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SPECTRAL ENERGY DISTRIBUTIONS OF YOUNG STELLAR OBJECTS.
I. A TURBOSPHERIC MODEL FOR DR TAURI

ROGER K. ULRICH[1], ALLEN W. SHAFTER, AND GEORGE HAWKINS
Department of Astronomy, University of California, Los Angeles
AND
GILLIAN KNAPP[1]
Department of Astrophysics, Princeton University
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ABSTRACT

We present measurements of the spectral energy distribution of the active T Tauri star DR Tau which can be matched in detail by a model with a reddened optically thin hydrogen plasma at 65,000 K. We propose that the temperature of 65,000 K is a result of equipartition between the particle kinetic energy density of the plasma and the kinetic energy density of strong turbulence. We term this chromosphere-like layer a turbosphere. We suggest that the turbulence is driven by the accretion of cometary clumps at a rate of $5 \times 10^{-7}\ M_\odot\ \mathrm{yr}^{-1}$. The model yields the following overall parameters for DR Tau: $M = 1\ M_\odot$, $R = 3\ R_\odot$, $L = 6\ L_\odot$. The turbosphere is described by: $T = 65{,}000$ K, $N_e = 5 \times 10^{12}\ \mathrm{cm}^{-2}$, and Δr (the turbospheric layer thickness) = 4×10^9 cm.

Subject headings: spectrophotometry — stars: chromospheres — stars: individual — stars: mass loss — stars: pre-main-sequence

I. INTRODUCTION

DR Tau is an active T Tauri star which has shown the inverse P Cygni line profiles of the upper Balmer lines characteristic of YY Orionis stars (Bertout *et al.* 1977; Appenzeller *et al.* 1980*b*; Krautter and Bastian 1980). These profiles indicate the presence of mass inflow. On one plate Krautter and Bastian (1980) found both red displaced absorption for the upper Balmer lines and blue displaced absorption for Hγ. Ulrich and Knapp (1982) found that Hβ and Hα showed blue displaced absorption. The Hβ profile was particularly interesting because it showed two distinct minima indicating the presence of two distinct outgoing clouds. Photometric and spectroscopic variations on time scales as short as days have been observed by Bertout *et al.* (1977), Appenzeller *et al.* (1980*b*) and Krautter and Bastian (1980). These results have been recognized by the above authors as qualitatively compatible with a highly turbulent process driven ultimately by the accretion of matter from the primordial cloud. The kinetic energy from accretion provides a natural and attractive source of power for the nonphotospheric radiation.

In a laminar accretion shock, very high temperatures and X-rays are produced (Ulrich 1976; Bertout 1979). A major fraction of the non-thermal accretion luminosity should be produced as X-rays. In fact, the X-ray luminosity of T Tauri stars is only in the range 10^{30}–10^{31} ergs s^{-1} (Feigelson and DeCampli 1981; Gahm 1980; Walter and Kuhi 1981), for those stars which have been detected and less for others. Since the nonthermal luminosity is comparable to the stellar luminosity as indicated by the blue and ultraviolet continuum radiation, we should see X-ray luminosities closer to 10^{33} ergs s^{-1}. However, as discussed by Mundt (1981), the absorption of the X-rays by the infalling matter makes their detectability uncertain and the severity of the conflict less obvious. The *IUE* observations as summarized by Giampapa *et al.* (1981) are more indicative of a chromosphere-like layer than an accretion shock.

In this paper we present a model for DR Tau which we believe combines the best features of the chromospheric and accretion shock models. In particular, we present here observations of the spectral energy distribution of the T Tauri star DR Tau which cover the range 3200 Å to 1.1 μm. We suggest that this energy can be produced by an optically thin hydrogen plasma at a temperature of 65,000 K. The energetics of this star including the luminosity, emission measure, Balmer line strengths, and the detailed continuum spectral energy distribution are well described by a model invoking a turbulence-dominated chromosphere-like layer. We refer to this emission layer as a turbosphere.

II. OBSERVATIONS

The observations were made over the span of 6 days on three different telescopes (Table 1 gives a journal of the observations). The blue spectra were obtained with the EMI-Reticon scanner on the Palomar 5 m Cassegrain spectrograph. The detector is similar to the system described by Schectman and Hiltner (1976). This system gives a resolution of 2 Å and a wavelength

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[1] Guest Investigators, Palomar Observatory.

