THE CLASSICAL T TAURI SPECTROSCOPIC BINARY DQ TAU. II. EMISSION LINE VARIATIONS WITH ORBITAL PHASE

GIBOR BASRI
Department of Astronomy, University of California, Berkeley, California 94720
Electronic mail: basri@soleil.berkeley.edu

CHRISTOPHER M. JOHNS-KRULL
McDonald Observatory, University of Texas, Austin, Texas 78712
Electronic mail: cmj@casa.colorado.edu

ROBERT D. MATHIEU
Department of Astronomy, University of Wisconsin, Madison, Wisconsin 53706
Electronic mail: mathieu@madraf.astro.wisc.edu

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ABSTRACT

We report on echelle observations of a variety of line profiles taken throughout the orbit of the close, eccentric binary T Tauri system DQ Tau. The stars themselves exhibit puzzling inconsistencies in the spectral types inferred from atomic versus molecular lines. The system shows clear evidence of an extensive circumbinary disk. The binary is expected to clear a central hole in the disk; however, the line profiles are similar to those from single classical T Tauri stars. This indicates that similar infall and outflow activities are taking place. The implication is that material is flowing through the supposed gap in the disk. It also means that these "classical" profiles do not require a stable circumstellar disk for their formation, since the stellar separation at periastron is too small to allow such disks. We present evidence that accretion increases (sometimes dramatically) as the stars approach each other. Both continuum veiling and emission line intensities can increase. In one outburst the Ca II IR lines brighten by a factor of 5. We discuss the line profiles during such outbursts in some detail. Along with increased accretion, the lines sometimes also imply high velocity outflows. Given the fact that outbursts can occur as much as 0.15 in phase away from closest approach, we favor accretion over direct magnetospheric interactions as the power source of the outbursts. Away from each other, the stars resemble moderate- to low-activity classical T Tauri stars. There is evidence that some material is stored near the stars and ingested throughout the orbit. These observations are generally consistent with a model for disks in binary systems proposed by Artymowicz & Lubow (1996, ApJ, 467, L77). The importance of this system is that it provides empirical support for continuing accretion through dynamical tidal gaps in disks. It demonstrates that very close binaries can be classical T Tauri systems. © 1997 American Astronomical Society. [S0004-6256(97)01908-0]

1. INTRODUCTION

Classical T Tauri stars (CTTS) are pre-main-sequence stars with properties indicative of active accretion disks—emission lines, spectral veiling, ultraviolet excesses, and infrared excesses. The deposition of material from the disk onto the star gives rise to many of these phenomena. Because the stars are very magnetically active, both the outflow and final accretion seen in CTTS may depend on the interaction of the stellar magnetosphere with the disk. One hypothesis has the disk truncated at a few stellar radii, with accretion flow down magnetic field lines at high latitude and the outflow generated in a magnetocentrifugally driven wind just outside the stellar magnetosphere (Shu et al. 1994). Close binaries among CTTS are important case studies, for the companions have been expected to clear gaps in the inner accretion disks and thereby terminate further mass flow from circumbinary disks (Artymowicz & Lubow 1994). Thus evidence for continued accretion at the stellar surfaces would challenge this picture of binary-disk interactions, and perhaps our understanding of the accretion process itself.

Fifteen years ago, the small number of binaries among T Tauri stars was a mystery, given the large frequency of binaries among field solar-mass main-sequence stars. Work since then has shown that we just had to look harder; now there is almost an embarrassment of riches at moderate to wide separations (for a review, see Mathieu 1994). Still, there are only a handful of spectroscopic binaries known among the classical T Tauri stars.

In our companion paper (Mathieu et al. 1997; hereafter Paper 1) we report the discovery that DQ Tau, a "typical" CTTS, is an eccentric double-lined spectroscopic binary.
with a 15.8 day orbit. That paper serves as the introduction to this one, and should be read first. The close approach of the two stars at periastron—8 stellar radii—precludes the presence of significant circumstellar accretion disks around either star. Nonetheless, DQ Tau displays an ultraviolet excess, spectral veiling, and emission line behavior characteristic of CTTS. In addition, the infrared spectral energy distribution (SED) shows a power-law structure also typical of CTTS, and at other orbital phases. We also determine the amount of spectral "veiling" from absorption lines; this provides a measure of the excess continuum due to accretion. Section 3 presents an analysis of the spectral variations seen in DQ Tau. We discuss the dependence on orbital phase, the consistency of behavior from orbit to orbit, and the occasional outbursts that are seen in this system. Section 4 discusses the significance of these results in terms of current theories of disk accretion in CTTS and close binary systems. We consider the fact that the magnetospheres of the two stars probably collide at periastron. We discuss what the line profiles can tell us about the geometry of line formation in this system, and how it relates to other CTTS. Section 5 summarizes our conclusions.

2. OBSERVATIONS

The observations undertaken in this spectroscopic campaign were motivated by the detection of occasional line broadening in earlier CfA data (Paper 1). While our first 3 observations (Table 1) with the Hamilton echelle at Lick Observatory appeared to be single-lined, our spectrum on
1993 December 23 UT (reduced JD 9344.89) showed obvious splitting of both photospheric absorption lines and narrow emission lines like Ca II and He I. On the following night the splitting was rapidly disappearing, changing visibly in four hours. These initial results suggested a short-period highly eccentric orbit. The following Fall we launched a campaign to monitor DQ Tau, enlisting other observers to enhance time coverage and bolstered by an apparent periodicity in a simultaneous photometric program (Paper 1). The product is a data set which is well-sampled in time and which revealed the binary orbit presented in Paper 1.

