THE CLASSICAL T TAURI SPECTROSCOPIC BINARY DQ TAU. I. ORBITAL ELEMENTS AND LIGHT CURVES

ROBERT D. MATHIEU AND KEIVAN STASSUN

Department of Astronomy, University of Wisconsin, Madison, WI 53706
Electronic mail: mathieu@astro.wisc.edu, keivan@astro.wisc.edu

GIBOR BASRI

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

ERIC L.N. JENSEN[1]

Department of Astronomy, University of Wisconsin, Madison, WI 53706
Electronic mail: jensen@astro.wisc.edu

CHRISTOPHER M. JOHNS-KRULL[2]

McDonald Observatory, University of Texas, Austin, TX 78712
Electronic mail: cmj@antaeus.as.utexas.edu

JEFF A. VALENTI

JILA, University of Colorado, Boulder, CO 80309
Electronic mail: jvalenti@pandora.colorado.edu

LEE W. HARTMANN

Harvard-Smithsonian Center for Astrophysics, 60 Garden St., Cambridge MA 02138
Electronic mail: hartmann@cfassp44.harvard.edu

Submitted to the Astronomical Journal:________________

---

[1] Now at the Department of Physics and Astronomy, Arizona State University.
[2] Now at JILA, University of Colorado.

ABSTRACT

We report the discovery that the classical T Tauri star DQ Tau is a double-lined spectroscopic binary. The orbital period is 15.804 days, with a large orbital eccentricity e=0.556. The mass ratio is 0.97 ± 0.15.

We have monitored DQ Tau photometrically over two observing seasons and observed recurring episodes during which the stars get brighter (≈ 0.5 mag in V) and bluer (≈ -0.2 mag in V-I). When combined with photometry in the literature (time span ≈ 5000 days), a Scargle periodogram analysis reveals a highly significant periodicity of 15.80 days, essentially identical to the binary orbital period. These brightening events occur shortly before or at periastron passage. They occur during at least 65% of periastron passages, but not during all periastron passages.

DQ Tau is surrounded by a circumbinary disk with mass of 0.002 $M_{\odot}$ - 0.02 $M_{\odot}$. The infrared spectral energy distribution resembles a power law from 1 μm to 60 μm. Remarkably, there is no paucity of near-infrared emission indicative of the inner disk having been cleared by the binary; there is clearly warm material within the binary orbit.

We interpret the brightening events as due to a variable mass accretion rate regulated by the binary orbit. The periodic brightenings, the associated increases in emission line strength and veiling reported in an accompanying paper (Basri *et al.* 1997), and the circumstellar material together are consistent with a recent theoretical finding that circumbinary disk material can stream across a binary orbit at certain orbital phases, resulting in a pulsed accretion flow onto the stars (Artymowicz & Lubow 1996). The theoretically predicted phase of maximum accretion rate is shortly before periastron, in good agreement with the phasing of the brightenings of DQ Tau.

The periastron separation is smaller than the inferred stellar magnetospheric radii of classical T Tauri stars, so that such magnetospheres would interact at each periastron passage. The magnetic energies are plausibly adequate to power the brightenings. However, the strongly enhanced continuum veiling and long duration of some of the brightenings are not naturally explained in a pure flaring scenario. Nonetheless, magnetospheres likely play a role in the detailed accretion flow near the stars.

1. INTRODUCTION

At present 26 pre-main-sequence (PMS) spectroscopic binaries are known (Mathieu 1994, Mathieu *et al.* 1996). Of these, only three - V4046 Sgr (de la Reza *et al.* 1986), GW Ori (Mathieu *et al.* 1991), and UZ Tau E (Mathieu *et al.* 1996) - are classical T Tauri stars, i.e. young stars with strong Hα emission and large infrared excesses. Indeed, the status of V4046 Sgr is not clear since it is isolated from any molecular gas or dark cloud. Here we report that the classical T Tauri star DQ Tau is also a spectroscopic binary, in particular a double-lined binary with a period of 15.804 days and a highly eccentric orbit.

DQ Tau is a classical T Tauri star with a long history of observational study. It was first discovered to be an emission-line object by Joy (1949). Much of the Balmer series is in emission, with an Hα equivalent width as large as 200 Å (Basri *et al.* 1997, hereinafter Paper 2). The spectrum is also veiled (Valenti *et al.* 1993, Hartigan *et al.* 1995, Paper 2). DQ Tau shows a large infrared excess (e.g., K-N=4.2 mag; Skrutskie *et al.* 1990), and was detected by the IRAS satellite at wavelengths of 12 μm, 25 μm and 60 μm (Weaver & Jones 1992). The infrared luminosity is of order half the stellar luminosity (Strom *et al.* 1989). These diagnostics are typically taken as indicative of an optically thick disk actively accreting material onto a stellar surface. Valenti *et al.* (1993) suggest an accretion rate of order 10^{-8} M_o yr^{-1}, while Hartigan *et al.* (1995) find an accretion rate of $5x10^{-8}$ M_o yr^{-1}.

Spectral-type determinations for DQ Tau are in reasonably good agreement, ranging from K5 (Paper 2) to M1 (Herbig 1977). Estimates for the total and stellar luminosities of DQ Tau vary greatly in the literature due to uncertainty in the extinction; estimates of extinction range from A_V=2.1 (Strom *et al.* 1989) to A_V=0.5 (Cohen & Kuhi 1979). For specificity, we adopt an effective temperature of 4000 K and a stellar luminosity of 0.95 L_o (K7, A_V=2.13; Hartigan *et al.* 1995). If we then divide the luminosity evenly between the two equal-mass stars of the binary (see below) and compare to the PMS evolutionary models of Swenson *et al.* (1994), we obtain a theoretical mass of 0.65 M_o and an age of $3x10^6$ yr for each star. The uncertainties on these numbers are large, but they nonetheless show DQ Tau to comprise two low-mass stars descending their Hayashi tracks. As modeled, the theoretical radii for both stars are 1.6 R_o.

Previous radial-velocity measurements from high-dispersion spectra were made by Herbig (1977) and Hartmann & Stauffer (1989). Herbig's stellar velocity measurement differed from the velocity of molecular gas along the same line of sight by -27 km s^{-1}, but he made no mention of line splitting. Projected rotational velocity measurements also exist in the literature, but these may be inflated by the double-line nature of the system. We measure vsin i = 10 km s^{-1} for each component (Paper 2).

We have monitored DQ Tau both spectroscopically and photometrically. The high-resolution spectroscopic data reveal DQ Tau to be a double-lined binary system; in Section 2 we present the radial-velocity data and discuss the orbital solution. The two comparable mass stars revolve about each other on an eccentric orbit (e=0.556) with a period of 15.804 days. Remarkably, our photometric data also show a periodicity of 15.80 days; as the stars pass through periastron, the system gets brighter and bluer. In Section 3 we discuss the photometric observations and our periodicity analysis. Additionally, in Paper 2 we show that Hα emission and veiling vary similarly in phase with the orbital period.

The binarity of DQ Tau is most notable in light of the substantial evidence for active accretion at the stellar surfaces. Past theoretical work has argued that a binary will clear a gap in a disk and inhibit the flow of material from a circumbinary disk inward across the binary orbit (e.g., Lin & Papaloizou 1993, Artymowicz & Lubow 1994). Nonetheless, the DQ Tau system shows many of the usual observational signatures for accretion of material onto stellar surfaces, including emission lines and spectral veiling. The photometric brightening at periastron may be a clue to the process by which circumbinary material reaches the stellar surfaces. In Section 5 we discuss the distribution of disk material in the DQ Tau system based on the observed spectral energy distribution (Section 4). The binary is surrounded by a circumbinary disk with a mass of 0.1% - 1% of the stellar mass. Circumstellar material is also present, although its amount and distribution are poorly constrained. We suggest that the periodic brightenings, the increases in emission line strength and veiling, and the circumstellar material are consistent with a recent theoretical finding that at certain orbital phases circumbinary material can stream across the binary orbit to the stars (Artymowicz & Lubow 1996). We also consider whether the brightenings may be the result of interacting magnetospheres during periastron passage, but find this a less satisfactory interpretation. Finally, in Section 6 we present our conclusions.