TABLE 1

JOURNAL OF OBSERVATIONS

Telescope	Time of Observation (JD) 244+	Spectral Coverage (Å)	$\Delta\lambda$ FWHM (Å)	Slit Size (arcsec)	Integ. Time (minutes)
Palomar 5 m..................	4921.03	3200–5450	2.2	0.52	30
	4921.03	3200–5450	6	3.6	10
Lick Observatory 3 m........	4927.01	7930–10,950	35	0.76	30
Mount Lemmon 1.5 m	4926.93	3800–6800	13	6.5	16
	4926.92	6000–8500	13	6.5	16

coverage of 2800 Å. The resolution and sensitivity are degraded slightly near the ends of the wavelength band. With this in mind, we centered the spectrum at 4100 Å so that the Balmer jump was within the central 50% of the covered region. This choice resulted in our sacrificing about 300 Å of spectral coverage. Although the performance falloff near the edges of the spectral range is much less with this system than with the Varo-Reticon scanners, we felt that the primary goal of measuring the Balmer jump justified this sacrifice.

We made two separate exposures—the primary one through a 0".57 slit to achieve the highest possible spectral resolution, and a shorter exposure through a 3".6 hole to minimize the loss of ultraviolet light due to atmospheric refraction. These spectra were reduced against the standard star Feige 110 for which Stone (1977) has published fluxes. Neutral density filters were used in the observations of Feige 110 and DR Tau through the 3".6 aperture. These filters were measured at UCLA with a monochromator, and the spectra were corrected for the filter transmission functions. The high signal-to-noise spectrum obtained with the 30 minute exposure through the narrow slit was corrected for ultraviolet losses to give the same spectral energy distribution as that observed with the large aperture. The Mount Lemmon observations were made with the Robinson and Wampler (1972) Image Dissector Scanner. Again, Stone standard stars were used to obtain fluxes. The observations were made through a relatively large 6".5 aperture to assure accurate fluxes. Finally, the near-IR data were obtained with the UCLA bare Reticon spectrometer described by Wood (1979, 1982) and Ulrich and Wood (1981). Flux calibration was made using observations of η Hyd and ϵ Ori made 2 hours after the observation of DR Tau. These two stars bracketed the air mass of DR Tau, and the water vapor correction was found by interpolating between their flux calibrations. Fluxes published by Cochran (1981) were used for $\lambda < 10100$ Å and Hayes (1970) fluxes were used for $10100 < \lambda < 10950$ Å. Cochran (1981) gives fluxes every 20 Å except near the Paschen lines. Thus the water vapor correction could be made at a resolution comparable to the observed resolution. One H_2O feature at 8980 Å was too close to Pa9 to be completely corrected and appears in the reduced spectrum as a spurious absorption.

The individual sections of the spectral energy distribution were joined together with a splicing algorithm which ensures continuity in the value of λF_λ. As indicated in Table 1, the spectral coverages of the observations overlapped so that we could interpolate between and compare the fluxes in a substantial wavelength range. The final level of the flux is a weighted average of the overlapping measurements. The weighting function was chosen to favor the higher resolution data in all overlap regions. The absolute flux levels of the Palomar 5 m blue and the Lick Observatory 3 m near -IR data were adjusted by a scale factor so that they match the larger aperture Mount Lemmon data in the overlap region. For the Palomar 5 m data which were obtained six nights earlier, some of the gray shift could have been due to stellar variations. However, we cannot confirm this possibility because thin cirrus was present during the Palomar observations. In any case, we note that the slope of F_λ versus λ in the overlap region agrees to within 3% except for the longest 100 Å of the Palomar data where edge of the scan effects becomes important. We estimate the absolute flux of the Mount Lemmon observations (and hence of our combined energy distribution) to be accurate to 10%. The residual level of uncertainty is due to phosphor afterglow in the image tube chain which prevents the Image Dissector Scanner from being a photon counting instrument.

III. THE SPECTRAL ENERGY DISTRIBUTION

Our principal result is shown in Figure 1 which gives log λF_λ versus log λ. The uniformity of slope, even across the Balmer jump, is noteworthy. The spectral energy distribution in this wavelength band is also remarkable for the absence of absorption features. Since our spectral resolution is 2 Å in the blue, even relatively weak atomic features should be apparent. The format of Figure 1 is mismatched to the data since in fact the complete numerical data set contains 1000 resolution elements in the left half of the plot and the plotter resolution is inadequate for display of these many points. Consequently, in Figure 2 we show the Balmer data in an F_λ versus λ format. This format of display shows clearly that the enhanced flux level between λ3800 and λ4600 is due to a large number of emission lines. Many of these have been identified by Bertout *et al.* (1977) as due to singly ionized species in the iron group and these identifications are shown in Figure 2. The absence of any absorption features including red- or blueshifted absorption components of the Balmer lines is also evident. Line profiles like those reported for