A log of all the observations obtained with cross-dispersed echelles is given in Table 1. We would like to thank the observers at the University of California Observatories (UCO), who employed the Hamilton and HIRES echelles for us at the Shane 3-m (Lick Observatory) and Keck 10-m (Keck Observatory), respectively. They are listed in the Acknowledgements. The instruments employed have been described in some detail in Paper 1. All reductions were done by CMJ and GB. Most required only standard echelle reduction procedures as described in Paper 1. There were detector problems in the McDonald observations on 9706.65, 9707.67, 9708.63 which required special handling before the general purpose routines could be applied.

Because of the variety of instruments and settings used and the fact that many of the observations were not taken with high velocity precision in mind, we had some difficulties in assigning accurate wavelength scales to all the observations. More vexing was the fact that our software was not yet equipped to handle the various lamps that were used. Different subsets of lines from ThAr were present with differing intensities, and the lines were grouped differently in spectral orders depending on the echelle. We determined at least one absolute wavelength scale for each instrumental configuration, but did not absolutely calibrate all observations.

2.1 Measurements

In order to determine spectral type, projected rotation velocity, and spectral veiling, we compare our DQ Tau spectra with a spectroscopic standard star. Choosing observations in which DQ Tau showed the least velocity splitting and spectral veiling, we compared several spectral orders containing a variety of photospheric lines with our library of echelle spectroscopic standards (obtained with the Hamilton echelle). It became clear that there are molecular features present suggestive of the spectral type of early M given in the Herbig/Bell Catalog (Herbig & Bell 1988). The photospheric lines clearly match better with mid to late K stars (compatible with the K7 type given by Hartigan et al. 1995). We discuss spectral typing later; here we note that we chose as a compromise standard the late K star G1380 (K6 V according to Reid et al. (1995), although this star was also previously classified as early M). It is a slow rotator ($v \sin i = 2 \pm 0.5$ km s$^{-1}$, Marcy & Chen 1992), and we have Hamilton spectra covering the full optical wavelength range, so matches with any of the DQ Tau spectra could be made.

The "veiling" $V_\nu$ is defined as the level of the extra continuum that needs to be added to the standard spectrum in order that the absorption line depths be reduced by the amount apparent in the observation of the veiled star. Thus a value of unity, for example, means that the veiling continuum has the same brightness as the photospheric continuum. In the case of a binary observation, the observed continuum is the sum of both photospheres, but it is still normalized to unity in our procedure. When computing our veilings, we add a single veiling to generate a model spectrum. This composite spectrum is normalized afterward to unity to compare with the normalized observation. Thus, the units of veiling in this case are the sum of the photospheric continua. As discussed in Sec. 3.2, it is not possible to measure individual veilings for each star.

In detail, our procedure was first to find a segment (from 1 to 3 nm in length) in each DQ Tau spectrum with a reasonable number of medium strength photospheric lines, and find the matching segment in Gl 380. We determined that the $v \sin i$ of DQ Tau was quite similar for both components, and roughly 10 km s$^{-1}$ (see below). This rotation is applied to the standard spectrum. We then flatten the continuum in both the DQ Tau and standard spectra (normalizing them to unity). A cross-correlation function is generated between the chosen segment of DQ Tau and the standard. This function was in turn "continuum normalized" (being of sufficient length to show a central peak and some "continuum"), and the result is the "observation" which we try to match.

Next the standard segment is fed to a routine whose purpose is to construct a model spectrum which yields a fit to the "observation" when treated in the same manner as the DQ Tau segment. In doing so we assume that the two stellar components have the same spectral type, which is supported by the similar appearance of their individual lines at maximum velocity separation. The model is constructed by taking the standard segment twice, with two different velocity shifts, adding a veiling to their sum, continuum normalizing the result, and cross-correlating with the same standard segment used in generating the "observation." The routine calls a fitting procedure (in IDL) based on the Marquardt method described in Bevington et al. (1992). (Our thanks go to J. Valenti for supplying the specific code.) This produces a model cross-correlation function which minimizes $\chi^2$ relative to the "observation." The velocity shifts required to do this are the free parameters of the fit (along with a veiling). We then take this composite spectrum and compare it directly to the DQ Tau segment to determine the best value of the veiling (by eye). This step is necessary because of the normalization of the cross-correlation functions, which destroys the actual veiling information (but promotes convergence to a good fit).

The entire procedure is typically repeated on at least 3 spectral orders, and the scatter in the derived parameters used as an estimate of the errors. In the red, only a few orders have enough lines (and little enough telluric contamination) to allow good determinations. Unfortunately, the spectra not taken with the Keck telescope are poorly exposed in the blue (shortward of 600 nm) where many absorption lines are available, while the Keck spectra were typically taken only in the red. We therefore often have only about 3 good segments to use in each observation. An example of the appear-
length scale was properly zeroed by checking nearby absorption lines. Then a simple measure of equivalent width was made by taking a linear segment under the line which was at the level of the continuum (determined by eye) and computing the equivalent width. We also placed the spectra on a common (systemic rest) velocity scale for comparison of the various observations of each line. Because of the disparate nature of the observations, individual echelle frames contained some, but not all, of the lines of interest. A summary of the line splittings, strengths, and continuum veilings measured appears in Table 2.

