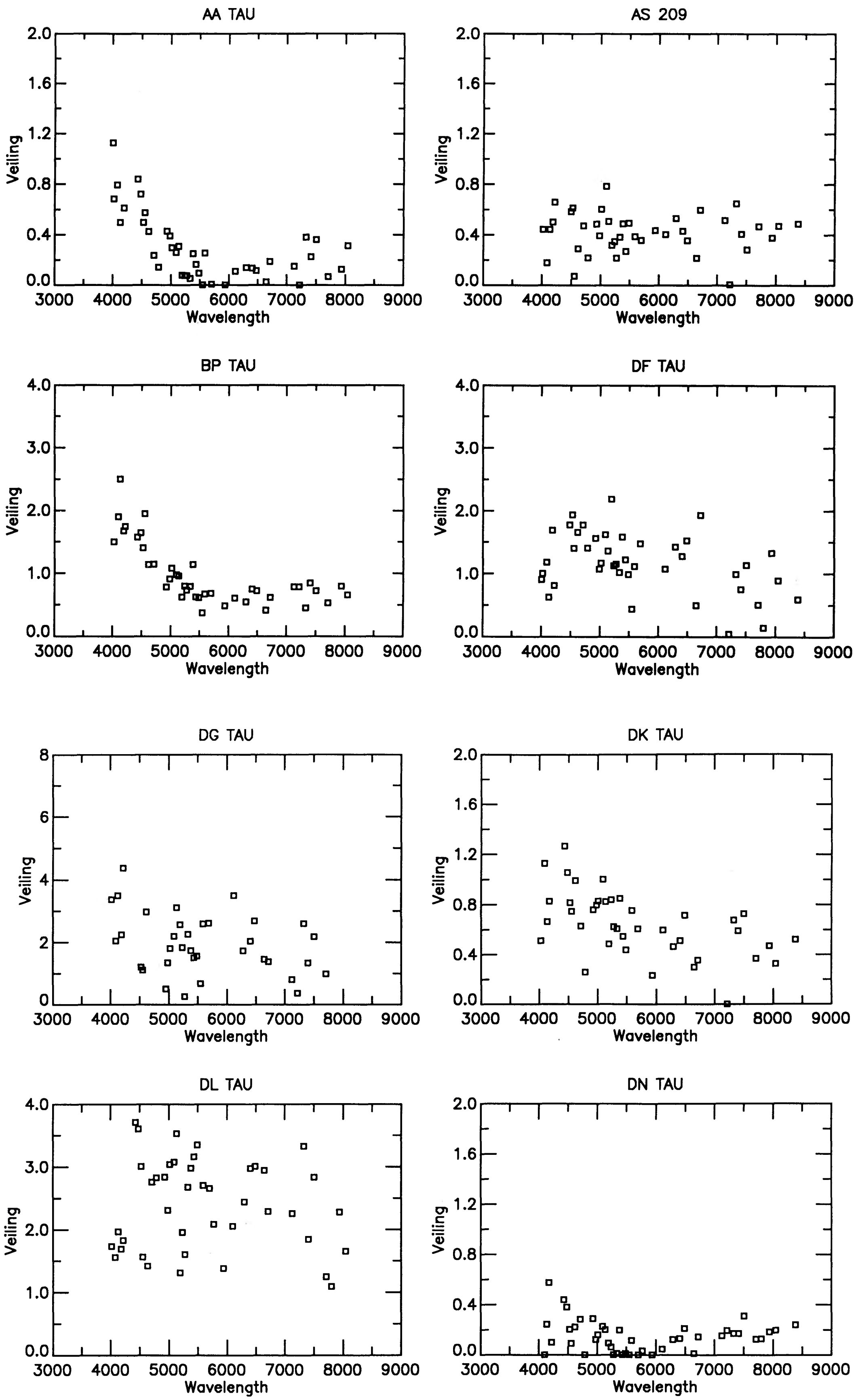

FIG. 3.—Each panel shows the veiling found for the indicated star, using with the LD method with both red and blue echelle frames obtained at nearly the same time. Each point shown is the average of the results within a 100 Å bin in the red and 50 Å in the blue. For most stars, several other measurements in the red were also analyzed. The epochs can be found by consulting Table 3.