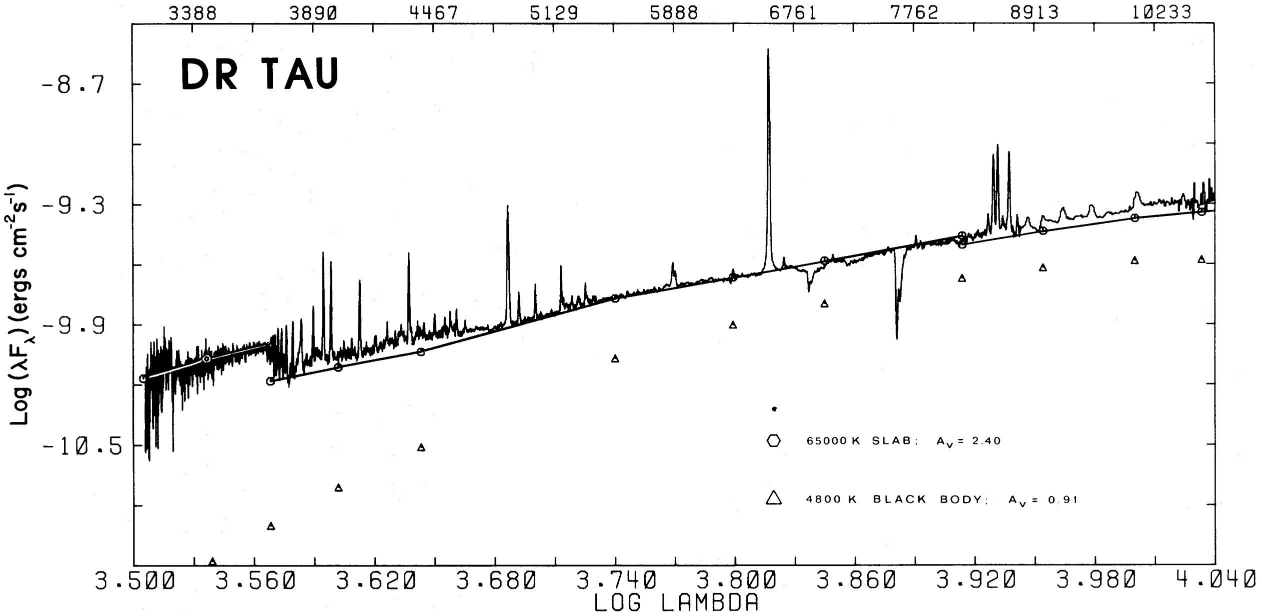

FIG. 1.—The combined spectral energy distribution for DR Tau compared to two models: the optically thin hydrogen plasma at 65,000 K with $A_v = 2.40$ and a 4800 K blackbody with $A_v = 0.91$. Both models were adjusted to fit the observed continuum slope near 7000 Å.

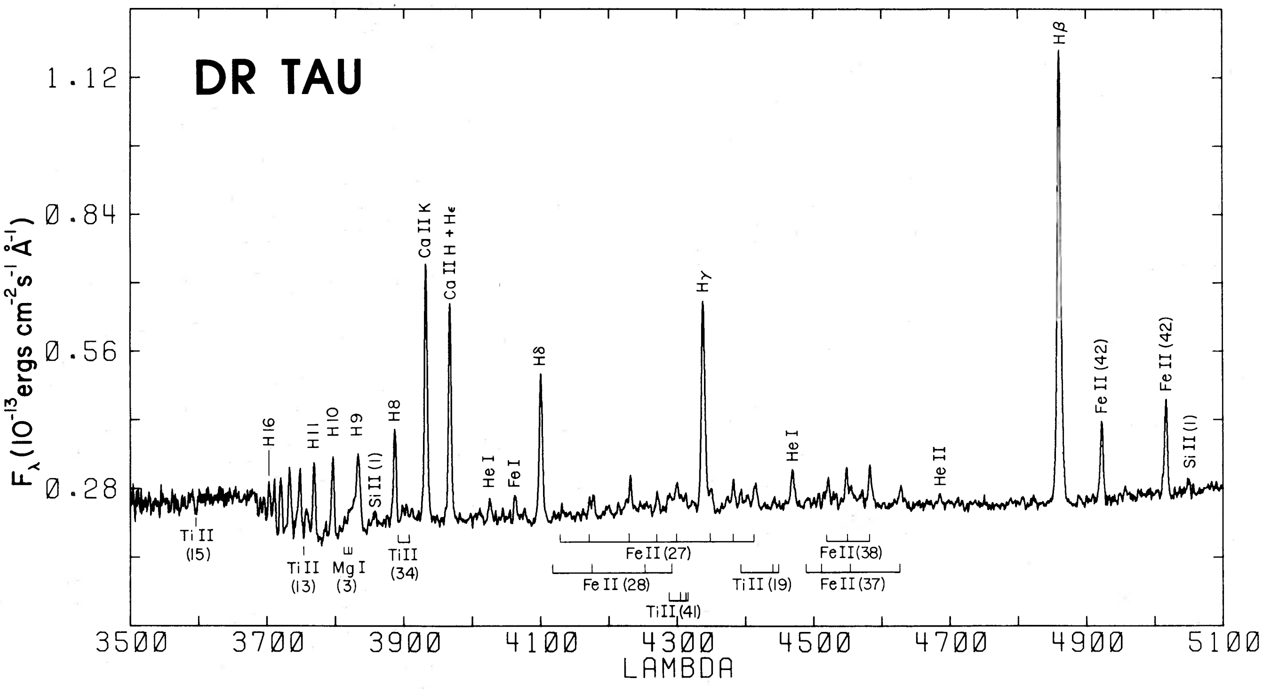

FIG. 2.—The blue spectral energy distribution shown with resolution appropriate for the data. Metallic lines due to Fe II, Ti II, Si II, and Mg I are identified following Bertout *et al.* 1977.