2. RADIAL-VELOCITY MEASUREMENTS AND ORBITAL SOLUTION

We first made precise radial-velocity measurements of DQ Tau as part of a Harvard-Smithsonian Center for Astrophysics survey of radial and rotational velocities of classical T Tauri stars (Hartmann *et al.* 1986, Mathieu 1992). Spectra were obtained with the echelle spectrographs and photon-counting detectors at the 1.5 m Tillinghast reflector of the Fred L. Whipple Observatory and at the Multiple Mirror Telescope. The instrumentation and reduction of the spectra are described elsewhere (Hartmann *et al.* 1986, Latham 1992). Most of the spectra covered a window of 45Å centered at 5187Å; a few of the earlier spectra were centered at 5197Å. Typically 20-40 photons were registered per pixel of 1.8 km s^{-1}.

The first CfA observation of DQ Tau was made in Fall 1984, and observations were continued at irregular intervals through Fall 1994. In total, 23 spectra were obtained. Early in the program, cross-correlation of several of the spectra with an M-giant spectrum showed double peaks, albeit always blended. In addition, the widths of single correlation peaks would vary over intervals of days. Thus it was evident that the system was double lined, but analysis procedures were inadequate for deriving good velocity measurements. Recently the powerful two-dimensional correlation procedure TODCOR (Zucker & Mazeh 1994) has been incorporated into the CfA reduction facilities (Latham *et al.* 1996). Dr. L. Marschall has kindly applied TODCOR to the DQ Tau spectra. Using a synthetic template (T_{eff} = 3850, log g = 4.5, vsin i = 10 km s^{-1}, solar abundance), pairs of velocity measurements have been extracted from 14 of the CfA spectra. For the remainder we adopt an upper limit on the velocity separation of 18 km sec^{-1}, this being the smallest velocity separation successfully measured with the TODCOR analyses.

We began observations with the Hamilton echelle (Vogt 1987) and the Shane 3-m telescope at Lick Observatory in Fall 1993. This instrument provides the entire optical spectrum at a resolution of about 60,000. Typical exposures were 30-60 minutes, giving a S/N of 25-50 in the continuum around Hα. In Fall 1994 we launched a spectroscopic monitoring campaign incorporating a variety of telescopes and spectrographs. We and others made observations with the Hamilton echelle and the HIRES echelle spectrograph (Vogt *et al.*1994) at the Keck 10-m telescope. In the latter case our settings typically covered part of the spectrum from about 6000-8500Å, although other observers used other settings. The resolution varied from 35,000-67,000. Typical exposures of 10 minutes yielded S/N of 50-100.

Spectra were also obtained at the McDonald Observatory. On six nights spectra were acquired with the Sandiford Cassegrain Echelle Spectrograph (McCarthy *et al.* 1993) coupled to the 2.1-m Struve telescope. The spectra were recorded with a cooled, thinned, backside-illuminated Reticon 1200 X 400 CCD detector. The spectral resolution was R = 60,000 from 6390 Å to 8700 Å, with continuous coverage below 8500 Å. Spectra were also obtained on three nights using the cross-dispersed coude echelle spectrometer (Tull *et al.* 1995) of the 2.7-m Harlan J. Smith telescope. The spectra were recorded with a Hughes 2048 X 2048 CCD at the F3 focus. The spectral resolution was R = 60,000 from 3500 Å to 9000 Å with incomplete coverage in the red above 5600 Å.

In total 28 spectra have been obtained in the 1993-1995 campaign. For brevity, we will refer to all of these observations as the “LKM” (Lick-Keck-McDonald) data.

The reductions of the LKM spectra are described in Paper 2. Because of the large variety of instruments, settings, and observers, secure absolute velocity calibrations were not generally available for these spectra. To obtain relative velocity measurements, we used a late-K spectral standard (Gl 380) as a cross-correlation template in spectral orders selected to have suitable absorption lines and no strong emission lines. Upper limits were determined for unsplit spectra by creating synthetic binary spectra of arbitrary velocity separation from the template spectrum (with appropriate noise added), and comparing the resultant correlation spectra with the observed correlation spectra.

The combination of the CfA and LKM velocity measurements is problematic in that the LKM observations are not on secure internal or external zero points. However, the relative velocities of the primary and secondary are very well determined. In order to link the two data sets, we first derived a double-lined orbital solution from only the CfA data; the resultant orbital elements are given in Table 2. This solution gives a center-of-mass radial velocity of $\gamma = 22.4$ km sec^{-1} $\pm$ 0.6 km sec^{-1} and a mass ratio $M_2/M_1 = 0.97 \pm 0.15$. Then, adopting $\gamma = 22$ km sec^{-1} and $M_2/M_1 = 1$, we derive primary and secondary radial velocities from the LKM relative velocities. The resulting set of radial velocities is tied to the CfA radial-velocity zero-point (Latham 1992).

All of our velocity measurements are presented in Table 1. The first column presents Julian Date, the second column gives the orbital phase (see below), the third column gives the telescope at which the spectrum was obtained, the fourth column presents the primary radial velocity, and the sixth column gives the secondary radial velocity. Here the primary is defined by the orbital solution to the CfA data. Since the mass ratio of that solution is indistinguishable from unity, it is not certain that the star chosen as the primary is in fact the more massive star. When independent primary and secondary radial velocities were not measurable, an upper limit on the velocity separation is given in the eighth column of Table 1.

A double-lined solution to the entire set of primary and secondary velocity measurements was obtained using the program SBOP, with equal weights for all observations. (Hereinafter this is referred to as the "combined solution".) The orbital elements are given in Table 2, where we list the period, P, in days; the center-of-mass velocity, γ, in km s^{-1}; the velocity amplitudes, K_1 and K_2, in km s^{-1}; the eccentricity, e; the longitude of periastron, ω, in degrees; the time of periastron passage, T, in heliocentric Julian Day; the mass ratio, $q=M_2/M_1$; the minimum masses, $M_1 \sin^3 i$ and $M_2 \sin^3 i$, in solar masses; the projected semimajor axes, $a_1 \sin i$ and $a_2 \sin i$, in AU; and the number of primary and secondary velocity measurements, N.

We remind the reader that because a γ-velocity and mass ratio were assumed in order to join the LKM radial velocities with the CfA radial velocities, the values for these quantities, the orbital amplitudes, and the projected masses and semimajor axes which are derived from the combined data set are biased. Consequently these elements are shown in italics in Table 2. However, the remaining orbital elements are very well determined from the combined data set. In order to establish this, we performed two tests. First, we did a single-lined orbital solution to the velocity differences (i.e., primary minus secondary) of the combined data set; the velocity differences do not suffer from any zero-point uncertainties. The resulting period, orbital eccentricity, longitude of periastron, and time of periastron passage were essentially identical to those of the combined solution (Table 2). Second, we combined the data sets adopting a mass ratio $M_2/M_1 = 0.85$ (the 1 σ deviation on the mass ratio derived from the CfA data alone). Again, the change in period, orbital eccentricity, longitude of periastron, and time of periastron passage were much smaller than the formal uncertainties. Hence the values and uncertainties for these elements derived from the combined data set are very secure. As expected, adopting a different mass ratio resulted in different γ-velocity, orbital amplitudes, and projected masses and semimajor axes; these values changed by 1-2 times the formal uncertainties in Table 2. Consequently, we recommend adopting the values and uncertainties from the double-lined orbital solution to the CfA data alone for these elements, as we will do throughout the paper.

The orbital period of DQ Tau is 15.804 days. The orbit is rather eccentric with e = 0.556. The γ-velocity of 22 kms^{-1} is consistent with membership in the Taurus association (Hartmann *et al.* 1986). The mass ratio of the system is indistinguishable from unity, but a mass ratio of 0.7 is permitted at the 2σ confidence level. Unfortunately, the lower limits of 0.04 $M_{\odot}$ on the stellar masses are not of great value. If we adopt a total stellar mass of 1.3 $M_{\odot}$ (Section 1), then the inclination angle is 23^{o} and the periastron separation is 0.060 AU or 13 $R_{\odot}$. These numbers do not change greatly within a reasonable range of uncertainty in the theoretical stellar masses.

The phased radial-velocity measurements and orbit curves from the combined solution are shown in Figure 1. The orbital solution is well covered in phase. Those spectra which provided only upper limits on the velocity separation are also shown in Figure 1; here a γ-velocity of 22 km s^{-1} has been assumed, and the upper and lower limits taken as a velocity excursion of half the limit on the velocity separation. The upper limits are always found at phases of small velocity separation, adding support to the period and phasing of the solution.