3. ANALYSIS

3.1 Stellar Parameters

The spectral type of DQ Tau based on low-dispersion spectra has previously been given as between K7-M1. We examined the strength of the TiO band at 712.5 nm and compared it to our high-dispersion spectral library. On this basis the spectral type is M1-1.5 when compared to dwarfs. However, these M standard stars have substantially different strengths of photospheric lines in the 600 nm range compared with DQ Tau in the sense that their low excitation lines are stronger. For specificity, we examined the Sc I resonance line at 621.07 nm in ratio to a pair of Fe I lines with medium excitation potentials at 620 nm, as employed earlier by Basri & Batalha (1990). The Sc line increases rapidly in strength...
as effective temperature decreases, while the Fe lines are relatively insensitive. On the basis of this line ratio measured throughout the K-M range, the spectral type of the stars in DQ Tau are both K4-5.

It is possible that part of this discrepancy is due to extensive spotting on the stars, although photometric modulation due to stellar rotation has not been clearly identified. It is also possible that the photospheric lines are moved to apparently hotter spectral types by the presence of strong chromospheric activity, although this effect has not been clearly shown for other active stars. Finally, the fact that the gravity on DQ Tau is lower than that in our standard stars may play a role via the strong sensitivity of molecular diagnostics on density.

The rotation of the two stars can be measured separately at orbital phases where they are well separated in velocity. Our best such observation is the Keck observation in the blue on RJD9787.70. We construct composite spectra from G1 380 using our derived velocity separation, and apply different \( v \sin i \) to each star. The best match is found with \( v \sin i \) of \( 10 \pm 2 \text{ km s}^{-1} \) for each star. There is slight evidence that the star shifted to the red on this date has slightly higher \( v \sin i \) than its companion, but they both lie within our quoted value.

If we assume the stellar parameters from Paper 1 (M \( \approx 0.65 \, M_\odot \), R \( \approx 1.6 \, R_\odot \), \( i \approx 23^\circ \)), then the implied rotation period is about \( 8 \, \text{v} \sin i \) days, or \( \approx 3 \) days for both stars. This is much shorter than the orbital period. Given that at periastron the stars pass within only 8 stellar radii of each other (Paper 1), the stars might be pseudosynchronized (meaning that their periastron orbital and rotational angular velocities try to equalize) as they tidally torque each other during periastron passage. It takes about 1.6 days for the stars to swap positions about the center of mass (from phase 0.95 to 0.05; see Fig. 7). If the orbital period were 3.2 days then the stars would also have gone through half a rotation, so an observer who saw the other star overhead at the first position would still see it overhead at the second position. In that sense the stars appear to be close to pseudosynchronized (but our accuracy on the rotation period is not high).

If one star were substantially more luminous than the other, their relative line strengths would be consistently different. We do not see a consistent trend in the relative line strengths when the spectrum is double-lined; the lines tend to have equal strength. There are exceptions, when the two components look different. Such differences can often be ascribed to the presence of line blends, which are superposed in various ways when the stars shift relative to each other. The specific example in Fig. 1 cannot be explained this way, however. The temperature sensitive lithium resonance line appears to be actually stronger on one star in this case. Additional magnetic activity on one star is a possible explanation.

### 3.2 Veiling

In Table 1 we give the measured veiling as a function of orbital phase for all our observations, and these are shown in Fig. 2(a). We first note that the veiling occasionally drops to zero, giving confidence that our spectral standard does not simply have deeper lines (due to a metallicity or temperature mismatch). Most of the time the veiling is present but rather low (0.35 ± 0.15), which means that the accretion luminosity is about one-third that from both photospheres in the 600 nm range. Note that it makes no difference from where this extra continuum arises; whether on either, both, or neither of the stars, so long as the source is also present in the spectrograph slit. Consequently we cannot derive independent veiling curves for each star. So-called "differential veiling," in which line cores are filled in by changing the atmospheric temperature gradient, could give rise to measured differences in the line strengths on each star, but we see no evidence that this is present. It would affect stronger lines more strongly. The line strengths on one star compared to the other do change a little, but not in a systematic way.

The implication is that most of the time, and at all orbital phases, some accretion is occurring. Thus there must be some reservoir of material near the stars. In Paper 1 we noted that DQ Tau shows a near-infrared excess indicative of material in the vicinity of the stars. Whether this material is in (very small) circumstellar disks, circumstellar clouds, or more broadly distributed throughout the binary orbit (or all of those) is not clear, but in any case this near-infrared excess does suggest that material is available to fuel accretion onto the stellar surfaces.

The other striking fact apparent in Table 1 and Fig. 2 is...
that the veiling is sometimes substantially higher near periastron. This is very similar to the photometric behavior of the system discussed in Paper I, where DQ Tau brightens around periastron passage. The rise in veiling to a maximum of 1.3–1.5 is consistent with the maximum brightening (about 0.5 mag) seen in the photometry. We have no simultaneous photometry and spectroscopy, but we see other periastron passages with smaller or no rise in veiling, also consistent with the photometric behavior. It would be very nice in the future to have simultaneous high resolution spectroscopy and photometry for this (and other) T Tauri systems.