DR Tau by Appenzeller *et al.* (1980*b*) and Krautter and Bastian (1980) were detected with the Palomar system for other objects, although narrow absorption components would have been missed (any feature broader than about 0.75 Å would have produced a detectable asymmetry in Hβ). We conclude that no major H absorbing clouds were in the line of sight to DR Tau at the time of our observations. We further conclude that no significant portion of the observed flux was contributed by a stellar photosphere with absorption lines.

The spectral energy distribution observed for DR Tau shows a Balmer jump in emission. It occurs at a wavelength about 50 Å redward of the vacuum position of 3646 Å. The value of the jump is about $F_\lambda(3700^+)/F_\lambda(3700^-) = 1.6$ with an uncertainty of 10% due to the extrapolation of the Paschen continuum to 3700 Å. A Balmer jump in emission indicates the presence of optically thin ionized hydrogen plasma. If the plasma has a typical temperature of 15,000–20,000 K, recombination theory as presented by Seaton (1960) requires the Balmer jump to be 4.5–7 instead of the observed 1.6. The Balmer jump can be reduced to this value in three possible ways: (1) The plasma temperature is 55,000–68,000 K; (2) The Balmer continuum is optically thick; or (3) Most of the radiation longward of 3700 Å is emitted by an optically thick region such as a stellar photosphere.

Possibility (2) is unlikely because of the similarity in slope of the Balmer and Paschen continua. If the Balmer continuum is optically thick and the Paschen continuum is optically thin, we would expect the former to be close to $B_\nu(T)$, while the latter should be close to $F_\nu = \text{constant}$. At $T = 20{,}000$ K, 3700 Å is longward of the peak of B_ν and the two slopes should be different.

Possibility (3) is not likely because of the absence of absorption lines. Specifically, the absence of the TiO bands, the G band, the Mg I lines near 5100 Å, the absence of Ca II H and K absorption wings, the absence of absorption due to high multiplets of Fe I and Fe II, and the absence of Stark absorption wings to the Balmer lines rules out the possibility of a photosphere-like emission layer under normal stellar conditions. Some of these absorption features were detected in other objects using the same observing system, even though these other objects also have strong metallic emission lines. However, an F star with the strong absorption lines filled in with the overlying emission is marginally possible. The flatness of the observed spectrum also presents a problem in adopting hypothesis (3). If the reddening is adjusted so that a cool blackbody fits the slope in the red part of the spectrum, then the blue flux drops off too quickly. A typical attempted flux is shown with the triangles in Figure 1. The points are displaced below the curve for the star for clarity. The best fit radius for this temperature and extinction is 1.6 $R_\odot$. Unless such a photospheric spectrum were to dominate by a substantial factor in the 5000–6000 Å range, it could not contribute enough radiation in the blue to modify the Balmer jump.

Possibility (1) is an attractive hypothesis since it is not contradicted by the observed spectral energy distribution. The red color requires the presence of interstellar or circumstellar extinction. A fit to the spectral energy distribution for an optically thin hydrogen plasma at $T = 65{,}000$ K is shown in Figure 1. The emissivity of the plasma was calculated with formulae given by Seaton (1960). The Gaunt factors were included explicitly, and recombination to levels up to $n = 20$ were summed individually. The remaining terms were treated as an integral. The required A_V using the Savage and Mathis (1979) extinction curve is 2.40. The plausibility of our value of A_V is supported by similar values of A_V for several other stars in the Taurus region found by Cohen and Kuhi (1979). Considering that only three parameters were used in obtaining the fit (T plasma, A_V, and λF_λ at $\lambda = 5500$ Å), the agreement is remarkable. The required value of A_V predicts a substantial dip in F_λ at $\lambda = 2200$ Å. Such a dip was not observed by Appenzeller *et al.* (1980*a*). Their spectrogram indicates F_λ ($\lambda = 3200$), which is a factor of 4 larger than we observed. It is thus possible that there was less circumstellar extinction at the time of their observation. Circumstellar shells are also known not to produce diffuse interstellar absorption (Snow 1973). The excellence of the fit shown in Figure 1 indicates that the model deserves consideration in spite of the possible difficulty with the ultraviolet fluxes.

