Disk-Disk Interactions and Orbitally-Modulated Accretion in the DQ Tau System

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Abstract

We present multi-epoch low and moderate resolution near-infrared spectra of the high eccentricity tight binary, DQ Tau. Similar to activity previously recorded in optical spectra, we see clear evidence of orbitally-modulated accretion activity phased with periastron passages in the system. However, during one of four apastron passes observed, we measure a significant enhancement in the infrared accretion indicators. The potentially anomalous accretion flare is interpreted as matter passing directly from the circumbinary disk onto one or both of the highly truncated circumstellar disks. The nature and frequency of these disk-disk interactions are important for constraining hydrodynamic models of accretion activity in such systems as well as in young planetary systems containing forming gas giants. We also explore a consistent spectral typing mismatch between atomic and molecular band absorption features. We determine that this discrepancy is consistent with the formation of the molecular features within large cool spots on the stellar surface(s) and is not due to the lower surface gravity associated with the contracting T Tauri stars. In addition to changes in continuum veiling, variations observed in the strength of the TiO bands at 0.85 and 0.88 μm could be explained by spot evolution and the heating of these spots during accretion events,.

The DQ Tau System

DQ Tau is a tight binary (P~15.8016 days; a = 0.13 AU)[1] composed of two nearly equal mass stars (~0.33 M_{sun})[2] on a highly eccentric orbit (e = 0.556)[2]. Multi-epoch broad-band photometry and optical spectroscopy have revealed periodic flares in this system that are phased with periastron passages[2,3]. The flaring activity depicted in Figure 1 is well-described by hydrodynamic models that predict orbitally-modulated flows of material between the outer circum*binary* disk and the inner circum*stellar* disks[4,5]. It has also been demonstrated that magnetospheric interactions contribute to the flaring activity, but cannot entirely account for the duration of the flares[6,7,8,9].

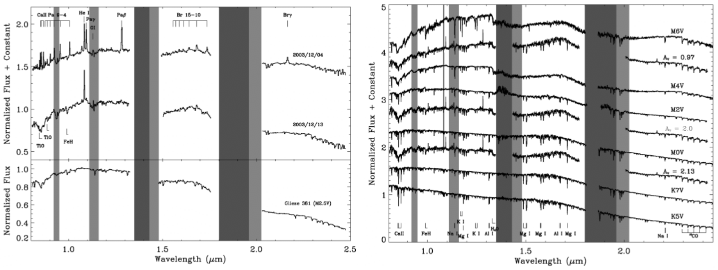

Figure 1: a) Left: Example of two low resolution DQ Tau spectra observed nine days apart with CorMASS on the Vatican Advanced Technology Telescope. The top spectrum taken near periastron (ϕ=0.876) and the second just before apastron (ϕ=0.437). Note the strong H I emission features and other accretion signatures present in the top spectrum. An M2.5V SpeX IRTF spectral standard is included for comparison. Regions of poor and moderate atmospheric transmission are denoted by the gray (<80%) and dark gray (<20%) vertical boxes.
b) Right: Sequence of near-IR spectra from SpeX IRTF spectral library[10]. Interspersed is a SpeX observation of DQ Tau taken on 2011 November 13 UT corrected with three different published values of the visual extinction. The DQ Tau spectra are positioned so as to be bracketed by the spectral standards that best match their overall shape.

Spectral Typing and Cool Star Spots

Moderate resolution near-IR spectra collected with SpeX (IRTF) and TripleSpec (Apache Point Observatory) provide an opportunity to measure the spectral type for DQ Tau. Figure 1b presents a sequence of spectral standards and one SpeX observation of DQ Tau dereddened using the three values for A_v found in the literature and the reddening law from Martin & Whittet 1990[11]. For the lowest A_v value, the shape of the spectrum is best matched by a late M-type star (M5V & M6V), which is far cooler than the M0-1.5V spectral type often quoted[12,13,14] for DQ Tau. The strengths of multiple temperature sensitive metallic features are in better agreement with the earlier M spectral types (Figure 2b). It is notable that the TiO bands at 0.85 and 0.88 μm are stronger than those in the early M spectra and agree better with the later M dwarf spectral types (Figure 2a). This is also true for FeH at 0.99 μm, the broad water absorption bands at 1.4 and 1.9 μm, and the 1.33 μm water feature. Direct comparisons to giant star spectral standards demonstrate that the discrepancy between the strengths of the molecular and metallic features cannot be accounted for by differences in surface gravity. Instead, we find that the most likely explanation to be the existence of large cool spots on the surface(s) of these companions. The observed spectrum is a synthesis of hotter photosphere and the cooler spot similar in nature to the spots observed in RS CVn systems[15,16,17,18]. Therefore, we agree with previous studies that have assigned an early M dwarf type to DQ Tau and attribute the discrepancy to star spots.