### 3.3 Phased Line Behavior

As discussed in Paper I, DQ Tau is a fine example of a "classical T Tauri star. It is of similar spectral type to the majority of T Tauri stars. It exhibits the same types of infrared excess, UV excess, continuum veiling, and emission line spectra as most members of the class. Indeed, it has been treated previously as just another member of the class. It is a little unusual in that there is typically no blueshifted absorption in Hα; two–three of CTTS show some absorption (Appenzeller & Mundt 1989; Edwards et al. 1994). Lack of absorption tends to go along with less "activity" (meaning smaller infrared excess and emission lines), such as in DN Tau, or with earlier spectral types, as in GW Ori (note this is also a spectroscopic binary). The appearance of Ca II and He I in DQ Tau is also typical of the less active CTTS or active WTTS.

Our measures of the equivalent widths of selected interesting lines are also given in Table 1. As discussed in Basri & Batalha (1990), equivalent widths must be used with care when there is spectral veiling present. Because the equivalent width is defined in terms of the observed continuum, a source of extra continuum light will reduce the measured equivalent width even if the actual line strength compared to the stellar photosphere is unchanged. The corrected equivalent width (that which would have been measured if there were no additional continuum source present) is found by the equation

\[ W_{\text{cont}} = W_{\text{obs}} \times \left(1 + V_c\right), \]

where \( V_c \) is the continuum veiling as we have defined it. In Table 2 these corrected values of equivalent width appear next to the measured values in parentheses.

Our coverage of the various lines is incomplete, with the best coverage on Hα. In Fig. 2(b) we show the corrected (and uncorrected) emission strength for this line as a function of orbital phase. There is a very striking dependence of line strength on phase, with the line growing in strength near periastron passage. In addition, there are points much higher than typical concentrated near periastron. This same behavior is seen in the other emission lines (though with many fewer data). The formation of Hα (and the other emission lines, for that matter) is still not fully understood in TTS. It seems that increasing Balmer line strength is directly related to increasing accretion rates (e.g., Basri & Batalha 1990; Cabrit et al. 1990; Valenti et al. 1993). Thus the emission line strengths deliver much the same message as the veiling: there is accretion at all phases but it increases, sometimes dramatically, near periastron.

As noted above, the appearances of the emission lines themselves are not unlike examples to be found among other CTTS. The Hα line of DQ Tau usually has a rather broad, symmetric appearance (like BP Tau), and its shape is not generally altered as it increases in strength (with an exception discussed below). The breadth of the line increases along with its strength (see Fig. 5). The wings are fairly symmetric, and the peak of the line is near the systemic rest velocity. Hβ is similar in shape to Hα, and does not show clear signs of either a blue or redshifted absorption feature. The higher Balmer lines are similar to Hβ (see Fig. 3). The Balmer lines are too broad to display overt splitting of the lines even at maximum velocity separation. There is a clear tendency in Hα to show enhanced red wings at phases near zero, whether or not the photospheric lines are split (recall that they are unsplit at phase \( \phi = 0.05 \)). This could be interpreted as increased accretion flow near periastron, but that is not the only possible explanation.

We have also examined emission lines from Ca II and He I. These tend to be much narrower than the Balmer lines (also the case in WTTS and mildly active CTTS or in low states of active stars such as DF Tau). They are not unlike lines from main sequence stars with very active chromospheres. These lines are narrow enough that the two components are easily split during periastron passage. Figure 3 shows the resonance lines of Ca II and the He I line at 587.6 nm. Such spectra make it clear that the activity levels on the two stars are fairly similar, though sometimes the activity ratio is not unity. The He I lines are always clearly in emission; this is not generally found unless stars are quite active. It is not necessarily true that these emission lines arise solely from an active stellar atmosphere—accretion may play a role (Batalha et al. 1996). We cannot, however, state unequivocally that both components are responsible for that part of the activity which clearly resembles only CTTS (the broad emission components).

On three occasions (noted in Table 1), the system was particularly active. During our second run we were treated to a spectacular outburst in the emission lines during periastron passage (RJD 9344.89). The Hα emission is 2 times higher than average at phase \( \phi = 0.95 \). The Ca II IR triplet is not much brighter than average, but the blueshifted component is stronger than the redshifted one. The Li I line at this time is stronger on the star with the weaker Ca II lines (Fig. 1). By 9345.74 (\( \phi = 0.01 \)) the Ca II lines increased by more than 5 times (Fig. 4). Even more spectacular are the profile changes. Hα developed blueshifted absorption features (Fig. 5), the only time we have seen them in DQ Tau. Between these two observations (less than 24 hours) high velocity absorption makes its first appearance (at \( -250 \) km s\(^{-1} \)), then increases its velocity to \(-300 \) km s\(^{-1} \) in 4 hours (at 9345.93). It deepens with time, reaching the level of the stellar continuum at the last observation.

The Ca II IR triplet lines generally have a FWHM of about 40 km s\(^{-1} \). We see 2 such lines on 9344.89, split by 56 km s\(^{-1} \) (Fig. 4). By 9345.74, when the blueshifted absorption appears in Hα, the Ca II lines develop spectacular blueshifted emission wings, extending to beyond \(-100 \) km s\(^{-1} \). Enigmatically He I, which is generally a little narrower
Fig. 3. Selected emission lines in the blue. All spectra were obtained in the same echelle observation on RJD 787.70. Both stars can be seen in the narrow lines. The Ca II H spectrum includes He just redward. The Hβ and He I spectra include a lower trace from 683.96 which have a more typical appearance.

and weaker than Ca II, resembles Ca II on 9344.89 but broadens more symmetrically with about half the width of Ca II at 9345.74, and then tightens up to a FWHM of about 60 km s$^{-1}$ with more red than blue emission at 9345.93 (Fig. 6).