The primary and secondary O-C values from the combined solution are listed in columns five and seven of Table 1. The rms residual of a single CfA velocity measurement (primary or secondary) from the combined solution is 2.7 km s^{-1}. This is the same as the rms residuals to the solution derived from the CfA data alone. Based on the orbital solution to the combined data sets, the rms residual of an LKM relative velocity measurement is 1.2 km s^{-1}.

3. PHOTOMETRY

DQ Tau was also monitored photometrically as part of a larger study of the variability of T Tauri stars. In particular, we obtained differential photometry on CCD images acquired with the 0.5-m telescope at Leuschner Observatory, hereafter referred to as BAIT (Berkeley Automated Imaging Telescope; Richmond *et al.* (1993)). It is equipped with a 512x512 CCD (30" x 30"), and all flat-fielding, bias subtraction, centroid finding, and simple aperture photometry are performed noninteractively by computer. Richter *et al.* (1992) have previously presented light curves for nine T Tauri stars obtained with BAIT, including DQ Tau.

We monitored DQ Tau at two epochs: the 86 nights between 1994 January 11 UT and 1994 April 7 UT and the 71 nights between 1994 September 30 UT and 1994 December 10 UT. One to three exposures were taken on each clear night in each of the three filter bandpasses V, R, and I. (Note that the data of Richter *et al.* were not filtered, i.e. the entire CCD bandpass was used.) Our exposure times of 240 sec, 180 sec, and 150 sec in V, R, and I, respectively, were chosen to keep the brightest comparison stars in the field just below the saturation level.

We have determined light curves using the method developed by Honeycutt (1992) for ensemble photometry from an inhomogeneous set of images. This method produces a set of differential magnitudes for the target star relative to a set of comparison stars in the field. Observations from the two epochs were reduced separately to avoid systematic offsets. In Table 3 we present a summary of the photometric data. For each bandpass and each epoch we show the time span of the observations, the number of observations, and the number of nights providing at least one datum. We also present σ_{dm}(DQ), the standard deviation of the differential magnitudes of DQ Tau, and σ_{dm}(comp), the same quantity for the brightest non-variable star in the field (Richter *et al.* 1992). The latter shows the precision limit of the photometry; similar standard deviations are found for stars of comparable brightness to DQ Tau (which is roughly 2 mag fainter). The individual photometric measurements are available upon request.

Our V, R, and I light curves for DQ Tau are shown in Figure 2. In each bandpass the differential magnitudes have been zeroed on the mean value in that bandpass. The error estimates for each point are computed as in Honeycutt (1992). DQ Tau clearly varies, and these variations are correlated in the three bandpasses. In particular the data show discrete brightening events, similar in behavior to the two events of DQ Tau observed by Richter *et al.* (1992).

Qualitatively, these brightening events appear to occur at regular intervals. To explore this quantitatively, we searched for periodicity using a Scargle periodogram analysis (Scargle 1982, as modified by Horne & Baliunas 1986). For this analysis we augmented our V-band data from both epochs (55 measurements) with the unfiltered data of Richter *et al.* (1992; 19 measurements) and with V-band photometry drawn from the compilation of Herbst *et al.* (1994; 76 measurements). By including these archival data, we extended the baseline of the period search to ~ 5000 days in V, and augment the precision of the period determination. In Figure 3a we show the result of applying the Scargle periodogram analysis to these data. Several significant peaks are evident in the power spectrum, the most prominent occurring at a period of 15.80 ± 0.05 days. We estimate the uncertainty in our period determination as the 1/T frequency resolution of a discrete Fourier transform, where T is the extent of the time baseline.

The reality of a periodicity can be expressed by a false-alarm probability, or the likelihood that a purely random signal (i.e. one with no periodic behavior) would generate a feature in the periodogram of similar amplitude. We have determined false-alarm probabilities via Monte Carlo simulations (Horne and Baliunas 1986), and in Figure 3a we show false-alarm probabilities for our specific sampling pattern. The likelihood of the peak at 15.80 days being due to a random fluctuation is less than 0.1%.

Nonetheless, several other peaks are also present at reasonably significant levels (e.g., false-alarm probabilities ≈ 1%). However, these other peaks are all aliases of the 15.80 day peak. By comparing the window function for the V-band light curve with the power spectrum in Figure 3a, we find that the power spectrum is consistent with a single periodicity at 15.80 days. An alternative treatment for distinguishing between multiple significant spectral features is provided by the technique of harmonic filtering (Ferraz-Mello 1981), or “pre-whitening”. This involves fitting and removing a sine wave from the data with the same frequency as that of the primary power spectrum peak. The periodogram is then recalculated, with aliases of the primary peak disappearing from the new power spectrum. In Figure 3b we show the result of applying such a harmonic filter to the DQ Tau data. By filtering at a period of 15.80 days *all* of the statistically significant features in Figure 3a are removed, suggesting none are not independent of the 15.80-day feature. Tuning the harmonic filter to the periods of the other significant peaks in the power spectrum revealed that there are no other independent periodic components; filtering at these other periods left behind several statistically significant spectral features, and invariably failed to remove the strong peak at 15.80 days.

The periodicity at 15.80 days is very robust. We find the same peak in the power spectra of our R- and I-band data, and in our V-band data alone. We also find this periodicity in the archival data of Herbst *et al.* (1994) alone. This assures that the periodicity is not due to some non-cosmic process intrinsic to our observations, nor is it a result of our window function. We note though that in these data subsets the 15.80-day peak, while prominent, is not always the strongest peak.

The agreement of the independently derived photometric and spectroscopic periods is striking. Given a binary orbital period of 15.8043 ± 0.0024 days, it is very likely that the photometric periodicity is related to the binary nature of the system. Hence we next phase the photometric data to the binary orbit. In Figure 4 we show several subsets of the database, phased with a period of 15.804 days and a zero-point of the periastron passage of the binary orbit. In Figure 4a we show the BAIT R-band data (these being the most numerous BAIT data). A significant signal is clearly evident, with all five brightenings (differential R > 0.1 mag) occurring within an interval of 0.3 in phase (or 5 days). This phase interval is centered at phase 0.9, somewhat in advance of periastron. The brightenings are not strictly repeated; at a given phase within this interval DQ Tau is sometimes brightened and sometimes not. As can be seen by examination of Figure 2, in which the phase interval is shown by tick marks around each predicted event, both the time and pattern of each brightening differ from one orbit to another. For example, at the JD 2449407 event the star brightens, returns to its original brightness, and then brightens again. In contrast, the JD 2449423 event lasts 4 days, reaching a maximum early and then slowly fading. And at some predicted events DQ Tau does not appear to brighten at all (e.g., JD 2449439 and JD 2449644).

In Figure 4b we show the archival V-band data phased in the same way. Although the measurement errors are larger, a brightening signal is evident in the same phase interval as for the BAIT data. The periodicity in the archival data shows that the periodic phenomenon is long-lived, with a duration of at least 5000 days. These extensive data provide some measure of the frequency of brightenings. Measurements were available within the periastron phase interval for 20 predicted brightenings; in 12 cases DQ Tau was observed to be at least 0.1 mag above its mean brightness. If our BAIT observations are included, these numbers become 19 brightenings out of 29 predicted events. Since occasionally only a single measurement was available near a periastron passage, some brightenings may have been missed and the actual frequency is likely higher. Nonetheless, the archival data also include several well-observed events during which DQ Tau clearly does not brighten. Thus we conclude that brightenings happen with a frequency of at least 65%, but not 100%.

Finally, in Figure 4c we show all observations plotted against phase. Here we have included our BAIT V-band data, the archival V-band data, and the Richter *et al.* unfiltered photometry. The two brightenings in the Richter *et al.* (1992) data also occur in the same phase interval as the other data sets, with numerous observations outside this phase interval showing no brightenings. The combined data set clearly shows that the brightenings of DQ Tau are confined to a limited range of binary orbital phase somewhat in advance of periastron passage.[3] During this time, DQ Tau can brighten by as much as a factor of 2 in the V band.

Examination of Figure 2 shows that these brightening events are not gray; DQ Tau becomes bluer as it brightens. To study the color variation of DQ Tau we use BAIT VRI observations and UBV observations from the literature (Herbst *et al.* 1994). In Figure 5a-d we show differential V-I, V-R, B-V and U-B plotted against V. The close correlation of color with brightness is evident, in the sense of the combined light becoming more blue with increasing brightness.