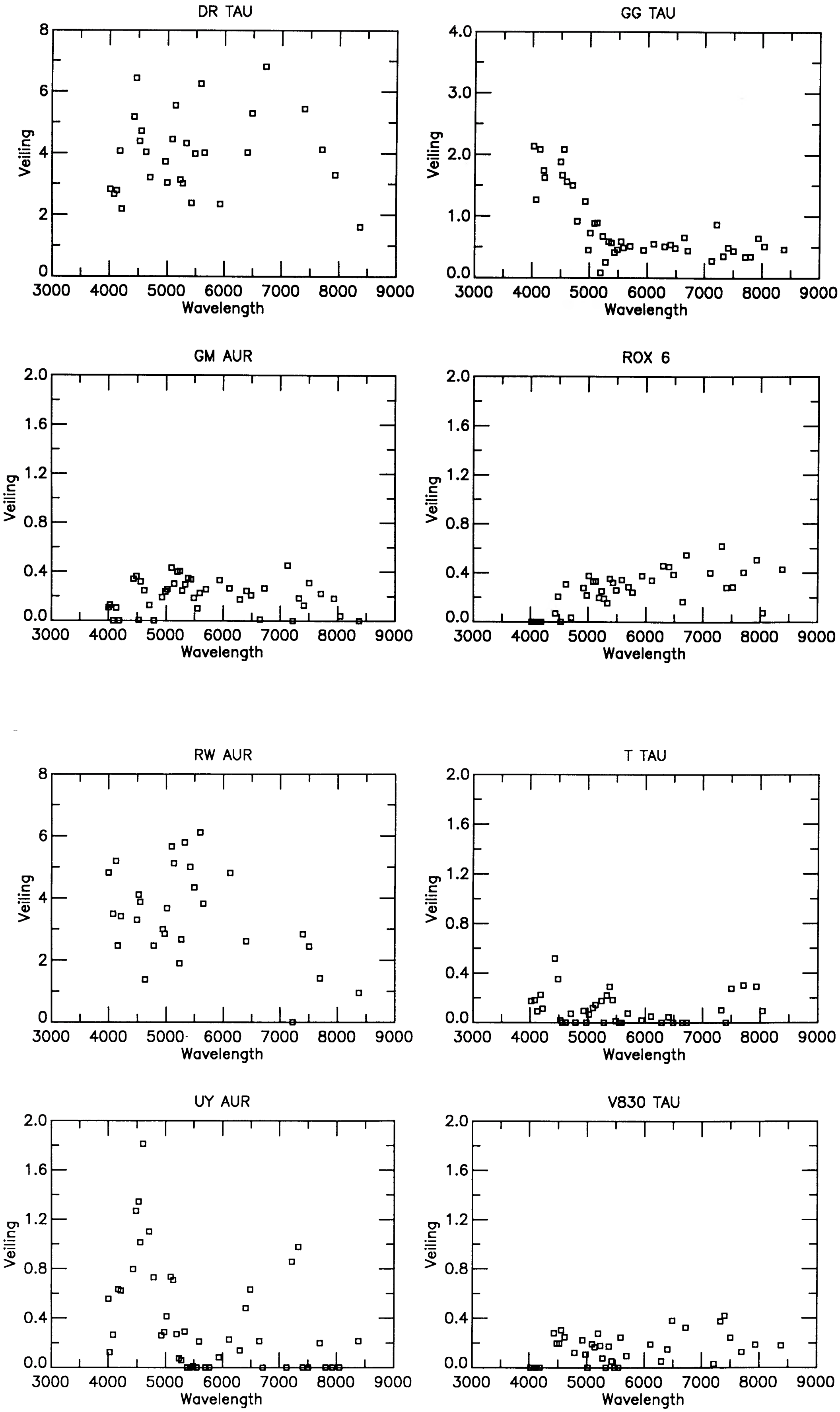

FIG. 3—*Continued*

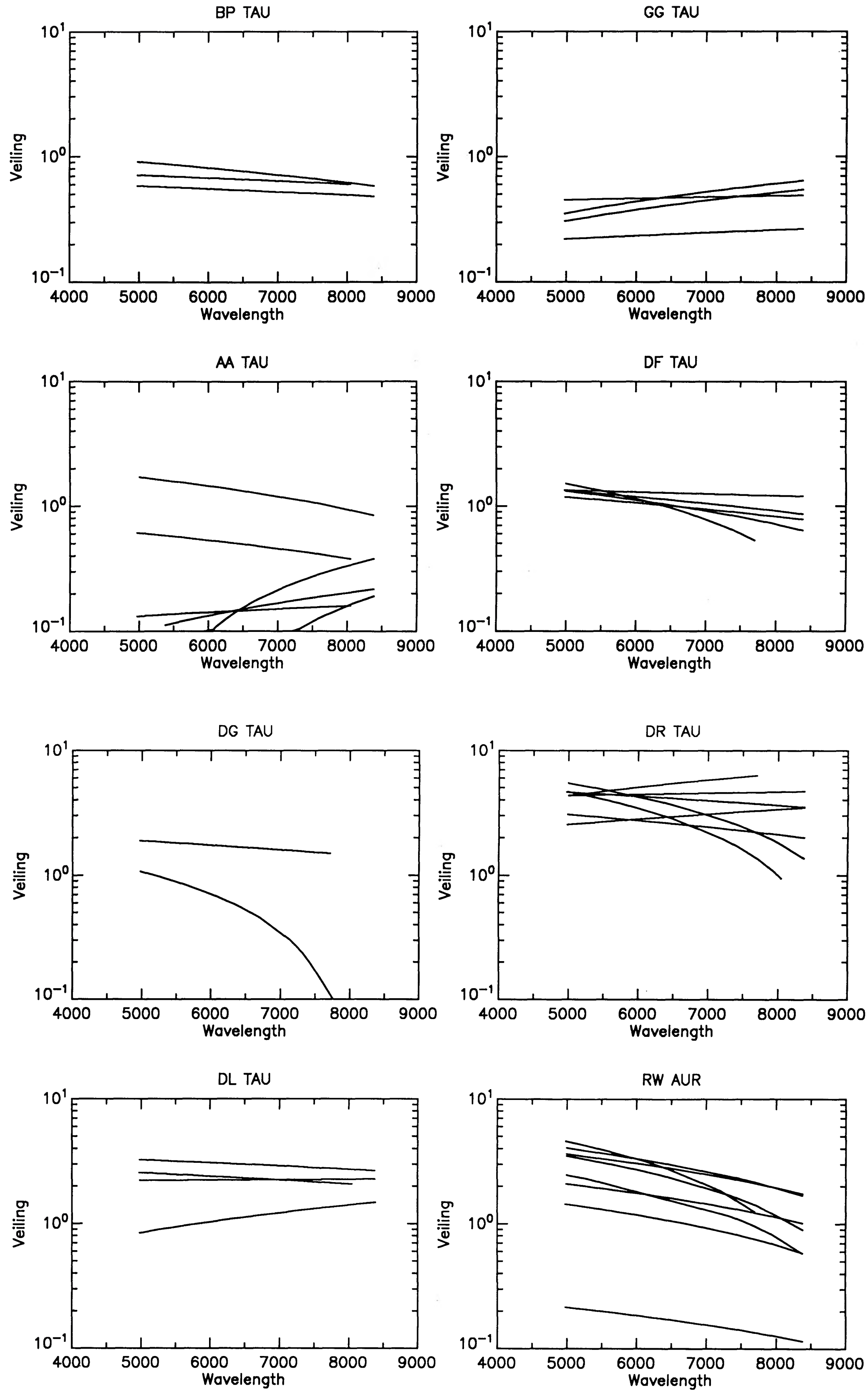

FIG. 4.—Approximate veilings at several epochs. For each star, a quadratic fit to the red veiling at the epochs listed in Table 2 is shown. The lines are misleadingly smooth, and their slopes in some cases are influenced by a few scattered points and so should not be overinterpreted (for example, DG Tau). The point of the figure is to show changes in the general level of veiling.

studied here and so can be used directly. A relation between Hα equivalent width and veiling was shown by Hartmann and Kenyon (1990), and a formula for it was proposed by Strom *et al.* (1989*b*). Our results agree very approximately, but are rather different in detail. The scatter is large (even within several observations of the same star). Using the formula to predict veilings from our Hα measurements yields overestimates by a factor of 3 at very low veilings and underestimates by the same factor at the largest veiling. There is good agreement in the neighborhood of unit veiling. Our sample does not contain weak Hα stars with measurable veiling as does theirs (nor does it contain many earlier spectral types which will tend to have smaller equivalent widths), but it does extend to substantially larger veilings and is made from simultaneous measurements. There is a weak trend for the equivalent width to be larger in heavily veiled stars (and this would certainly be strengthened by including a number of weak TTS), but veiling is a poor predictor of actual Hα equivalent width (and vice versa) among the TTS.

There are a number of reasons to be cautious about interpreting such a relation in any case. Since the equivalent width is measured with respect to the observed continuum, the veiling is implicitly included. In many cases the variations in Hα equivalent width are partly due to changes in the absorption components, which also tend to be larger in brighter lines. The physical meaning of equivalent width is not clear—not only because of the absorption but also because the lines are not necessarily effectively optically thin. One might just as well consider the total line flux (though with similar caveats). Normalizing the stellar contribution for each star to 1.0, the total flux in the line profile (in stellar units) is $F_{\mathrm{H}\alpha} = (1.0 + V) \times W_{\mathrm{H}\alpha}$. Not surprisingly, the veiling correlates better with this than with $W_{\mathrm{H}\alpha}$ by itself. One must be careful in these units to only compare systems with fairly similar absolute stellar luminosity. The relations with both equivalent width and flux are shown in Figure 5 for the cool TTS.