As an additional test of the continuum flux model, we compare the infrared colors predicted from the 65,000 K, optically thin plasma with $A_V = 2.40$ to the observed colors reported by Cohen (1974). Table 2 shows this comparison. The zero points of the observed magnitude scale were taken from Low and Rieke (1974). The agreement is surprisingly good, although the variability of DR Tau makes it difficult to draw any conclusions from this comparison.

The strengths of the Balmer lines provide an additional constraint on the physical condition in the emitting layer. Because the red spectral regions were measured 6 days after the blue measurements, we did not attempt to model the Hα flux. Table 3 gives the observed line strengths and three fits to these strengths using the theory described by Drake and Ulrich (1980). The observed fluxes are dereddened with $A_V = 2.40$. We show the strength ratios using two different definitions. The first observed column shows the ratios of the integral line flux while the second shows the ratios of the peak line intensities. For both definitions a smooth continuum flux is subtracted from the observed flux to obtain the flux due to line emission alone. The theoretical models involve four parameters: T_e, $\tau_{\mathrm{Ly}\alpha}$, R_{1C}, and N_e, where

TABLE 2

INFRARED COLORS

λ (μm)	Calculated	Observed (Cohen 1974)
[2.2[–[3.5]	1.24	1.30
[2.2]–[10]	3.91	3.95

$\tau_{\mathrm{Ly}\alpha}$ is the optical depth of the slab at Lyα, R_{1C} is the radiative ionization rate, and N_e is the electron density. The continuum fit provides a constraint on T_e and for $T_e = 65{,}000$ K, the collisional ionization rate dominates over R_{1C}. We thus have just two parameters—$\tau_{\mathrm{Ly}\alpha}$ and N_e—to fit the three observed line ratios: Hλ/Hβ, Hδ/Hβ, and H8/Hβ. Although there is some compensation possible between the effects of $\tau_{\mathrm{Ly}\alpha}$ and N_e, the range of these parameters over which a satisfactory fit is possible is restricted. The three models shown in Table 3 represent the best fits we were able to find, and the sense of the change going from $\tau_{\mathrm{Ly}\alpha} = 1250$–$2000$ persists to values outside this range. We always pick the value of N_e which gives Hδ/Hβ equal to 0.57 and find that for smaller $\tau_{\mathrm{Ly}\alpha}$, Hγ/Hβ is too large and H8/Hβ is too small, while for larger $\tau_{\mathrm{Ly}\alpha}$, H8/Hβ is too large and Hγ/Hβ is too small. This calculation gives us $N_e = (4\text{–}6) \times 10^{12}$ cm^{-2} and a slab thickness Δr equal to 7×10^8 (v_{dopp}/25 km s^{-1}) with an uncertainty of a factor of 2 due to the range of acceptable combinations of $\tau_{\mathrm{Ly}\alpha}$ and N_e. Additional uncertainties in the model such as the assumption of uniform temperature increase the possible range of slab thickness. Nontheless, a slab of thickness greater than 10^{10} cm or less than 10^8 cm is excluded by these models. We also find the Paschen continuum optical depth to be in the range 10^{-4} to 10^{-3}, indicating that our assumption of an optically thin slab is valid.

The unreddened emission measure required to fit the continuum shown in Figure 1 is $N_e^2 V = 2.4 \times 10^{58}$ cm^{-3} for a distance of DR Tau of 160 pc (Cohen and Kuhi 1979). Using an electron density of 5×10^{12} cm^{-3} as indicated by the slab models, we find an emitting volume of 9.6×10^{32} cm^3. Since the slab must be smaller than stellar dimensions we find for a stellar radius R, the slab thickness Δr is constrained by

$$2\pi R^2 \Delta r = 0.6 \times 10^{32}\ \mathrm{cm}^{-3}\ . \tag{1}$$

We could use Δr from the model above and calculate R, but in view of the large uncertainty in Δr we prefer to leave the constraint in the form of equation (1). We note, however, that R of a few $R_\odot$ will be consistent with the models.

IV. THE TURBOSPHERE MODEL

The model presented in the preceding section is reasonably successful in accounting for the observed properties of DR Tau. However, it is physically incomplete in that it requires optically thin gas to have a temperature of 65,000 K. Chromospheric regions are normally characterized by a temperature in the range of 10,000–20,000 K. The higher value of 65,000 K tends to be unstable because of intense radiative cooling through hydrogen emission—the conditions we have suggested imply a cooling time of order 1 s. Since we directly observe this emission, there is no reason *a priori* that we should reject this temperature. The model does require a source of energy to maintain these losses, and the identification of the energy source is our major objective in this section. The total dereddened flux due to the slab corresponds to a luminosity of about 6 $L_\odot$ (assuming the Lyman continuum radiation is trapped and does not constitute an additional energy loss). Since the slab is optically thin, this luminosity must be produced or deposited nonthermally.