Thus DQ Tau becomes both brighter and bluer with the same period as that of the binary orbit. Furthermore, the brightenings occur somewhat in advance of and during periastron passage. In Section 5 we discuss possible physical mechanisms linking the binary orbit with enhanced system luminosity and temperature.

---

[3] As shown in Figures 4b and 4c, the archival data show DQ Tau having substantially brightened once outside this phase interval. Whether this was real or due to photometric error is unknown.

4. SPECTRAL ENERGY DISTRIBUTION

Photometric observations of DQ Tau over a broad range in wavelength exist in the literature. We have supplemented these data with additional observations at near-infrared and submillimeter wavelengths. Images in the JHKL'M bands were taken 31 October 1996 UT using the IRCAM3 camera as part of the UKIRT[4] service observing program. Photometry was obtained with aperture techniques, and absolute calibration was achieved with images of a standard star taken at the same time and airmass. Our observations are 0.24 mag - 0.72 mag brighter than the photometry of Strom *et al.* (1989). [5]

Flux measurements at wavelengths of 450 μm, 800 μm and 1100 μm were obtained at the James Clerk Maxwell Telescope[6] as part of an observational program described in Jensen *et al.* (1994, 1996). The acquisition and reduction of these data are discussed there. The 450 μm and 800 μm flux measurements were obtained on 25 January 1993 UT; the 1100 μm flux measurement was obtained on 4 September 1994 UT.

The photometric data for DQ Tau are tabulated in Table 4 and the observed spectral energy distribution (SED) is shown in Figure 6 (filled squares).

5. DISCUSSION

5.1 Accretion Disks

The SED of DQ Tau is typical of classical T Tauri stars, being much broader than a stellar photosphere with a power-law distribution in the infrared which turns over at submillimeter wavelengths. In Figure 6 the long-dashed line shows a theoretical atmosphere[7]

---

[4] The United Kingdom Infrared Telescope is operated by the Royal Observatory, Edinburgh on behalf of the Particle Physics and Astronomy Research Council of the United Kingdom.

[5] The images also show a previously unreported faint star 7.3" from DQ Tau at P.A. ~ 150 degrees. The magnitudes of this faint companion are J=16.6 +/- 0.3, H=15.7 +/ 0.2, and K=15.2 +/- 0.2; the field of view of the L' and M images did not include the companion. This star is fainter than the limiting magnitude of previous imaging surveys for companions in Taurus-Auriga (Leinert et al. 1993). The fluxes and J-K color are consistent with this star being either a late-type tertiary companion to DQ Tau or a reddened background object. This object's flux is ~ 10-3 that of the DQ Tau binary, and thus does not appreciably affect the photometry.

[6] The James Clerk Maxwell Telescope is operated by the Royal Observatories on behalf of the Particle Physics and Astronomy Research Council of the United Kingdom, the Netherlands Organization for Scientific Research, and the National Research Council of Canada.

[7] The atmosphere used was calculated by R. L. Kurucz and was obtained on the World Wide Web at http://www.stsci.edu/ftp/instrument_news/Observatory/k93models.html. This set of atmospheres are similar to the models of Buser & Kurucz (1992).

with an effective temperature of 4000 K, a gravity of log g = 4.5, and solar metallicity. We have fit this atmosphere to the VRI data, with both the stellar luminosity and the extinction A_V as free parameters (using the extinction curve of Cardelli *et al.* 1989). We find an extinction of A_V = 2.0 and a combined stellar luminosity of 0.85 $L_\odot$. We have not included a hotter veiling continuum in this analysis, but note that our results are similar to those of Hartigan *et al.* (1995) who do account for veiling. Given these parameters, DQ Tau shows excess emission at all wavelengths longward of 1 μm. Similarly, Strom *et al.* (1989) measure an excess at 2.2 μm of ΔK=0.18 dex and Skrutskie *et al.* (1990) measure an excess at 10 μm of ΔN=1.62 dex. Both fall within the range of values typical of classical T Tauri stars.

These infrared excesses are indicative of extended material in the system. In the case of single PMS stars numerous arguments have been made for the association of infrared excesses with accretion disks (e.g., Beckwith & Sargent 1993). In the case of a binary the morphology of such disks becomes more complex. Resonant and tidal forces generated by the binary are expected to clear a gap which separates a circumbinary disk from one or two circumstellar disks. At the same time these forces have been argued to terminate any flow of material from the circumbinary disk to the circumstellar disks or stars. With continued accretion from and exhaustion of any circumstellar disks, the binary will eventually reside in a hole within a circumbinary disk (Artymowicz *et al.* 1991, Artymowicz & Lubow 1994). In the next section we interpret the SED of DQ Tau in the context of such disk morphologies.

5.1.1 Circumbinary Disk

Given an orbital semi-major axis of ≈ 0.1 AU, the excess emission at mid-infrared and longer wavelengths must derive primarily from circumbinary material. Here we consider this circumbinary material in the context of a disk geometry. We first model the disk as a flat, geometrically thin, optically thick, reprocessing disk which is coplanar with the binary (i = 23°, Section 2). Initially we ignore the clearing of the disk by the binary and extend our model into a (single) stellar surface at 1.6 $R_\odot$. We will consider the impact of the binary clearing on the model SED in the next section.

In Figure 6a we show the SED (short-dashed curve) of such a disk when illuminated by a single central star with the properties of the combined light of DQ Tau. The observed fluxes at wavelengths of 10 μm and longer exceed the predicted fluxes of this model. This excess luminosity may be indicative of flaring of the circumbinary disk (e.g., Kenyon & Hartmann 1987, 1995), or internal generation of energy in the circumbinary disk (e.g., Adams, Lada & Shu 1988), or both. Resonant coupling of the disk to the binary represents yet another possible source of energy.

For young stars the emission from disks is often parameterized by a power-law radial temperature distribution (with exponent q) and the disk luminosity. Fitting only the IRAS data for DQ Tau, Beckwith *et al.* (1990) found $q \approx 0.59$ and a disk luminosity of 0.5 $L_\odot$, to be compared to a total stellar luminosity of 1.1 $L_\odot$. With additional assumptions of a mass opacity function $\kappa_\nu \propto \nu^\beta$ and a power-law surface-density distribution ($\sigma \propto r^{-1.5}$), Beckwith & Sargent (1991) found $\beta = 0.7 \pm 1.1$ and derived a disk mass of 0.017 $M_\odot$ with an uncertainty of a factor 5. This circumbinary disk mass[8] is $\approx$ 1% of the theoretical stellar mass of 1.3 $M_\odot$ in the binary.

We have repeated this analysis with the more extensive photometric data tabulated in Table 4. Our procedures are described in Jensen & Mathieu (1996); here we take the 4000 K theoretical atmosphere, adopt inner and outer disk radii of 1.6 $R_\odot$ and 100 AU, and an inclination angle of 23°. We adopt a dust opacity function that is normalized to the 250-μm opacity of Hildebrand (1983) and leave β as a free parameter. The best-fit model, shown as a solid curve in Figure 6a, has $q \approx 0.57$, a disk luminosity of 0.44 $L_\odot$, β = -0.5, and a disk mass of 0.002 $M_\odot$.

The lower disk mass is a direct result of our smaller value for the opacity index β. This smaller value derives primarily from the new 450-μm measurement, which describes a shallow slope for the submillimeter SED. Given the large uncertainties the two measures of β for DQ Tau are not in contradiction. More generally, though, β = -0.5 is at the lower limit of values found in the Beckwith & Sargent (1991) survey of 25 T Tauri stars.

In summary, the detection of both mid-infrared and submillimeter emission from DQ Tau is strong evidence for the presence of a circumbinary disk. For a typical mass opacity function having $\beta \approx 1$ the inferred circumbinary disk mass is of order 0.02 $M_\odot$, roughly 1% of the stellar mass. However, the shallow slope of the observed submillimeter SED is not consistent with this model. The shallow slope implies an opacity index of β = -0.5, unusually small among T Tauri stars. The corresponding disk mass is of order 0.002 $M_\odot$. Such a small disk mass could not support the observed accretion rates for a substantial fraction of the binary lifetime. We recommend that additional measurements be obtained at wavelengths between 100 μm and 800 μm in order to more securely determine the submillimeter SED.