The question is what is the physical significance of a relationship? Equivalent width measures the relative power in the line and continuum, while flux measures the total power. If the line were formed in a large disconnected region unrelated to the source of veiling, whose flux did not change with veiling, the equivalent width should actually decrease as the veiling increases. If the power in the line increased proportionately to the continuum, the equivalent width might not change, while flux-flux relations would clearly show the increase. Greater clarity comes with multiple observations of the same system, since then fluxes relative to the photosphere can be safely compared. The continuum stars RW Aur and DR Tau have multiple observations with large variations in veiling. The lack of correlation of veiling with equivalent width and strong corelation with line flux for these stars is evident in Figure 6. Both results carry the physical implication of a common mechanism which powers the line and continuum together.

This behavior is not that proposed for the *higher* Balmer lines by BB, in which the power in those lines is determined primarily by optical depth effects and higher veilings lead to lower equivalent widths (and we unfortunately do not have enough blue spectra to address this directly). Those authors had recognized that the lower Balmer lines (and particularly Hα) are brighter than would be possible with only that effect. If the line is formed in or near the boundary layer as they propose, the most likely explanation for the brightness of Hα is geometrical. These results could imply that the emitting volume increases as the accretion rate increases (through increased filling of magnetic field lines, for example). Another possibility is that the line emission process is not in LTE and is enhanced by the increased accretion through higher densities or increased recombination rates (via increased ionization). It is less likely to be due to an optically thick temperature gradient, since the temperatures inferred for the boundary layer itself are already in the range which ionizes hydrogen, and much greater temperatures would be needed to brighten Hα sufficiently. Finally, if Hα really arises in a wind (see Hartmann *et al.* 1990), then our results can be constructed as supporting a