Possible sources of energy for the slab are continuing accretion or relaxation of the internal state of the star. The latter might include an unstable rotation law, a stressed magnetic field, or some other chaotic initial state. We tend to favor accretion because the energy loss rate is so high and occurs at a low optical depth. Dissipation of some internal source would require the energy to be transported across a region of moderate optical depth with little dissipation and then dissipated at a very rapid rate at a low optical depth. In the case of the solar chromosphere, the optical depth of dissipation is similar, but the temperature of 20,000 K implies a much lower rate of energy loss. While a transport process with the required characteristics cannot be ruled out, we feel that the low optical depth of dissipation in our model suggests the action of an external energy source such as accretion.

Dissipation of strong turbulence through many weak shocks is an attractive source of energy. Equipartition between the turbulent kinetic energy density and the thermal kinetic energy density of the gas is a likely outcome of such strong turbulence. The equipartition assumption leads to

$$\tfrac{1}{2}kT = \tfrac{1}{2}\mu m_{\mathrm{H}} v_{\mathrm{turb}}^2\ . \tag{2}$$

We term a shell governed by equation (2) a turbosphere. For $\mu = 0.65$ and $T = 65{,}000$ K, equation (2) requires $v_{\mathrm{turb}} = 30$ km s^{-1}.

We propose that the turbulence is driven by inhomo-

TABLE 3

LINE STRENGTH MODELS, $T_e = 65{,}000$ K

PARAMETER	$\tau_{\mathrm{Ly}\alpha}$			OBSERVED	
	1000	1250	2000		
N_e (cm^{-3})	6.4×10^{12}	5.4×10^{12}	4.1×10^{12}	Integrated Flux	Peak Flux
Δr (cm)	4.4×10^8	6.8×10^8	1.6×10^9		
Hγ/Hβ	0.731	0.719	0.696	0.784	0.730
Hδ/Hβ	0.570	0.570	0.570	0.564	0.585
Hδ/Hβ	0.337	0.355	0.393	0.368	0.422

1983ApJ...267..199U

geneities in an accretion flow. The energy for the slab can then be derived from the kinetic energy of the accretion flow

$$L_{\rm acc} = \tfrac{1}{2}\dot{M}v_{\rm ff}^{2}\ . \tag{3}$$

Quantitative use of equation (3) requires that we know $v_{\rm ff}$. Appenzeller *et al.* (1980*b*) and Krautter and Bastian (1980) show line profiles with redshifted absorption components of up to 418 km s^{-1} and 370 km s^{-1}, respectively. Assuming the matter responsible for these absorption components has acquired its velocity as a result of gravitational forces, we can take $v_{\rm ff} \approx 400$ km s^{-1}. Equation (3) then yields:

$$M = 2.9 \times 10^{19}\ {\rm g\ s^{-1}} = 4.5 \times 10^{-7}\ M_{\odot}\ {\rm yr^{-1}}\ . \tag{4}$$

The second figure is not significant but is carried in order to maintain consistency. An accretion rate of this magnitude is conceivable but, as we see below, must be substantially clumpy in order to remain compatible with the observed reddening. However, first we need to estimate the stellar radius before we can discuss the reddening problem quantitatively.

We can obtain an estimate of the stellar radius by identifying Δr in equation (1) as the pressure scale height H (which is also equal to the density scale height for an isothermal slab). Recognizing that turbulent pressure and gas pressure are comparable, we have

$$H = \frac{P_{\rm turb} + P_{\rm gas}}{\rho g} \tag{5}$$

with

$$P_{\rm turb} = \rho v_{\rm turb}^{2} \tag{6}$$

and

$$P_{\rm gas} = \frac{\rho k T}{\mu m_{\rm H}}\ . \tag{7}$$

A convenient parameter is the ratio of turbulent velocity to free fall velocity

$$\beta = v_{\rm turb}/v_{\rm ff}\ . \tag{8}$$

Since $v_{\rm ff} = (2gR)^{1/2}$ we can use equation (2) to write equation (5) as

$$H = 4\beta^{2}R\ , \tag{9}$$

where R is the stellar radius. The values of $v_{\rm turb} = 30$ km s^{-1} and $v_{\rm ff} = 400$ km s^{-1} give

$$H = 2.3 \times 10^{-2}R\ . \tag{10}$$

The volume constraint in equation (1) then allows us to calculate R by setting $H = \Delta r$:

$$R = 1.9 \times 10^{11}\ {\rm cm} = 2.7\ R_{\odot}\ . \tag{11}$$

We can then find

$$\Delta r = 4.4 \times 10^{9}\ {\rm cm}\ , \tag{12}$$

and using the value of $v_{\rm ff}$, we find the mass M to be:

$$M = 1.1\ M_{\odot}\ . \tag{13}$$

We believe equation (12) is more likely to be correct than the direct estimates in Table 3. Note that the values in Table 3 must be multiplied by a factor of about 2 since they represent the slab thickness in the case that thermal Doppler broadening is the only source of Gaussian width. The rough agreement between the adjusted values of Δr in Table 3 and the value in equation (12) is an indication that the model is internally consistent, since up to this point we did not use the constraint arising out of the determination of $\tau_{\rm Ly\alpha}$.