All the lines have returned to their normal strengths and appearances by the following apastron ($\phi=0.46$, 9352.85). Then at $\phi=0.85$ of the next orbit (9374.86), the lines are in outburst again, with similar shapes (except that blueshifted Hα absorption is not present). Again, the He I line is rather different from the Ca II lines, with the Ca II lines showing predominantly blueshifted emission while the He I line is clearly dominated by redshifted emission (and gives a suggestion of a sharp blue cutoff).

It is clear that just as the stars passed each other (since maximum velocity separation is very close to minimum physical separation) material was heated and ejected from the system with very high velocities. The Ca II lines are most informative about this event. The peak of the emission on 9345.74 is shifted blueward of both stellar velocities at first, and has moved somewhat back towards the center by 9345.93 ($\phi=0.02$). There is a slight enhancement of redshifted emission, which begins to disappear. There is very substantial emission of material at chromospheric temperatures (characteristic of Ca II) to more than $-100$ km s$^{-1}$ in a gently decreasing wing. Remarkably similar shapes appear on 9345 and 9374.9.

Both apparitions are accompanied by the highest veiling

Fig. 4. Same as Fig. 1 but for the Ca II line at 866.2 nm.

Fig. 5. Same as Fig. 1 but for the Hα line at 656.3 nm. Note that the intensity scale is logarithmic.
we found on DQ Tau, providing a clear link between accretion and outflow. During outburst, DQ Tau resembles a very active CTTS. The width and strength of the Hα line and its high velocity blueshifted absorption (which almost goes below the stellar continuum in our observations), are reminiscent of stars like T Tau itself. The strength of the Ca II and He I lines are comparable to stars like BP Tau, which also sometimes show only narrow emission and sometimes much broader emission (Batalha et al. 1996).

Later periastron passages did not reliably repeat this behavior, for example at 9767.85 and 9708.63. The photometry in Paper 1 revealed that brightenings do not occur at every periastron passage, although they do occur at least two thirds of the time. Furthermore, they exhibit different strengths and some phase jitter. At 9787.70 we do not have observations in the red, but the Hβ line clearly indicates that another outburst is in progress (showing its greatest measured strength), and He I is strong (Fig. 3). On the other hand the veiling is not as enhanced in this case as in the previous two outbursts. Furthermore, on the following nights the Ca II lines show no unusual emission, although Hα is enhanced by a factor of more than 2 and shows enhanced red wings. Thus the outbursts come in a variety of manifestations.

4. DISCUSSION

Except near periastron, DQ Tau looks like a moderately active classical T Tauri star in its emission lines. As discussed in Paper 1, its infrared SED is also unexceptional in both luminosity and shape. The normalcy of the SED is surprising, given that an eccentric binary is expected to clear a gap in the circumbinary disk with an outer radius of about three times the orbital semi-major axis. Similarly, continued accretion is surprising given that previous theoretical work has argued that material will not cross this gap. Furthermore, in this system there is really no room for circumbinary disks of sufficient size to act as reservoirs for ongoing accretion. Thus the substantial evidence that material is present in the vicinity of the stars and that accretion continues at the stellar surfaces is unexpected, and strongly suggests that in fact the circumbinary region must be replenished, likely with material from the circumbinary disk.

A possible mechanism for this replenishment is accretion streams, as recently proposed by Artymowicz & Lubow (1996, hereafter AL; Artymowicz & Lubow 1994). As discussed in Paper 1, this mechanism has the significant strength of predicting variable accretion rates, and in particular enhanced accretion rates at periastron passage. If the circumbinary disk is sufficiently "warm" and its viscosity is sufficiently high, gas pressure in the disk pushes material over the potential barrier at the 2:1 Lindblad resonance (which is responsible for the gap clearing). AL predict that as each star passes nearest the circumbinary disk (at apastron), an accretion stream of low angular momentum material can be produced. This material then falls in a spiral path down towards the central region of the system. The DQ Tau system provides an opportunity to test some of these ideas.

4.1 Phase–Dependent Accretion and Outflow in DQ Tau

Paper 1 suggested that the brightenings of DQ Tau near periastron passage were the result of increased accretion rates. Here we have shown that spectral veiling is also enhanced near periastron. Similarly, emission line strengths and widths increase at periastron passage, mimicking in a time-dependent way the correlation between veiling and emission line activity seen among CTTS in general (Basri & Batalha 1990; Cabrit et al. 1990). These new observations add strong support to the idea of increased accretion rates near periastron. AL found that for a system with orbital elements like DQ Tau, accretion streams intersect the paths of the stars very near periastron. Paper 1 linked the periastron brightenings of DQ Tau with such accretion streams.

In Fig. 2 we show the veiling corrected Hα equivalent width (analogous to Hα flux) as a function of orbital phase. Note that all these points do not come from a single orbit; there is remarkable repetition of the level of Hα emission as a function of phase from orbit to orbit. We find the contrast between minimum and maximum Hα strength is only a factor of 3, and there is a rather smooth variation in Hα strength throughout the orbit, with similar behavior in the veiling. AL predict an increase by an order of magnitude in the flow of material into the vicinity of the stars at periastron, fairly well-confined in phase. However, their codes are not able to follow in detail the flow of material near the stars. Our data suggest that some of the material remains in the circumstellar environment after arrival there at periastron, and is ingested by the stars in a more leisurely fashion throughout the orbit.