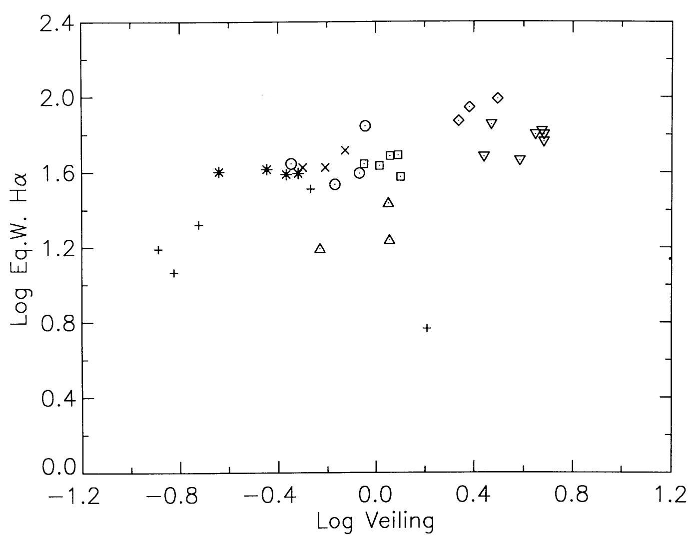

FIG. 5*a*

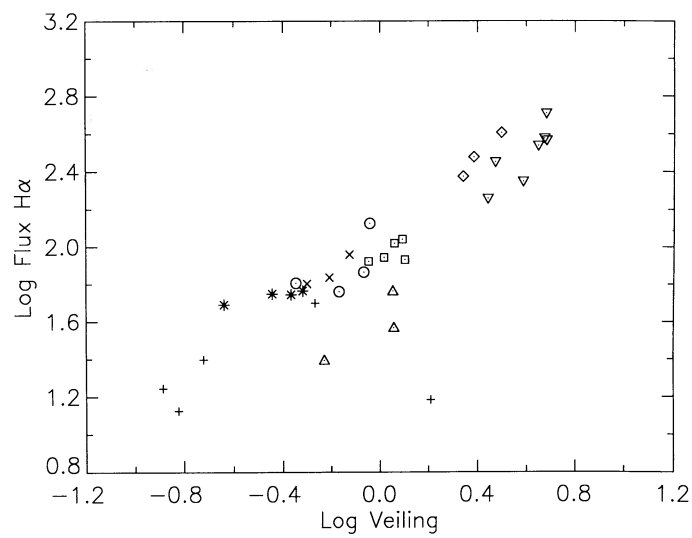

FIG. 5*b*

FIG. 5.—The relation of Hα emission to veiling. Fig. 5*a* (*left panel*): the relation between equivalent width (measured with the observed continuum) and veiling for the late-type TTS. Each symbol represents a different star; multiple symbols mean multiple epochs of observation. The symbols are plus, AA Tau; asterisk, GG Tau; circles, UZ Tau E, W, DE Tau, HL Tau; cross, BP Tau; square, DF Tau; triangle, DK Tau; inverted triangle, DR Tau; diamond, DL Tau, DN Tau. Note the rather weak correlation between the two. Fig. 5*b* (*right panel*): Same as (*a*) but using the normalized "flux" instead of equivalent width (see text for definition). Here the correlation is much stronger and implies a direct connection between the power sources for the veiling and line emission.

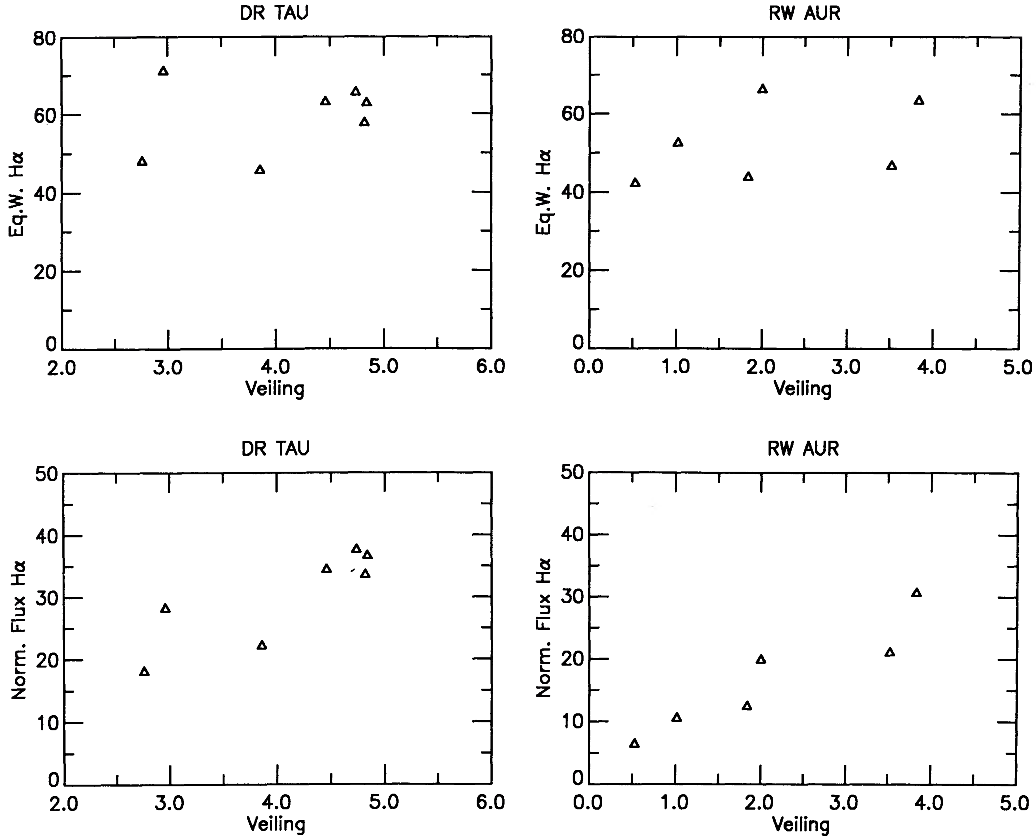

FIG. 6.—Comparison of the relation between veiling and equivalent width (*upper panels*) or normalized "flux" (*lower panels*) in Hα for several observations of two continuum stars. Note that in both cases the equivalent width remains roughly constant through the veiling changes, implying correlated changes in the flux. The epochs of observation are listed in Table 2.

fairly direct connection between the accretion and outflow. This idea is supported in a more generalized context by Cabrit *et al.* (1990).

In our sample, there are no late K–M stars with an Hα equivalent width higher than 15 Å which also have veiling less than about 0.4. This is consistent with the proposition that the Hα emission of classical TTS is directly related to the presence of an accretion disk (see Cabrit *et al.* 1990). The converse is not strictly true due to AA Tau, for which a large increase in the veiling is accompanied by a drop in Hα equivalent width. In this case, the high veiling is not accompanied by a stronger Hα flux either, as was the case for RW Aur and DR Tau. For AA Tau the line flux is the same for veilings of 0.15 and 1.6, while the veiling is the same for line fluxes of 13 and 25. The Hα line for this star is relatively weak (equivalent widths between 5 and 20 Å) and somewhat unusual in having an unshifted absorption component (occasionally accompanied by a slightly red-shifted one). This star has been seen with a large Balmer jump and is expected to have an accretion disk.