5.1.2 Circumstellar disks and disk clearing

In the immediate vicinity of the binary the radial temperature and surface-density distributions must differ greatly from the disk model used above. Artymowicz & Lubow (1994)

---

[8] While derived in the context of a single star, this disk mass determination serves equally well as an estimate for the circumbinary disk. With the adopted surface-density power law 94% of the disk mass lies exterior to 0.4 AU, the expected inner radius of a circumbinary disk.

predict that an eccentric binary will clear a gap extending from roughly 0.2*a* to 3*a*, where *a* is the binary semi-major axis . Given an inclination angle of 23^{o}, this corresponds to a gap from 0.03 AU to 0.4 AU in the case of DQ Tau. The inner boundary is only 4 stellar radii, so there is very little room for circumstellar disks. Indeed, an equally plausible hypothesis is that DQ Tau resides within a central hole in a truncated circumbinary disk. Given a completely cleared gap or hole, a deficit of near-infrared emission is expected (Mathieu *et al.* 1991, Jensen & Mathieu 1997).

In fact, the infrared SED of DQ Tau resembles a power law and does not show any marked structure indicative of a cleared inner region. For comparison, in Figure 6b we show the SED derived from a $q \approx 0.75$ disk model from which a central hole of radius 0.4 AU has been removed (solid curve). While such a circumbinary disk is reasonably consistent with the mid-infrared data, the model cannot account for the observed excesses at wavelengths of 3.8 μm and 4.8 μm. Evidently the DQ Tau system has warm extended material in the vicinity of the stars.

However, very little material is needed to produce the near-infrared emission. In Figure 6b we also show the theoretical SED (short-dashed curve) derived from a q=0.75 circumbinary disk with a 0.4 AU hole in which we place 5×10^{-10} M_{o} of material (gas:dust ratio of 100) with a uniform distribution and a temperature of 1000 K. This small amount of warm, optically thin material roughly provides the observed near-infrared excess luminosity. Assuredly this simple model is not physically accurate, but it demonstrates that the observed SED can be consistent with a dynamically cleared region in which only a very small amount of material remains.

Nonetheless, the similarity of the DQ Tau SED with the SEDs of single T Tauri stars is remarkable, presuming that the binary modifies the spatial distribution of material on size scales comparable to its semimajor axis. Similar SEDs have been found from two other close binaries, UZ Tau E (Mathieu et al. 1996) and AK Sco (Jensen & Mathieu 1997). In the case of AK Sco a strong silicate emission feature is seen, possibly additional evidence for optically thin material. A search for silicate emission from DQ Tau would be worthwhile.

5.2 Periodic Brightenings: Accretion Hypothesis

The combined light of DQ Tau both brightens and becomes bluer with a period equal to the binary orbital period (Section 3). The brightenings occur near periastron passage, as do increases in both emission line strengths and spectral veiling. All of these diagnostics are suggestive of mass accretion rates at the stellar surfaces that are regulated by the binary orbit. Here we consider the link between the orbit and the accretion.

Periodic bluenings have been observed in other classical T Tauri stars (e.g. DF Tau; Bertout, Basri & Bouvier 1988, Herbst *et al.* 1994). In these cases the interpretation has been the presence of hot spots, with the periodic photometric modulations being associated with the stellar rotation periods. However, this explanation for the photometric periodicity of DQ Tau seems unlikely. Given the large orbital eccentricity it is not expected that the rotation periods of the stars equal the binary orbital period (although they may be pseudosynchronized with the angular velocity of the orbital motion at periastron, leading to rotation periods shorter than the orbital period). Furthermore, the morphology of the DQ Tau light curve does not have the sinusoidal-like variation characteristic of spot modulation.

Recently, Artymowicz & Lubow (1996; hereinafter AL) have suggested that in certain situations accretion streams can flow from a circumbinary disk across a dynamically cleared gap onto either circumstellar disks or the stellar surfaces. One model which they investigate is a binary with e=0.5 and a mass ratio of $q = 0.8$ surrounded by a circumbinary disk. In this case two accretion streams develop, spiral-like in morphology, roughly symmetric about the center of mass, and each terminating on a different star. Both streams are narrow, so that the gap region remains almost empty. Nonetheless, the streams carry approximately as much mass flux as would a similar disk extending to the surface of a (single) star. Finally, AL find the accretion flow to be time variable with a periodicity equal to the binary orbit.

The parameters of this model binary are rather similar to those of DQ Tau. If this streaming phenomenon is occurring in the DQ Tau system, then the brightening and bluening may be associated with the deposition of kinetic energy from accreting material. Significantly, AL find that the maximum gas accretion rate near the stars occurs just prior to periastron, as does the brightening of DQ Tau. In Figure 7 we show both the AL plot of gas accretion rate against orbital phase for the particular model described above and our phased photometric data from Figure 4c. The agreement in phase is striking. The agreement between the width of the accretion pulse and the phase interval of observed brightenings is also encouraging, but the reader is reminded that the durations of individual brightening events vary, as do their amplitude. As such there is clearly a complexity to the DQ Tau system that is not present in the theoretical model.

During an event the system typically brightens by roughly a factor 1.5 at V. In Paper 2 we find that outside of the phase interval of brightening events the veiling luminosity at V is typically 0.4 times the photospheric luminosity. Presuming that the brightening is entirely due to an increase in veiling luminosity, then a factor 1.5 increase in system luminosity at V implies an increase in veiling luminosity of a factor 2.75, during which time the veiling luminosity is comparable to the photospheric luminosity. This is consistent with spectroscopic observations of veiling in the brightening phase interval (Paper 2), with the exception of one remarkable outburst. All else being the same, this increase in veiling luminosity implies a similar increase in mass accretion rate. Since this increased accretion rate lasts for no more than 0.3 of an orbit, the amount of material accreted during a pulse is comparable to the amount of material accumulated from the steady accretion observed outside of the pulse. Finally, we note that the observed increase in veiling luminosity at V during periastron is smaller than the increase in accretion rate found in the numerical simulations (Figure 7).

In this scenario, the increase in luminosity is due to the deposition of kinetic energy and the consequent heating of a region in the system. However, the nature of the interaction of such streams with either circumstellar disks, magnetospheres, or the stellar surfaces is not known; the resolution of the AL simulations is not adequate to study the mass flows within ≈ 0.1 *a* of the stellar surfaces. Thus whether the heated regions are on the stellar surfaces or circumstellar disks, whether they are localized in hot spots or more broadly distributed, whether they are heated directly by the stream or indirectly through replenishment of circumstellar material, is unknown. There are well-studied analogies to this phenomenon in the hot spots of cataclysmic binaries, which are thought to be created by streams originating in the companion star. These systems demonstrate that luminosity evolution after energy deposition can be rapid. Thus it is plausible that given a pulsed accretion stream the consequent luminosity evolution would also be pulsed, as observed in DQ Tau.

DQ Tau shows spectral veiling at all orbital phases, indicating a continuous low-level flow of material onto the stars (Paper 2). This continuous veiling suggests a reservoir of material that exists throughout the orbit, perhaps replenished by accretion streams. The spatial distribution of this reservoir is unknown, but if the material is widely distributed it would contribute to the observed near-infrared excess. The infrared excess may also derive from the streams themselves, although they likely do not subtend an adequate solid angle at the star to entirely power the observed emission.

Finally, AL find that accretion streams only develop in warm, moderately viscous circumbinary disks. Specifically, for accretion streams to form they require $z/R_{in} = c/\omega > 0.05$ if the viscosity parameter $\alpha > 0.01$. Here z is the local density scale height, c is the sound speed, and ω is the rotational velocity, all at the radius of the inner edge of the circumbinary disk R_{in}.. The physical conditions - and particularly the viscosity parameter - of the DQ Tau circumbinary disk are not known. An isolated blackbody particle at 0.4 AU would have a temperature of 400 K. Alternatively the inner edge of a spatially thick disk irradiated at normal incidence will have a dust temperature ≈ 600 K. If we take $M = 1.3\ M_{\odot}$, $R_{in} = 0.4$ AU, and T = 600 K in a pure molecular hydrogen gas, then $z/R_{in} \approx 0.03$. An upper limit on the temperature might be the dust sublimation temperature of 1500 K, which gives a $z/R_{in} \approx 0.045$. These numbers are somewhat smaller than the AL criterion. Given the unknown viscosity parameter and the youth of the theory, it is not clear whether this is a serious concern.