We suggest that the stars collect material near periastron and ingest it throughout the orbit. The inflowing streams may create a "nimbus" of material which sits in the circumstellar environment of each star and contributes to the continued emission line activity and infrared excess. The dynamics of this material is not clear, but is likely influenced by the stellar magnetic fields. Indeed, in Paper 1 we suggested that it may perhaps be the interaction of the magnetospheres at periastron which permit a rapid inflow of material which is supported throughout the rest of the orbit. Alternatively, the interaction of the stars with the accretion streams may be greatest at periastron but continue at a lower rate throughout the orbit. Some of the infalling material in the AL simulations is perturbed by the stars away from periastron and dis-
The formation of the outburst and outflow are probably associated with the impulsive accretion. In the absence of strong continuous accretion flows from circumstellar disks, the stellar magnetospheres are freer to expand and the bending of field lines required to drive a wind may be more difficult to attain. Perhaps only when there is a powerful accretion impulse does the structure more closely resemble those around other active CTTS, producing the Hα outflow signature.

4.2 The Geometry of the Emitting Regions

The geometries of the stellar environments are almost certainly complicated, particularly at periastron where magnetospheres, accretion streams, and circumstellar matter all enter the same volume. The emission line profiles provide a rich set of clues to the stellar environments.

Forbidden line emission is likely to arise from a relatively large region. The preferential blueshifting of forbidden lines in CTTS generally has been interpreted as due to the screening of the receding component by the disk. High velocity forbidden lines in CTTS are strongly blue asymmetric, and associated with jets; these show almost complete occultation of the receding flow. So far as we know, DQ Tau does not have such a jet. Hartigan et al. (1995) show that the forbidden line emission in DQ Tau has lower velocities, is preferentially blueshifted (although not by much), and there is substantial redshifted emission. They suggest low velocity forbidden lines arise in a region of order 1–2 AU (perhaps from an inner disk wind). The gap cleared by the binary would be about 0.4 AU in extent, a substantial fraction of the formation region. The appearance of the forbidden lines is compatible with the idea that the gap is optically thin or has a filling factor less than unity, allowing a substantial view of the receding flow.

Near the star there is enough hydrogen to produce optically thick Balmer lines. The Hα profiles are very broad and have mostly symmetric wings apart from the narrower blueshifted absorption, as is usually the case in CTTS (Fig. 5). It is now becoming accepted that such emission will arise in the vicinity of the magnetosphere (rather than in an extended wind). On the other hand, the Hα emission region is not likely to be much larger than a few stellar radii, so the stars themselves block a significant fraction of it. The symmetric appearance of the Balmer wings in CTTS means that the velocity broadening is produced on a scale small compared with the size of the stars. In the magnetospheric accretion scenario (Shu et al. 1994) there should also be an inner disk hole of a few stellar radii. For DQ Tau, this region would be comparable to the distance between the stars at close passage, so there is no room for an occulting disk outside it near the stars. Note, however, that this region is not empty, but contains the accretion flows. During an outburst the veiling increases by a factor of 5 or more, so there is likely to be much more material near the star during such events.

The Ca II lines should be formed in a smaller region than Hα, and during outburst they brighten with a strong preferential blueshift (Fig. 4). Blueshifted material is flowing preferentially poleward because of the low inclination of the system. In the RID 9345 outburst (Fig. 4), the bright part of the red wing of the Ca II lines is consistent with the non-outburst line width, even displaying a slight narrowing from ϕ=0.01–0.02, consistent with the narrowing of the photospheric Li I line (Fig. 1). Thus, the redward counterpart of the spectacularly bright blueshifted outburst is largely absent. We must conclude that either any corresponding receding material is fairly effectively blocked, or that there is only material flowing toward the observer. If the flow occurs near the points at which material is accreted onto the star and is fairly localized, there might not be receding material. The fact that the blueward asymmetry in Ca II also occurs at ϕ=0.85 (RID 9375) supports the idea that it is not a geometrical effect which relies on the proximity of the stars to each other (Fig. 7). Other CTTS rarely show such asymmetric Ca II lines. It may be that the impulsive nature of the accretion in DQ Tau plays a role.

One reason to place at least part of the outburst off the star, however, is that the Ca II lines do show a very broad but low plateau of red emission at 9345.73, which extends in
velocity to the same limit (about 150 km s\(^{-1}\)) as the much brighter blueshifted emission. Interestingly, this is comparable to the velocity of the stars relative to each other at periastron. We do not believe such velocities can be found “on” the star, and material coming toward the star so fast must originate well above it. The red Ca II plateau decreases perceptibly in 4 hours (similar to what is seen in the wings of H\(α\)). The red wing of He I is brighter than its blue wing when the low red Ca II plateau appears, becoming symmetric 4 hours later. This is quite different from what is seen in Ca II. Of course, it is possible the He I lines suffers from blueshifted absorption, perhaps corresponding to the blueshifted emission in Ca II. At 9375 the He I line (Fig. 6) looks very much like there is blueshifted absorption (especially in comparison to the Ca II lines then). He I is probably formed in the smallest region (perhaps near the accretion “splash”) because of the high excitation required to produce this line, and would be geometrically easier to absorb with overlying material than Ca II. Because of the rapid variability, most of the line emission must arise fairly near the stars.