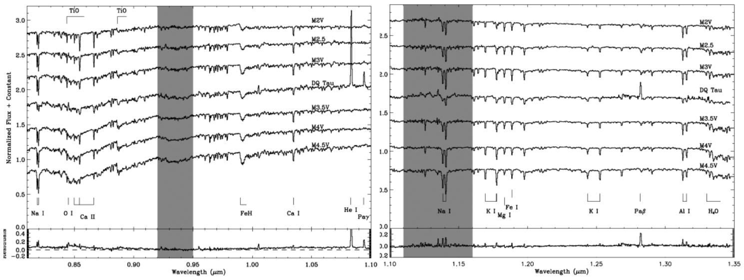

Figure 2: a) Left: A comparison of M dwarf spectra to a dereddened spectrum of DQ Tau for A_v = 0.97. M dwarfs chosen to bracket DQ Tau based on strengths of the TiO and FeH features. The residual spectrum is the difference between DQ Tau and the M3.5V standard. b) Right: A similar comparison over a different wavelength regions containing several metal lines. Residuals shows the the metal features more strongly agree with the earlier M type standards, while the strength of the 1.33 μm water band suggests a cooler spectral type.

Spectral Variability and Veiling

After choosing an M1 spectral type, we next take a look at variations in the veiling and the spectral type. Figure 3a (below) shows measurements of veiling for multiple epochs. A correlation between orbital phase and accretion activity is not obvious from these data. Figure 3b highlights the variations observed in the TiO bands and the continuum between 0.8 and 1.3 μm. Using the ϕ=0.500 observation as a reference, we measured maximum variations on the order of 15-20% in the strength of the continuum and the TiO absorption band. Lacking a correlation between veiling and accretion activity, we conclude that fluctuations in the TiO band and the overall spectral shape may be related to heating and evolution of the cool spots.

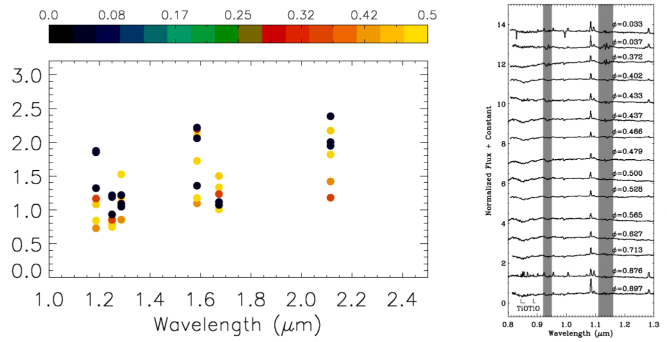

Figure 3: a) Left: Veiling is plotted as a function of wavelength determined from Fe I (1.189 μm, K I (1.253 μm), Mn I (1.29 μm), Mg I (1.589 μm), Fe I (1.676 μm), and Al I (2.117 μm) for seven epochs of DQ Tau spectra using the non-accreting T Tauri star, LkCa 3 (M1V), as a reference. Color coding represents the proximity in orbital phase of the observation to periastron. b) Right: Plotted from 0.8 to 1.3 μm are 15 DQ Tau spectra arranged by orbital phase.

Apastron Flare and Disk-Disk Interactions

On back-to-back nights 2006 October 4 & 5 UT (ϕ = 0.372 & 0.433), we detect an accretion-like flare as the system approaches apastron (see Figures 3b & 4). The mass accretion rate measured for the anomalous flare is an order of magnitude stronger than the quiescent accretion activity observed during the majority of the orbit. Little evidence currently exists to suggest that orbitally-modulated accretion flares occur near apastron when the stars make their closest approach to the circumbinary disks. Hydrodynamic models of circumstellar-circumbinary disk interactions predict that pulsed-accretion activity phased with periastron passages is dominated by interactions between the circumstellar disks[5]. The timing of the anomalous flare with respect to an apastron passage suggests that this outburst is due to the interactions of the circumstellar disk(s) with the circumbinary disk. In the four apastron passes observed with infrared spectra, only one shows obvious signs of flaring activity above the quiescent accretion level. With no other reported detections of apastron accretion flares, we conclude that these events occur more rarely than those at periastron. Long term monitoring of such tight binary systems will be important for understanding orbitally-modulated accretion activity in these system and analogous young planetary systems with forming gas giant planets.

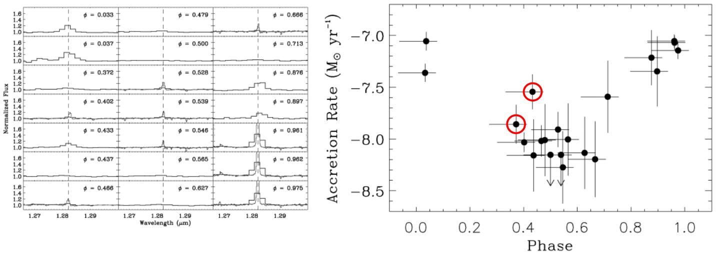

Figure 4: a) Plots of the Pa β emission feature for all 21 observations of DQ Tau. Moderate resolution observations have deresolved spectra overplotted for comparison. b) A log plot of the mass accretjon rates as a function of phase were determined from Pa β line fluxes. The flare values detected near apastron are circled in red. Upper limits are denoted with down arrows.

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