5.3 Periodic Brightenings: Interacting Magnetospheres Hypothesis

It is currently thought that accretion onto classical T Tauri stars proceeds via the stellar magnetosphere (Camenzind 1990; Konigl 1991; Shu *et al.* 1994). In this picture, the circumstellar accretion disk is disrupted by the magnetosphere and accreting material falls from the disk through magnetic flux tubes onto the stellar surface. Since the stars in the DQ Tau binary do not appear to differ greatly from many other classical T Tauri stars, it is plausible that they possess similarly strong magnetic fields.

Such stellar magnetospheres provide an alternative means to power the brightenings seen near periastron. Magnetospheric radii in single T Tauri stars - i.e. the radius inside of which the magnetic field can hold off the disk and channel the accretion flow - are thought to be $\approx 5\ R_*$ (e.g., Bouvier *et al.* 1993; Edwards *et al.* 1993, 1994). If each component of DQ Tau has such a magnetosphere, then the periastron separation of $\approx 8\ R_*$ insures that the magnetospheres will overlap. Such interactions of the magnetic fields may result in reconnection and strong flaring.

Energetically such a scenario is a plausible explanation of the observed brightenings of DQ Tau at periastron. For a simple dipole field with an average field strength B_o at R_o, the magnetic energy density integrated over all space exterior to R_o is $B_o^2\ R_o^3 / 3$. If we adopt a surface stellar magnetic field of 1 kG (Konigl 1991), then the total magnetic energy available per star exterior to $4\ R_*$ (half the periastron separation) is $\approx 7 \times 10^{37}$ erg. If half of this magnetic energy were released by the interaction in each star over a timescale of $8\ R_* / 100\ \mathrm{kms}^{-1} \approx 1$ day, then the release energy would be $\approx 8 \times 10^{32}$ erg/sec $\approx 0.2\ L_o$. This is comparable to the $1\ L_o$ of additional energy released in the brightenings of DQ Tau, particularly given the sensitive dependence on the unknown surface stellar magnetic field.

That the brightenings occur at periastron as observed is an immediate prediction of this hypothesis. However, one concern with this scenario is that the DQ Tau can brighten at phases moderately far from periastron. This is not straightforward to achieve with dipole fields which vary as r^{-3}. In addition, it is not evident that the large increase in spectral continuum veiling is consistent with this hypothesis. Other examples of strongly flaring systems, such as RS CVn binaries, do not show such continuum enhancement. Finally, the regeneration of a substantial fraction of the magnetic field on orbital timescales may be problematic.

Even if the evidence ultimately supports enhanced accretion rates over flaring as the origin of the DQ Tau brightenings, magnetic fields must nonetheless be considered in any detailed picture of the accretion flows near the stars. For example, the presence of line emission and veiling at all phases suggests reservoirs from which material continually accretes onto the stars. While these reservoirs may be replenished by accretion streams, magnetic fields may play a role in their support. Indeed, the brightenings at periastron might be the result of interactions between the magnetic fields which result in enhanced accretion rates. Alternatively, the material in the reservoirs may directly interact at periastron. In either case, the brightenings would not necessarily reflect on the behavior of the accretion streams themselves. The complexity of interacting magnetic fields may also be responsible for the fact that these outbursts are not precisely repeatable from orbit to orbit, especially if the stellar magnetic fields are not precisely aligned with the orbit and the stars have a different rotational period from the orbit.

6. CONCLUSIONS

An outstanding issue in our understanding of binary-protostellar disk interactions has been the observational evidence for continued accretion of material onto stellar surfaces in even the closest pre-main-sequence binaries (Mathieu 1994). The recent discoveries that the classical T Tauri stars DQ Tau and UZ Tau E are both short-period binaries emphasize the generality of this phenomenon. In such close binaries continued accretion demands replenishment of material in the circumstellar environment, with the most likely reservoir being the circumbinary disks. However, dynamical theory has argued that the binary dynamically clears gaps and prevents inward material flow from the circumbinary disk.

The significance of DQ Tau lies not only in the fact that accretion continues in this close binary system, but also in the discovery that the accretion rate is variable and regulated at least in part by the binary orbit. The photometric brightenings, the spectral veiling, and the emission line profiles and strengths all indicate that accretion rates are increased by a factor of a few near periastron.

Recently, Artymowicz & Lubow (1996) have proposed that pulsed accretion streams from circumbinary disks can carry material into the circumstellar environment, and presumably thereafter onto the stars. For a binary with orbital properties very similar to those of DQ Tau, they predict that the streaming material will reach the vicinity of the stars near periastron passage. This is in very good agreement with the observed enhancement of accretion diagnostics at periastron in DQ Tau. While this congruence in the orbital phasing is only one point of contact between the theory and DQ Tau, it nonetheless is encouraging evidence for the Artymowicz & Lubow mechanism.

It is of interest to consider possible implications of accretion streams for the evolution of young binary systems. Clearly they can resolve the issue of continued accretion at the stellar surfaces in PMS binaries. However the generality of this solution depends upon both the frequency and physical conditions of circumbinary disks. While circumbinary disks are reasonably common around close binary stars (e.g., Jensen & Mathieu 1997), they are much less frequent around binaries with separations greater than roughly 1 AU (Dutrey *et al.* 1996, Jensen *et al.* 1996). Even when circumbinary disks are present, it remains unclear whether they have the requisite scale heights and viscosity for such accretion streams to form. Monitoring of other short-period pre-main-sequence binaries is in order to determine the frequency of the DQ Tau phenomenon.

Interestingly, accretion streams from a massive circumbinary disk will equalize component masses and increase orbital eccentricity, both properties of DQ Tau. In addition, accretion streams may slow or even reverse the evolution of binary orbits to smaller semimajor axes in the presence of circumbinary disks (Lubow & Artymowicz 1997). Of course, not all short-period binaries have equal mass ratios or very eccentric orbits. Thus the agreement in the case of DQ Tau may be fortuitous, or the mechanism may not operate for all young binaries. Nonetheless, if accretion streams are found to be a general phenomenon they can substantially modify our present picture of the early orbital and mass evolution of young binaries. In this regard, it is quite possible that accretion streams are more prevalent during the protobinary stage when circumbinary disks are likely to be more massive and warmer.

The small periastron separation of DQ Tau also ensures that strong stellar magnetospheres will interact. We have argued that the available magnetic energy could be sufficient to power flaring activity, which might contribute to the observed brightenings. However, the enhanced continuum veiling and the long duration of some of the brightenings are not easily explained in a pure flaring scenario. Even so, magnetospheres likely play a significant role in the details of the accretion process, and it remains possible that the enhanced accretion rates seen at periastron are also related to reconfiguration of the magnetic fields.

Finally, the similarity of the DQ Tau spectral energy distribution with those of single T Tauri stars is striking. The power-law infrared spectral energy distribution of DQ Tau, even in the near-infrared, gives no indication that the inner region of the disk is cleared by the binary. Such clearing is not precluded; very little material is required to produce the observed near-infrared emission and the data are consistent with some residual material in a dynamically cleared hole. Indeed such residual material might be linked to the low-level accretion seen throughout the binary orbit. Even so, the similarity of the DQ Tau and single-star spectral energy distributions suggests that the origin of near-infrared emission from binaries, and even perhaps from single stars, merits further consideration.

We would like to thank R. Davis, E. Horine, A. Milone, J. Peters and G. Torres who joined in the CfA observations, and P. Butler, S. Hawley, M. Keane, D. Lambert, G. Marcy, D. Popper, D. Tytler and S. Vogt who obtained spectra for us during our monitoring campaigns of Winter 1993 and 1994. R. Davis, L. Marschall and G. Torres kindly assisted in the CfA data reductions. We have also benefited from numerous insightful conversations with P. Artymowicz, D. Cohen and S. Lubow, and the comments of the referee, P. Hartigan. We thank R. Treffers for his continued support of BAIT, and M. Richter for guidance in the photometric analyses. The photometry archive of W. Herbst was invaluable for this work. We appreciate the availability and superb support of the UKIRT service observing program. RDM and ELNJ are supported by NSF grant AST-941715. KS acknowledges the support of an NSF Graduate Fellowship.