Our high-resolution spectra sometimes show two distinct components in the infrared Ca II lines: a narrow component with a total width of about 50 km s^{-1} and a broad, usually asymmetric component wider than 100 km s^{-1} (see Basri 1990). The narrow component is symmetric about zero stellar velocity suggesting a chromospheric origin. We selected TTS with late spectral types in which the broad component at λ8542 is absent or, if present, is easily removed from the whole profile by Gaussian fitting. The equivalent width of the narrow component is measured above the minima which define the line. As can be seen in Figure 7, support is found for both the proposition that the narrow components are stellar and that the veiling is nonstellar, since increasing veiling is related to decreasing narrow-line *equivalent width.* Note that by "stellar"

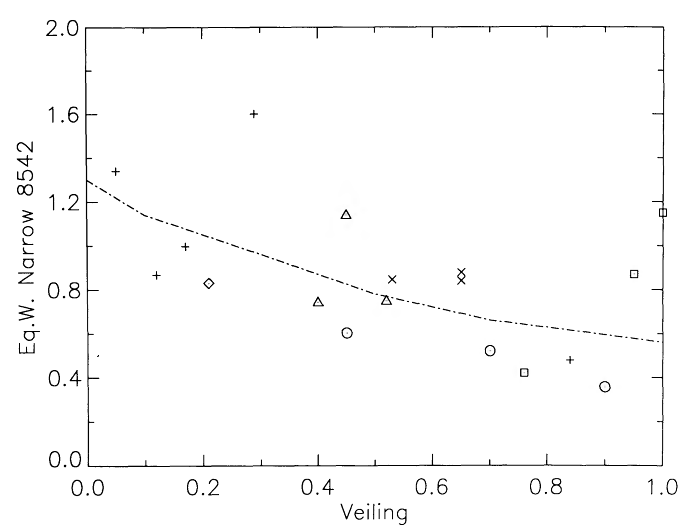

FIG. 7.—The relation between veiling and equivalent width for the "narrow" (see text) component of the Ca II infrared triplet line at λ8542. The equivalent width is measured from the minima surrounding the emission feature. The dashed line is the expected behavior of a fixed emission line with a veiling continuum added to it. The symbols are as in Fig. 5.

we really mean either on the stellar surface or in magnetic field lines attached to the surface.

The dotted line is Figure 7 is produced by constructing a hypothetical C II emission profile with a constant emission equivalent width of about 1 Å and then veiling it by the measured amount. The theoretical curve matches the observations fairly well even though scatter is to be expected since the Ca II lines are sensitive to the amount of chromospheric activity on each star. The approximate constancy of line strength may indicate chromospheric saturation. The relation found is not expected if veiling is derived from chromospheres, since increased chromospheric activity would strengthen both the equivalent width of Ca II lines and the optical continuum. This exercise also shows that after correcting the measured W_{8542} for veiling, the equivalent widths are all approximately 1 Å. This is more than is found in all but the most active late K and M main-sequence stars, which supports the idea that TTS are objects with very enhanced solar-type activity. It is possible, of course, that chromospheric loop footpoints are enhanced in part because accreted material is loaded into the loops.

c) Relation to Accretion Disks

The relation between the disk and boundary layer in the accretion disk hypothesis implies that near-infrared, ultraviolet, and optical continuum fluxes (i.e., veiling) are all dependent on the accretion rate. On the other hand, it is possible to have a near-infrared excess from passive disks (due to reprocessed stellar light), without the shorter wavelength excesses. Thus, the relation between veiling and near-infrared brightness is a direct test of the accretion hypothesis for veiling. Strom *et al.* (1989*a*) present a measure of near infrared excess $\Delta K \equiv \log F_{2.2\,\mu\text{m}}(\text{TTS})/F_{2.2\,\mu\text{m}}(\text{standard})$, by normalizing TTS and standard fluxes at R (0.65 μm). They assume a negligible veiling at R to calculate ΔK. As can be seen in Table 2 the amount of veiling at R cannot be disregarded for some stars, in which case the calculated ΔK is underestimated.