We are now able to calculate the extinction which would result if the accretion flow is smooth and contains a normal gas-to-dust ratio. Ignoring possible asymmetries due to a magnetic field or rotation, a free-fall accretion flow has a column depth $n_{\rm H}$

$$n_{\rm H} = \frac{\dot{M}}{2\pi\mu m_{\rm H} R v_{\rm ff}} \tag{14}$$

which for values of $\dot{M}$, R, and $v_{\rm ff}$ determined above yields

$$n_{\rm H} = 5.2 \times 10^{23}\ {\rm atoms\ cm^{-2}}\ . \tag{15}$$

The standard interstellar mix of gas to dust gives $n_{\rm H}/E(B-V) = 5.8 \times 10^{21}$ atoms cm^{-2} mag^{-1}. Thus, for a smooth flow we should expect to have $E(B-V) = 90$, a clearly unacceptable result. Stabler, Shu, and Taam (1981) have discussed the decrease in extinction expected because of grain evaporation. While their mechanism can help alleviate the problem, they assumed the grain and gas temperatures to be equal and treated the case $\dot{M} = 10^{-5}\ M_{\odot}$ yr^{-1}. It is not clear such an assumption is valid at the low density appropriate to our required $\dot{M}$. Alternatively, we note that severe clumpiness is indicated by the presence of erratic variations in brightness and by the requirement of strong turbulence for our model. If most of the mass is accreted in clumps 90 times denser than average, the extinction due to the lower density gas will not be in conflict with observation. However, even a factor of 90 reduction in density between the clumps does not permit the Lyman continuum flux to penetrate far into the accretion flow. Our assumption at the beginning of this section that the Lyman photons do not constitute a loss to the turbosphere is therefore justified, although recombination in the precursor region of the accretion flow could add to the strength of Hα.

V. DISCUSSION

The irregular variations in absorption components to the line profiles have presented a problem in understanding the nature of the activity in DR Tau. The presence of matter both infalling and outgoing is indicated by the line profiles. In our model, the bulk of the matter is infalling, but in very dense clumps. Because the clumps are much smaller than the stellar disk, they would not produce an absorption component unless their outer portions were evaporated off much in the manner of comets. Presumably, only exceptionally massive clumps could obscure enough of the stellar disk to produce absorption lines. The bulk of the accretion flow can be unrelated to the redshifted absorption components as long as the clump size distribution is dominated at the small end. The outgoing matter observed as blueshifted absorption can then be similar to the solar wind with the strength of the wind depending on the strength of the turbosphere. It is conceptually attractive to postulate that the T Tauri phase of evolution as represented by DR Tau is the era of final accretion where cometary lumps from the protostellar cloud fall into the star. This era could also be related to an early period of cratering in the solar system.

The idea that the envelope surrounding T Tauri stars is clumpy is not new. Walker (1972) mentioned clumpiness as a natural explanation for the variations he observed in the star YY Ori. Wolf, Appenzeller, and Bertout (1977) and Mundt (1979) extended these ideas to S CrA and discussed the possibility that radiation pressure is the cause for the clumpiness. Chevalier (1983) has discussed the behavior of clumps in an accretion wind environment with emphasis on the implication for variability. Gahm *et al.* (1974) proposed variable obscuration due to clumps in Keplerian orbits as the cause for the variability of RU Lup. In a somewhat different context, Kuan (1976) proposed clumpiness as the cause for the small line-to-continuum ratio in the T Tauri wind. His argument is less compelling because there is a variety of other models (such as the one discussed in the preceding section) which can produce a reduced line-to-continuum ratio. We believe that our concept of the evaporation of cometary clumps as the source of the redshifted absorption components is new. As Chevalier (1983) points out, the clumpy flow concept has the advantage of reconciling the conflicting evidence about the direction of gas flow since a cometary nucleus with a density of 1 g cm^{-3} would not be impeded by an outflowing wind. Our discussion of the reddening does not require the density to be as high as 1 g cm^{-3}, but such a density is compatible with our model. As the core evaporates when the cometary nucleus approaches the stellar surface, the envelope will begin to interact with the wind and be driven to a lower infall velocity. Thus, a spread in velocity of the redshifted absorption components is to be expected. The line profiles of the Na D lines seem to show a wide velocity range for other stars (Ulrich and Knapp 1979, MM Mon; Ulrich 1978, AS 205), while the evidence is less clear for the upper Balmer lines of DR Tau (Appenzeller *et al.* 1980*b*).