REFERENCES

Adams, F. C., Lada, C. J., & Shu, F. H. 1988, ApJ, 326, 865

Artymowicz, P., Clarke, C. J., Lubow, S. H., & Pringle, J. E. 1991, ApJL, 370, L35

Artymowicz, P. & Lubow, S. H. 1994, ApJ, 421, 651

Artymowicz, P. & Lubow, S. H. 1996, ApJL, 467, L77

Basri, G., Johns-Krull, C. M., & Mathieu, R. D. 1997, AJ, submitted (Paper 2)

Beckwith, S. V. W. & Sargent, A. I. 1991, ApJ, 381, 250

Beckwith, S. V. W. & Sargent, A. I. 1993, in Protostars and Planets III, edited by E.H. Levy & J.I. Lunine (University of Arizona Press, Tucson), p. 521

Beckwith, S. V. W., Sargent, A. I., Chini, R., & Gusten, R. 1990, AJ, 99, 924

Bertout, C., Basri, G., & Bouvier, J. 1988, ApJ, 330, 350

Bouvier, J., Cabrit, S., Fernandez, M., Martin, E.L., & Matthews, J.M. 1993, A&AS, 101, 485

Camenzind, M. 1990, Rev. of Mod. Astro, 3, 234

Cardelli, J. A., Clayton, G. C., & Mathis, J. S. 1989, ApJ, 345, 245

Cohen, M. & Kuhi, L. V. 1979, ApJS, 41, 743

De la Reza, R., Quast, G., Torres, C. A .O., Mayor, M., Meylan, G., & Llorente de Andres, F. 1986, in New Insights in Astrophysics, ESA SP-263, p. 107

Dutrey, A., Guilloteau, S., Duvert, G., Prato, L., Simon, M., Schuster, K., & Menard, F. 1996, A&A, 309, 493

Edwards, S., Hartigan, P., Ghandour, L., & Andrulis, C. 1994, AJ, 108, 1056

Edwards, S., Strom, S.E., Hartigan, P., Strom, K.M., Hillenbrand, L.A., Herbst, W., Attridge, J., Merrill, K.M., Probst, R., & Gatley, I. 1993, AJ, 106, 372

Ferraz-Mello 1981, AJ, 86, 619

Frank, J., King, A.R. & Raine, D. 1992, Accretion Power in Astrophysics, Cambridge University Press, 127

Hartigan, P., Edwards, S., & Ghandour, L. 1995, ApJ, 452, 736

Hartmann, L. W., Hewett, R., Stahler, S., & Mathieu, R. D., 1986, ApJ, 309, 275

Hartmann, L. W. & Stauffer, J. R. 1989, AJ, 97, 873

Herbig, G. 1977, ApJ, 214, 747

Herbst, W., Herbst, D. K., & Grossman, E. J. 1994, AJ, 108, 1906

Hildebrand, R. A. 1983, RAS, 24, 267

Honeycutt, K. 1992, PASP, 104, 435

Horne, J. H. & Baliunas, S. L. 1986, ApJ, 302, 757

Jensen, E. L. N. & Mathieu, R. D., 1997, AJ, submitted

Jensen, E. L. N., Mathieu, R. D., & Fuller, G. A. 1994, ApJL, 429, L29

Jensen, E. L. N., Mathieu, R. D., & Fuller, G. A. 1996, ApJ, 458, 312

Joy, A. H. 1949, ApJ, 110, 424

Kenyon, S. J. & Hartmann, L. W. 1987, ApJ, 323, 714

Kenyon, S. J. & Hartmann, L. W. 1995, ApJS, 101, 117

Konigl, A. 1991, ApJL, 370, L39

Latham, D. W. 1992, in Complementary Approaches to Double and Multiple Star Research, IAU Colloquium 135, edited by McAlister, H. A. & Hartkopf, W. I. (ASP, San Francisco), p. 110

Latham, D. W., Nordstrom, B., Andersen, J., Torres, G., Stefanik, R. P., Thaller, M., & Bester, M. 1996, A&A, 314, 864

Leinert, Ch., Weitzel, N., Zinnecker, H., Christou, J., Ridgeway, S., Jameson, R., Haas, M., & Lenzen, R. 1993, A&A, 278, 129

Lin, D.N.C. & Papaloizou, J.C.B. 1993, in Protostars and Planets III, edited by E.H. Levy & J.I. Lunine (University of Arizona Press, Tucson), p. 749

Lubow, S.H. & Artymowicz, P. 1996, in IAU Colloquium 163, edited by Wickramasinghe, D., Ferrario, L. & Bicknell, G. (ASP, San Francisco), in press

Mathieu, R. D. 1992, in Complementary Approaches to Double and Multiple Star Research, IAU Colloquium 135, edited by McAlister, H. A. & Hartkopf, W. I. (ASP, San Francisco), p. 30

Mathieu, R. D. 1994, ARAA, 32, 465

Mathieu, R. D., Adams, F. C., & Latham, D. W. 1991, AJ, 101, 2184

Mathieu, R. D., Martin, E. L., & Magazzu, A. 1996, BAAS, 188, 60.05

McCarthy, J. K., Sandiford, B. A., Boyd, D., & Booth, J. 1993, PASP, 105, 881

Richmond, M. W., Treffers, R. R., & Filippenko, A. V. 1993, PASP, 105, 1164

Richter, M., Basri, G., Perlmutter, S., & Pennypacker, C. 1992, PASP, 104, 1144

Scargle, J. D. 1982, ApJ, 263, 835

Shu, F.H., Najita, J., Ostriker, E., Wilkin, F., Ruden, S., & Lizano, S. 1994, ApJ, 429, 797

Simon, M. & Prato, L. 1995, ApJ, 450, 824

Skrutskie, M. F., Dutkevich, D., Strom, S. E., Edwards, S., Strom, K. M., & Shure, M. A. 1990, AJ, 99, 1187

Strom, K. M., Strom, S. E., Edwards, S., Cabrit, S., & Skrutskie, M. F. 1989, AJ, 97, 1451

Swenson, F.J., Faulkner, J., Rogers, F.J., & Iglesias, C.A. 1994, ApJ, 425, 286

Tull, R. G., MacQueen, P. J., Senden, C., & Lambert, D. L. 1995, PASP, 107, 251

Valenti, J. A. 1994, PhD Thesis, University of California, Berkeley, CA

Valenti, J. A., Basri, G., & Johns, C. M. 1993, AJ, 106, 2024

Vogt, S. S. 1987, PASP, 99, 1214

Vogt, S. S. *et al.* 1994, Proc. SPIE, 2198, 362

Weaver, W. B. & Jones, G. 1992, ApJS, 78, 239
Zucker, S. & Mazeh, T. 1994, ApJ, 420, 806

TABLE I. Radial Velocity Measurements of DQ Tau

			Resolved Velocity Measurements				Velocity Separation Upper Limits
			Primary		Secondary		
Julian Date	Phase	Tel.[a]	R.V. (km s^{-1})	O-C (km s^{-1})	R.V. (km s^{-1})	O-C (km s^{-1})	R.V. (km s^{-1})
2445982.03	0.18	M	32.4	-3.2	13.8	5.0	
2447073.94	69.27	F	34.8	0.3	10.8	0.9	
2447075.99	69.40	M	33.0	1.8	14.0	0.8	
2447078.01	69.53	M					< 18
2447127.82	72.68	M					< 18
2447128.81	72.74	M					< 18
2447159.62	74.69	M					< 18
2447427.93	91.67	M					< 18
2447546.63	99.18	M	33.0	-2.6	7.5	-1.3	
2447789.94	114.58	M					< 18
2447840.80	117.79	F					< 18
2447844.76	118.04	M					< 18
2447845.87	118.11	M	38.4	4.4	11.8	1.4	
2447896.73	121.33	M	33.2	0.1	10.1	-1.3	
2447898.77	121.46	M	34.7	5.4	15.4	0.3	
2447902.70	121.71	M					< 18
2448525.96	161.15	M	33.9	-1.4	6.4	-2.8	
2448670.64	170.30	M	35.0	1.2	12.9	2.3	
2449288.96	209.42	L	30.0	-0.5	14	0.1	
2449289.72	209.47	L	31.0	2.0	13	-2.4	
2449290.90	209.55	L	27.5	1.1	16.5	-1.6	
2449344.86	212.96	M	-9.0	-3.2	49.9	-0.3	
2449344.89	212.96	L	-6.5	-0.7	53.0	2.8	
2449345.74	213.02	L	8.0	-1.5	36.0	1.1	
2449345.93	213.03	L	16.5	1.1	27.5	-1.5	
2449352.85	213.47	L	28.5	-0.7	15.5	0.2	
2449373.69	214.79	M	12.4	-1.4	32.7	2.0	
2449410.63	217.12	F	30.6	-3.8	5.2	-4.8	
2449644.83	231.94	M	-0.2	4.1	46.9	-1.8	
2449664.84	233.21	Mc	36.7	1.2	7.3	-1.7	
2449665.85	233.27	Mc	33.5	-1.0	8.5	-1.5	
2449666.77	233.33	Mc					< 5
2449670.87	233.59	L					< 5
2449675.88	233.91	L	-1.0	0.6	45.0	1.2	
2449676.85	233.97	K	-3.5	2.2	47.5	-2.6	