We recalculated the near infrared flux excess for our sample later than K5, correcting them for the veiling at R. For stars with multiple observations, the average veiling was used. The visual extinctions should also be corrected as HHKHS have already pointed out, but this must wait until detailed star-disk models including veiling are made. The stellar atmosphere is now assumed to be a blackbody curve lying at $F_{0.65\,\mu\text{m}}/(1+V)$, instead of normalized at $F_{0.65\,\mu\text{m}}$ (see their Figs. 1*a* and 1*b*). Note while that this procedure might seem to place V into both correlated quantities, it is actually just correcting the stellar R for veiling which is erroneously included in the original observations. This restores the correlation to the one which is really meant to be tested, namely between a naked star and the observed TTS systems. If V were not independently correlated with ΔK, our correction procedure could not produce a correlation by itself. For DL Tau and DR Tau we used the extinctions calculated by BB since Strom *et al.* (1989*a*) do not list extinctions for "continuum" TTS. Of course, it must be noted that the infrared and veiling observations do not refer to the same epoch, which should introduce scatter into the correlation.

Figure 8 shows that the expected trend for the accretion hypothesis is clearly seen in the subsample of late K–M TTS. This relation can also be found for earlier type objects even though the hot photospheres of TTS earlier than K5 have reduced contrast with the boundary layer emission. Low veiling for these stars therefore does not mean there is less accretion or no disk (as is the case in late-type weak TTS). In

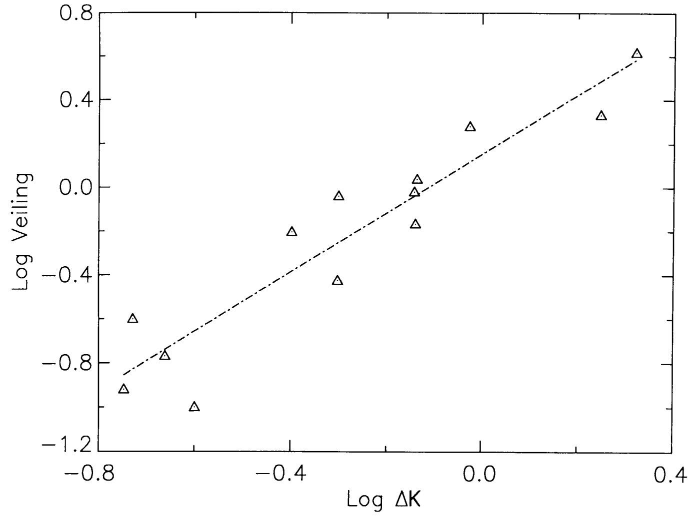

FIG. 8.—The relation between a measure of near-infrared excess (over the expected stellar photosphere) and veiling is shown. These are expected to be directly correlated in the accretion disk scenario, while they should be uncorrelated with a chromospheric hypothesis. The excesses have been corrected for veiling and extinction. Only the late-type TTS are shown. The broken line is a linear fit using the equation: $\log V = 1.35 \log(\Delta K) + 0.153$.

fact, the average veilings of RY Tau (K2) and T Tau (K0) are lower than 0.2 but their fluxes rise steeply in the infrared. The rapidity and strength of the veiling variations are also consistent with the accretion hypothesis, if nonsteady accretion is allowed.

Predicted spectral veilings from accretion disk models can be crudely checked against the measured values. The details of how the stellar flux decreases towards the blue compared with the much hotter boundary layer continuum determines the location of the blue rise and explains it. We found that generally the models derived without the constraint of veiling did not happen to yield the observed veiling (not to mention the problem that they typically refer to different epochs). We leave that question of a detailed match to a modeling paper and here only schematically show that the models are reasonable. We calculate a predicted veiling by comparing a blackbody at the photospheric temperature (4000 K) with a blackbody at the boundary layer temperatures given by BB (their Table 3A).

An example of such predicted veilings is shown in Figure 9 for BP Tau and GG Tau where the accretion luminosity ($L_{\text{acc}}/L_{\text{pho}}$) is, respectively, 0.794 and 0.936 of the stellar luminosity. Qualitative agreement is seen in the shape of the veiling, although some details are not matched in this simplistic approach. To produce a reliable disk model requires a concurrent measurement of both the veiling and the continuum distribution from the ultraviolet to the infrared (including the size of the Balmer jump), which is beyond the scope of this paper. BB give a detailed description of how the parameters of a disk model can be adjusted to make a match; the current results confirm that optical veilings are a powerful and necessary addition to the observational constraints.