The implications of clumpiness for the accretion shock have not previously been discussed. Although the high temperature just behind the shock may still exist, the surface of the shock in a clumpy accretion flow will be so distorted that high density matter will undoubtedly be exterior to the shock and prevent the formation of a radiative precursor. The outcome we propose is that the turbospheric layer is formed instead and that the kinetic energy dissipation occurs in this thick layer rather than in a thin transition which obeys the Rankin–Hugoniot jump conditions. Clearly, our assumption of a turbosphere would not be compelled by a theoretical argument, but the observational evidence favoring a temperature of 65,000 K is moderately strong. This temperature has not been previously suggested for T Tauri stars, although Rydgren, Strom, and Strom (1976) proposed an optically thin 20,000 K envelope as a contributor to the spectral energy distribution, and a temperature of 10^6 K has been proposed as a consequence of an accretion shock by Ulrich (1976) and Bertout (1979). The turbosphere assumption is a natural way to explain our proposed temperature.

The geometric effects discussed by Ulrich (1976) as a possible explanation for the T Tauri line profiles probably do not play a role in the turbosphere. The laminar layer below the accretion shock was critical to producing the velocity shifts required to match the line profiles. Such a laminar layer cannot exist in the presence of strongly clumped accretion. Some line profiles such as the Hα profile of MM Mon shown by Ulrich and Knapp (1979) will continue to be difficult to explain and may require some special geometry involving rotation or magnetic fields.

The possibility that the T Tauri phenomenon is related to the formation of the Oort (1950) cometary cloud deserves further study. Donn and Rahe (1982) give masses of cometary nuclei as falling in the range 10^{13}–10^{21} g. Thus, our accretion rate given in § IV corresponds roughly to one cometary nucleus every 100 s even for the largest mass. While this seems a bit extreme, especially since Weissman (1982) estimates the total number of cometary nuclei in the Oort cloud to be 10^{12}, we do not have much direct information about this stage of evolution. Hills (1982) has shown how radiation pressure can cause clumping in the outer part of the protosolar nebula. Also, present cometary masses may be lower than is appropriate since the cometary masses at this early stage of evolution may contain a large quantity of H_2 condensed out at an even earlier stage and not yet evaporated. DR Tau is one of the more active T Tauri stars and possibly represents an extreme case. Some of the sophisticated theories of cometary structure developed on the basis of extensive observational data could be applied to the structure and evolution of the postulated clumps as they approach the surface of the star to determine if the redshifted absorption components can be attributed to cometary evaporation as we have suggested. However, the possibility of a large H_2 content as well as the major differences between the solar environment and the circumstellar environment make an immediate application of these comet models inappropriate. Specifically, the wind is likely to be cooler and up to 10^5 times denser in the T Tauri case, and the radiation reaching the clump is not going to include the Lyman continuum radiation but may be more intense in the X-ray range.

As a final aspect of the turbosphere model, we comment briefly on the nature of the irregular light variations. Both variable obscuration and variable turbospheric temperature are possible in this model. We would expect the level of turbulence to be increased following the accretion of an unusually large lump, and the temperature would rise according to equation (2). Thus, we predict that the color and brightness variations should be describable by two parameters—reddening and turbosphere temperature. The first should show up primarily as Paschen continuum slope changes, and the second, primarily as Balmer jump changes. Unfortunately, a test of such a two-parameter model requires more spectral resolution than is provided by existing *UBV* photometry because of the effects of emission lines.

VI. CONCLUSIONS

We have shown that the spectral energy distribution of DR Tau is well represented by an optically thin layer of plasma at a temperature of 65,000 K with a reddening of $E(B-V) = 0.77$. The absence of a 2200 Å feature in the ultraviolet observations of Appenzeller *et al.* (1980*a*) represents the only failure of the model, and this failure could be a result of variability or a peculiarity in the dust near DR Tau. We show that a turbulence-dominated, chromosphere-like layer termed a turbosphere can account for the physical conditions required for the model of the spectral energy distribution. Based on this model we derive the following quantities of interest: $L = 6\, L_\odot$, $M = 1\, M_\odot$, $R = 3\, R_\odot$, $v_{\rm turb} = 30\,{\rm km\,s^{-1}}$, $N_e = 5 \times 10^{12}\,{\rm cm^{-3}}$, $\dot{M} = +5 \times 10^{-7}\, M_\odot\,{\rm yr^{-1}}$, and Δr (the emitting layer thickness) $= 4 \times 10^9$ cm. In order to avoid excessive reddening we postulate that the accretion occurs as lumps of order 30 or more times denser than average. These are likened to cometry masses. The T Tauri phase of evolution may be a result of a process similar to the cratering process in the solar system.

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G. Hawkins, A. K. Shafter, and R. K. Ulrich: Department of Astronomy, University of California, Los Angeles, CA 90024

G. Knapp: Department of Astrophysical Science, Princeton University, Princeton, NJ 08544