4.3 Interacting Magnetospheres?

In the DQ Tau system, the stars approach within about 8 stellar radii from each other. According to the magnetospheric accretion theory of Shu et al. (1994), a circumstellar disk will be disrupted inward of the corotation point where disk orbital angular velocities match the surface of the star. For a 3 day rotation period this would occur at 4.7 stellar radii, which means that the corotation points of the two stars would overlap during periastron passage. As noted above, the magnetospheres in DQ Tau may extend even further, given the likely absence of a stable accretion disk to compress them (so that the Shu et al. 1994 theory is not actually applicable). There is good evidence that TTS have the required field strengths and structures. Much of this has been summarized by Edwards et al. (1994); it includes the observation of extended nonthermal radio emission around WTTS, direct and indirect suggestions that the magnetic fields are strong and pervasive enough, and spectroscopic evidence of magnetospheric flows. Johns & Basri (1995) find direct evidence of outflow and inflow modulated by the stellar rotation period in a CTTs, as expected in the Shu et al. (1994) model, which supports the presence of a large and strong magnetosphere (even with substantial accretion). Thus it is quite possible, even likely, that the magnetic fields of the two stars come into contact with each other during close approach.

We may therefore ask whether the outbursts seen in DQ Tau are fundamentally due to the interaction of the stellar magnetic fields, rather than the collection of accretion material near the stars at periastron. For example, material could be collected in the circumstellar environment (though a pair of extensive circumstellar disks is not possible). Accretion of this material could occur throughout the orbit (as it seems to), but the accretion rate could be enhanced when the magnetospheres (and collected circumstellar material) for the two stars collide. This could occur either simply because of the concomitant increase in the amount of material in the circumstellar environment as the two stars merge their structures, or because of some disruption (reconnection or compression) of the magnetic fields as they interact with each other. The former case is not unlike collection of material near periastron. In the latter case, there is the possibility of large flares.

Strong interactions between the stellar magnetospheres near periastron are expected. This system during close passage is not unlike the RS CVn systems. The large flares that are often seen in those systems could be a result of such interactions (Uchida & Sakurai 1983; Kuijpers 1990). It must be pointed out, however, that the DQ Tau outbursts are accompanied by continuum veiling not seen in RS CVn stars. We do not see evidence that photospheric lines in DQ Tau are filled in preferentially by their strength (differential veiling) which would indicate general heating of the upper photosphere by a flare. Such effects are seen in strong solar flares, indicating that the DQ Tau events are fundamentally different (or have rather small filling factors implying very high surface fluxes).

The line profiles seen by Simon et al. (1980) in a flare on UX Ari (an RS CVn system) and ascribed to them to an interstar flare have some resemblance to the Ca II outburst in DQ Tau, though with redshifts rather than blueshifts. The amount of energy released in a DQ Tau outburst can exceed \(10^{38}\) ergs with a luminosity around \(L_\odot\), far larger than even very large stellar flares (Pettersen 1991). Of course, in stellar flares one does not have two strong stellar fields interacting with each other. The energetic requirements might possibly be met by dissipating a major fraction of the available magnetic energy external to the stars, as discussed in Paper I. We are skeptical that it could be regenerated for another outburst within an orbit or two (as is sometimes seen).

The timescale of the outbursts are longer than those of flares in either RS CVn or dMe stars (the strongest stellar flare examples), being sometimes a couple of days long (based on the photometry, Paper I). Of course, one could be dealing with a long episode of continued flaring as the stars pass each other, rather than an individual flare or two. The velocity breadth of the outburst profiles are comparable to those for flares on dMe stars. There is a suggestion of a pedestal of such broad emission in the UV lines on a dMe star even outside of strong flaring (Linsky & Wood 1994), which is ascribed to constant microflaring. The velocity width is set by the Alfvén velocity, which can be quite high. One might also expect high energies to be present, which would enhance “hot” lines like He I preferentially. This is not seen.

Another argument against the flaring hypothesis is the phase breadth of the outbursts. As can be seen in Fig. 7, the fact that outbursts occur as far as 0.15 in phase away from closest approach makes it less likely that direct magnetospheric interaction could be responsible for those, as the stars are then 14 stellar radii from each other. If the magnetospheres extend as far as 7 stellar radii, however, as implied by some radio observations of WTTS (Phillips 1992), then it is not out of the question. One of the best such cases, HD 283447 (V773 Tau), turns out to be a 51 day WTTS binary in which there is sometimes evidence for nonthermal radio emission with systemic dimensions. This may be viewed as
evidence for far-reaching magnetic fields in a young close binary system (Phillips et al. 1996). While this system exhibits flares, it shows nothing like the outbursts in DQ Tau (but its orbital eccentricity is only about half that of DQ Tau).

We conclude that a strong case for a predominantly magnetic explanation for the outbursts cannot be made, but neither can it be ruled out. In any case we expect interacting magnetospheres to have some effect. We have argued above that the behavior of the system is far more complex and violent near periastron than away from it; the stellar magnetic fields almost certainly play some role in this. Perhaps we should ask instead how the system manages to get through as many as a third of its close passages without having a perceptible outburst. The amount of material available for accretion during close passages is apparently variable, and also seems to be crucial to the outburst phenomenon. The stellar fields interact on each passage, but do not necessarily cause the emission lines to become broader or brighter. It will be very valuable to have further observations of periastron passage in this system. It will also be very interesting to observe the UZ Tau E system, which has a different orbital geometry and 19 day period (Mathieu et al. 1996).