IV. SUMMARY

We have analysed the continuum veiling over most of the optical range for a variety of TTS. We first considered carefully what kind of standard stars would provide the proper match and how to assess the spectral types of both standards and TTS. We propose a line-ratio method for spectral typing and

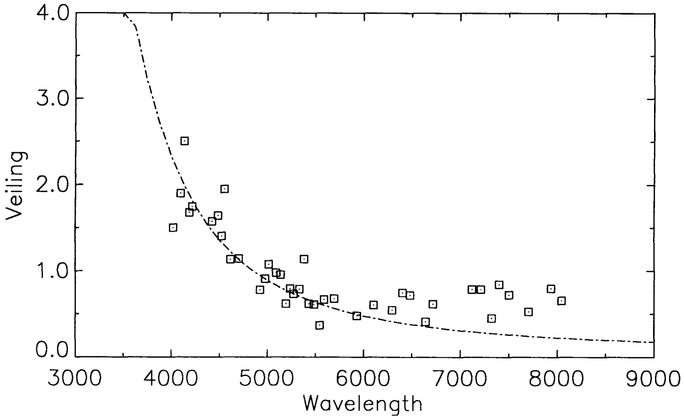

FIG. 9a

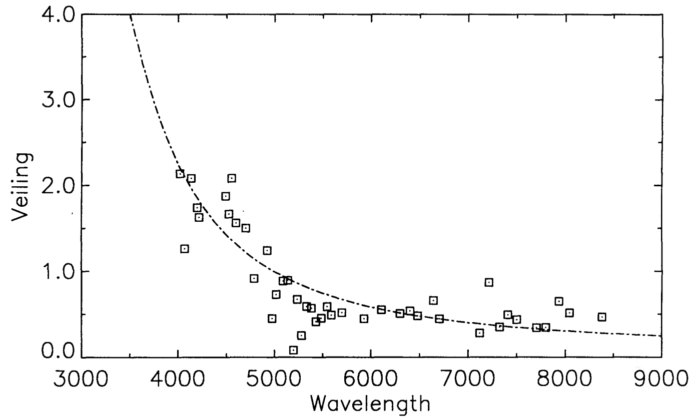

FIG. 9b

FIG. 9.—A schematic estimate of how veiling due to a boundary layer should vary is compared to the measured veiling in BP Tau (Fig. 9*a*) and GG Tau (Fig. 9*b*). The dashed line is the ratio of blackbodies at the photospheric and boundary layer temperatures (taken from Basri and Bertout 1989), assuming accretion luminosities (L_{acc}/L_{phot}) equal to 0.794 and 0.936, respectively. Detailed new models should be constructed with contemporaneous data (including veiling) to fully test this scenario.

show that it is both useful and sensitive to effective temperature. Despite the classification of TTS as luminosity class IV, we find that main-sequence stars make better standards. In order to use Hyades dwarfs (following HHKHS) we classify them with the line-ratio method. We then consider the problem of measuring veilings from data which is of less than ideal quality. We propose two methods: one an average line profile matching using autocorrelation functions and the other a detailed line depth matching using selected lines throughout the spectrum. The second method is much more laborious to implement but able to handle more difficult cases. The first method works well shortward of 6000 Å. Finally we check the rotational velocities and spectral types of our TTS and apply the veiling analysis with appropriate (artificially spun-up) standards.

A nonstellar origin for the continuum emission is clearly supported by the results presented in the previous section. In fact, the general shape of the veiling spectra—i.e., flat at longer wavelengths and increasing values at blueward wavelengths—matches predictions from accretion disk models (though any hot continuum will suffice). In these models, half the accretion power is radiated away by the disk in the infrared, and the other half is dissipated in a small hot boundary layer between disk and star. The boundary layer temperature is always predicted to be higher than the photospheric effective temperature, and this is apparently the case. A blue rise in veiling results from the dropping cool photospheric flux and rising continuum, given that the typical photosphere is about half the temperature of the boundary layer. One expects (and sees) that this effect is less dramatic when the veiling continuum is either very small or very large compared to the photosphere. The veilings derived here (and by others) should serve as a powerful additional constraint on new disk models for the TTS.

The veiling and emission lines are seen to be rather variable, sometimes on very short time scales, again suggesting they arise from (unsteady) accretion power near to the star (and this is no doubt the underlying reason that most TTS have variable star designations). We have examined the relation between the veiling and permitted line emission. There is evidence that Hα emission derives its power from the same source as the veiling, while the narrow symmetric component of the Ca II triplet lines may be more closely related to stellar phenomena. We find rather little relation between Hα equivalent width and veiling, but much stronger evidence that Hα flux is correlated with veiling. The near-infrared excess is also correlated with veiling, providing a crucial confirmation of the accretion disk hypothesis.

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