TABLE I. (continued)

			Resolved Velocity Measurements				Velocity Separation Upper Limits
			Primary		Secondary		
Julian Date	Phase	Tel.[a]	R.V. (km s^{-1})	O-C (km s^{-1})	R.V. (km s^{-1})	O-C (km s^{-1})	R.V. (km s^{-1})
2449680.09	234.17	K	34.5	-1.1	9.5	0.6	
2449681.10	234.24	K	33.5	-1.6	10.5	1.2	
2449682.99	234.36	L	32.0	-0.5	12.0	0.0	
2449683.96	234.42	L	30.8	0.1	13.3	-0.4	
2449684.95	234.48	K	27.0	-1.7	17	1.3	
2449685.78	234.53	Mc					< 8
2449686.11	234.55	K	26.0	-0.1	18	-0.3	
2449686.78	234.60	Mc					< 8
2449687.79	234.66	Mc					< 8
2449699.80	235.42	M	34.2	3.6	16.6	2.8	
2449706.65	235.85	McD	7.0	-0.4	37.0	0.0	
2449707.67	235.92	McD	-0.9	0.1	44.9	-0.5	
2449708.63	235.98	McD	-4.7	0.1	48.7	-0.5	
2449787.70	240.98	L	-5.0	-0.8	49.0	-0.4	
2449788.73	241.05	K					< 5
2449789.72	241.11	L	34.0	0.3	10.0	-0.8	

[a] Telescope: F = FLWO 1.5m; K = Keck 10m; L = Lick 3m; M = MMT; McD = McDonald 2.7m; Mc = McDonald 2.1m

TABLE II. Spectroscopic Orbital Elements of DQ Tau

Element	CfA	CfA + LKM
P (days)	15.810 ± 0.006	15.8043 ± 0.0024
γ (km s^{-1})	22.4 ± 0.6	*22.21 ± 0.24* [a]
K_1 (km s^{-1})	21.6 ± 2.3	*20.7 ± 0.5*
K_2 (km s^{-1})	22.4 ± 2.3	*20.7 ± 0.5*
e	0.58 ± 0.07	0.556 ± 0.018
ω (degrees)	228 ± 5	230.6 ± 2.2
T (JD_o - 2440000)	9582.78 ± 0.23	9582.54 ± 0.05
$q = M_2/M_1$	0.97 ± 0.15	*1.00 ± 0.03*
$M_1 \sin^3 i$ (M_o)	0.039 ± 0.008	*0.033± 0.002*
$M_2 \sin^3 i$ (M_o)	0.037 ± 0.008	*0.033± 0.002*
$a_1 \sin i$ (AU)	0.026 ± 0.003	*0.024 ± 0.009*
$a_2 \sin i$ (AU)	0.027 ± 0.003	*0.024 ± 0.009*
N (prim + sec)	28	72

[a] Values in italics are biased, as discussed in Section 2. Use of the CfA values and uncertainties is recommended in these cases.

TABLE III. Summary of BAIT Optical Photometry of DQ Tau

Filter	JD Range (2440000+)	No. of Measurements	No. of Nights With Data	σ_{dm} (DQ Tau) (mag)	σ_{dm} (comp star) (mag)
V	9364 - 9447	43	33	0.20	0.02
V	9637 - 9670	12	9	0.18	0.02
V†	4673 - 6774	76	76	0.24	--
R	9364 - 9444	57	41	0.16	0.02
R	9625 - 9696	38	23	0.14	0.02
I	9363 - 9449	73	49	0.08	0.02
I	9625 - 9687	31	18	0.06	0.01
Unfiltered‡	8200 - 8233	19	19	0.10	0.03

† Source: Herbst *et al.* (1994)
‡ Source: Richter *et al.* (1992)

TABLE IV. Photometric Measurements of DQ Tau

λ (μm)	Flux (mJy)	Reference
0.36	0.68	Strom *et al.* 1989
0.44	3.7	"
0.55	13.8	"
0.64	33.5	"
0.79	80.6	"
1.25	380. ± 20	This paper (J = 9.07)
1.65	490. ± 50	" (H = 8.3)
2.2	480. ± 25	" (K = 7.84)
3.8	660. ± 60	" (L' = 6.45)
4.8	610. ± 60	" (M = 6.1)
10.1	630	Simon & Prato 1995
25	1220	Weaver & Jones 1992
60	1260	"
450	320 ± 60	This paper
769	290	Beckwith & Sargent 1991
800	180 ± 25	This paper
1056	125	Beckwith & Sargent 1991
1100	110 ± 20	This paper
1300	91	Beckwith *et al.* 1990

Figure Captions:

Figure 1: The phased radial-velocity measurements and orbit curves for DQ Tau. The filled symbols represent radial-velocity measurements of the primary, while the open symbols represent radial-velocity measurements of the secondary. Squares represent data obtained at CfA telescopes, while triangles represent data obtained from the Keck/Lick/McDonald observations. Limits derived from unresolved spectra are shown as arrows.

Figure 2: V, R and I light curves obtained with the Berkeley Automated Imaging Telescope. In each bandpass the mean of the differential magnitudes has been set to zero. DQ Tau shows discrete brightening events, which are correlated in the three bandpasses. These events are periodic with the same period as the binary; line segments mark those time intervals during which brightening events are expected to occur (orbital phase -0.25 to 0.05).

Figure 3: a) A Scargle periodogram of all available V photometry of DQ Tau. The confidence levels are derived by Monte Carlo simulations of the actual time distribution of observations. Note that the strongest peak is at 15.80 days, equal to the binary orbital period. b) The Scargle periodogram from the same data after applying a harmonic filter at a period of 15.80 days. This filter eliminates all of the statistically significant features in Figure 3a, suggesting that they are all aliases of the 15.80-day feature.

Figure 4: Several photometric data sets phased to the binary period of 15.804 days. Phase zero corresponds to the binary periastron passage. The brightenings of DQ Tau are confined to a limited range of binary orbital phase centered on periastron passage. a) The R data from the Berkeley Automated Imaging Telescope. b) The V data from the literature compilation of Herbst *et al.* (1994). c) The combination of V data from the Berkeley Automated Imaging Telescope, V data from the literature, and the unfiltered CCD photometry of Richter *et al.* (1992).

Figure 5: Differential V-I (panel a), V-R (panel b), B-V (panel c) and U-B (panel d) plotted against V. The (V-I) and (V-R) data are from the Berkeley Automated Imaging Telescope; the (B-V) and (U-B) data are from the literature. Note the close correlation of color with brightness, in the sense of the combined light becoming more blue with increasing brightness.

Figure 6: The spectral energy distribution of DQ Tau (filled squares; error bars are smaller than the symbols unless shown). The long-dashed line shows a 4000 K theoretical atmosphere fit to the VRI data, giving a stellar luminosity of 0.85 L_O and an extinction of A_V=2.0. a) The short-

dashed curve shows the theoretical SED of a geometrically thin, optically thick, reprocessing disk. The solid curve shows the SED of an active (q=0.57) disk. The power-law index of the submillimeter opacity is β = -0.5. b) The solid curve shows the SED of a disk with a central hole of radius 0.4 AU in which the binary resides. The dashed line represents a similar disk but with 5×10^{-10} $M_{\odot}$ of warm (1000 K) optically thin dust in the hole.

Figure 7: The triangles show the V data for DQ Tau phased with the binary orbit. Phase zero corresponds to the binary periastron passage. The solid line shows the theoretical accretion rate due to time-variable mass flows from the circumbinary disk, plotted as a function of orbital phase (Artymowicz & Lubow 1996). The agreement in the *phasing* of the predicted bursts in accretion rate with the observed brightenings of DQ Tau is striking. The duration and magnitude of the DQ Tau brightenings are more variable than the theory would suggest.