5. CONCLUSIONS

We have presented extensive spectroscopic observations of the close binary CTTS DQ Tau. The system consists of two late K or early M stars in a tight, eccentric orbit contained within a circumstellar disk. We use the photospheric lines to deduce that both stars have similar rotations, with $v \sin i$ about 10 km s$^{-1}$, implying rotation periods of around 3 days. This is much shorter than the orbital period, but roughly consistent with the stars having similar parallactic and rotational angular velocities near periastron (i.e., pseudosynchronization). The spectral types of the two components are also quite similar. There is a puzzling mismatch between the spectral type deduced from molecular features compared with atomic lines. The spectral type compared with main sequence stars seems to be M1-2 from the TiO features, while it looks more like K4-5 on the basis of temperature sensitive atomic absorption lines. This may indicate strong spotting on the two stars, or it may have to do with the lower gravity in these stars than in spectral standards. Chromospheric lines indicate strong magnetic activity on both stars.

We show that the suggestion in Paper 1 that there is ongoing accretion onto the stars is borne out by the presence of spectral veiling. Spectral veiling is present throughout the orbit; the typical level of this continuum is about two-thirds the luminosity of one of the stars. We cannot determine the site of the veiling continuum. Consistent with photometric brightening, the veiling increases near periastron passage. Accretion is also indicated by the close resemblance of the line profiles of DQ Tau to those of other CTTS which display accretion diagnostics. CTTS are thought to be surrounded by an extensive stable circumstellar disk which provides material for the accretion. In DQ Tau there is no room for such disks because the stars pass within a few radii of each other. The implication is that CTTS line profiles do not require the disk as such; accretion onto a young magnetically active star is enough.

The forbidden lines seem to come from a region not much larger than 1 AU, and their relatively symmetric appearance suggests that the reprocessing flow is not strongly blocked, consistent with the expectation that the circumstellar disk has an optically thin hole in it of close to 0.4 AU. Near the stars, the accretion geometry is likely to be quite complicated given the ever changing gravitational potential and the complex and changing stellar magnetic fields. Rather little is known about how much material is carried around with the stars, and in what configuration. We see evidence for complex occultations, ejections, and absorptions near periastron, while the stars look rather placid away from each other.

Signatures of outflow are not normally present in the permitted lines. We have observed several large outbursts in the emission lines near periastron passage. During these events the Hα equivalent width increased by factors of 3-4. During periastron outbursts the lines do show outflow signatures. In particular Hα develops blueshifted absorption features, and Ca II can display strong blueshifted emission. There is good evidence that the accretion rate increases by several times during these events. A direct connection between increased accretion and outflow is clear. The magnetosphere is freer to expand in the absence of a strong continuous accretion flow from a circumstellar disk, and the bending of field lines required to drive a wind may be more difficult to attain. Perhaps only when there is a powerful accretion impulse does the structure more closely resemble those around other active CTTS, producing the Hα outflow signature. The appearance of the Ca II lines during outburst suggests that bright blue-shifted material comes off from near the surface of the star, but there is also a faint redshifted plateau of emission which probably arises further out.

As in Paper 1, we note that the increase in accretion activity at periastron passage is consistent with predictions for accretion streams from the circumbinary disk (Artymowicz & Lubow 1996). Such streams are pulsed, with material arriving at the stars at periastron passage. The amount of material in these streams varies from orbit to orbit. However, we stress that both spectral veiling and the emission lines indicate that accretion continues at a lower level throughout the orbit. The variation in accretion rate is both smoother and has less contrast than is predicted from the AL calculations (taken at face value). We suggest that some material which arrives at the stars at periastron is not immediately accreted but remains in the circumstellar environment for some time after. This "nimbus" of material which sits in the circumstellar environment of each star could contribute to the infrared excess and emission line activity.

We also consider whether the direct interaction of the two stellar magnetospheres could be responsible for some or all of the increased emission near periastron. We argue that the case for "superflaring" is not very strong, but cannot be fully dismissed. We consider it weak primarily because the behavior of DQ Tau is not seen in WTTS systems which are similar, and the increased emission occurs in a somewhat wider orbital phase range than might be expected. Another
point against it is that the system passes through periastron without outburst more than a third of the time. $H\alpha$ does tend to be brighter near periastron even without an outburst, but the veiling (and photometry) can show little effect. $H\alpha$ may be a more sensitive indicator of accretion than the continuum processes, or we may be observing effects in the magnetosphere which enhance the line emission without powering the accretion shock.

The primary importance of these observations of DQ Tau is to show that dynamical effects do not terminate accretion onto binary stars. Despite the absence of substantial circumstellar disks, DQ Tau continues to accrete material, presumably from its circumbinary disk. Thus stars in binary systems continue to evolve in mass and angular momentum as a consequence of accretion. One can speculate that the same may be true of the formation of giant planets; perhaps tidal truncation is not as effective as first thought. The second key result is that apparently much of the T Tauri emission line phenomenology does not depend directly on a large circumstellar disk interacting with a stellar magnetosphere. The DQ Tau environment must be much less organized and more time variable than is typical, yet it is not readily distinguishable from other CTTS by the appearance of the emission lines. We still have much to learn about accretion and outflows from young stars.

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