The Accretion Process in the DQ Tau Binary System

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Abstract

Mass accretion from the circumstellar disk onto the protostar is a fundamental process during star formation. Measuring the mass accretion rate is particularly challenging for stars belonging to binary systems, because it is often difficult to discriminate which component is accreting. DQ Tau is an almost equal-mass spectroscopic binary system where the components orbit each other every 15.8 days. The system is known to display pulsed accretion, i.e., the periodic modulation of the accretion by the components on eccentric orbit. We present multi-epoch ESO/Very Large Telescope X-Shooter observations of DQ Tau, with the aim of determining which component of this system is the main accreting source. We use the absorption lines in the spectra to determine the radial velocity of the two components, and measure the continuum veiling as a function of wavelength and time. We fit the observed spectra with nonaccreting templates to correct for the photospheric and chromospheric contribution. In the corrected spectra, we study in detail the profiles of the emission lines and calculate mass accretion rates for the system as a function of orbital phase. In accordance with previous findings, we detect elevated accretion close to periastron. We measure the accretion rate as varying between $10^{-8.5}$ and $10^{-7.3} M_\odot$ yr$^{-1}$. The emission line profiles suggest that both stars are actively accreting, and the dominant accretor is not always the same component, varying in a few orbits.

Unified Astronomy Thesaurus concepts: Stellar accretion disks (1579); Spectroscopic binary stars (1557); Young stellar objects (1834); Circumstellar disks (235); Stellar accretion (1578); Spectroscopy (1558)

1. Introduction

In the last few decades, the star formation process has been investigated and studied in detail for single low-mass stars. In the scenario described by the magnetospheric accretion model (Hartmann et al. 2016), a strong magnetic field of the young star guides the accretion flow, which is responsible for the interplay between the star and the disk. This strong magnetic field truncates the inner edge of the circumstellar disk in a region where the viscous pressure balances the magnetic pressure, called the magnetospheric radius ($R_{\text{MD}}$). This typically occurs at a distance of $R_{\text{MD}} \sim 5-10 R_*$ This single-star accretion scenario has been confirmed by a large amount of observational evidence of classical TTauri stars (CTTs) that supports the physical mechanism of the inner disk truncation (e.g., Rigliaco et al. 2012; Antoniucci et al. 2014; Alcalá et al. 2014, 2017; Manara et al. 2017, 2019; Fiorellino et al. 2021). However, the single-star accretion scenario fails to describe close binary systems (with separation below 100 au), for which the presence of the other component affects the dynamics or even the presence of the circumstellar disks, and, as a consequence, the accretion process.

The current binary system accretion scenario has two main predictions (Monin et al. 2007; Tofflemire et al. 2017). First, the orbital motion clears a certain region around the two components, leading to the formation of up to three disks: two circumstellar disks, one around each component, and a circumbinary disk (CBD; Artyomowicz & Lubow 1994), which has been confirmed through observations (e.g., Andrews et al. 2011). Second, due to the dynamics of the binary system, some material from the CBD periodically forms accretion streams that directly fuel the circumstellar disks, if any, or the forming stars (Artyomowicz & Lubow 1996). The theoretical simulations by Muñoz & Lai (2016) predict that in equal-mass binary systems, if the orbit is highly eccentric, the main accretor has a mass accretion rate up to 10–20 times larger than its companion, and the main accretor changes after about 100 periods, always with a larger mass accretion rate. This prediction makes highly eccentric, equal-mass binaries the ideal laboratory for studying the accretion and verifying hydrodynamical simulations.

The double-lined spectroscopic binary DQ Tau is the archetype of equal-mass, highly eccentric, close binary systems. It was discovered by Mathieu et al. (1997). DQ Tau is composed of two low-mass M0–M1 type CTTs that orbit each other with an orbital period of $P = 15.80158 \pm 0.00066$ days and an eccentricity of 0.568 (Czekala et al. 2016). The rotational period of the stars is $T = 3.017 \pm 0.004$ days (Kóspál et al. 2018). The most recent and accurate determination of the stellar mass was given by Czekala et al. (2016), by combining the orbital solution fitted to radial velocity (RV) data and a disk model fitted to Atacama Large Millimeter Array CO observations. Adopting a distance of 155 pc, they obtained $M_{\star,1} \pm M_{\star,2} = 1.21 \pm 0.26 M_\odot$. Here, we adopt the Gaia Early Data Release 3 (EDR3) distance of $d = 195$ pc (Bailer-Jones et al. 2021). Since the mass scales linearly with the distance (Czekala et al. 2016), the total mass of the system at 195 pc is $M_{\star,1} \pm M_{\star,2} = 1.52 \pm 0.33 M_\odot$. Using the mass ratio computed by Czekala et al. (2016), $M_2/M_1 = 0.93 \pm 0.05$, the masses of the individual components are $M_{\star,1} = 0.74 M_\odot$ and $M_{\star,2} = 0.78 M_\odot$. The new distance together with the constraints
from the orbital solution of Czekala et al. (2016) provide a new inclination of 20.7 deg and a new orbital major axis of a = 0.142 au.

One of the first estimates of the mass accretion rate (\(M_{\infty}\)) of DQ Tau was obtained by studying the luminosity of the boundary layer, providing log \(M_{\infty}\) = −7.3 (Hartigan et al. 1995). They provided the first results for its orbit and light curves, and they interpreted the accretion process of DQ Tau in the frame of the "pulsed accretion model" (Artymowicz & Lubow 1996), according to which the accretion is highly modulated by the binary’s orbital motion, peaking during periastron passages, with 90% of the total mass accreted between phases \(\phi = 0.7–1.3\). At those phases, the accretion rate increases on average by a factor of five, in agreement with the Muñoz & Lai (2016) simulations. This interpretation has been confirmed in the following DQ Tau accretion studies (e.g., Salter et al. 2010; Tofflemire et al. 2017; Köspál et al. 2018; Muzerolle et al. 2019). However, while the average results confirm the model predictions, Tofflemire et al. (2017) found a complex variability from epoch to epoch, suggesting that the material accretes from the inner edge of the CBD in a more complex way than predicted by models. Accretion events near apastron were also observed and seem to be (quasi)periodic in nature.

To better understand the complex accretion process in the DQ Tau system, we computed the mass accretion rate of this source by analyzing the emission lines that trace accretion streams over a wide wavelength range, from the ultraviolet (UVB) to the near-infrared (NIR), for eight epochs, with high-resolution spectra. In this way, we were able to study the accretion variability, and to discuss which component is accreting the most.

The structure of the paper is as follows. In Section 2, we report the observations and the data reduction, including telluric correction and flux calibration. In Section 3, we describe how we computed the radial velocity, the veiling, the extinction, and the spectral type of DQ Tau. In Section 4, we describe how we subtracted the photospheric and chromospheric contributions to our spectra, focusing on the analysis of the accretion rates. In Section 5, we summarize our results and draw conclusions.

2. Observations and Data Reduction

Observations were taken at eight different epochs between 2012 November 18 and 2013 March 11 with the X-Shooter spectrograph on the Very Large Telescope (VLT) at ESO’s Paranal Observatory in Chile (Vernet et al. 2011). X-Shooter simultaneously covers a wide wavelength range from 300 nm to 2480 nm, and the spectra are divided into three arms: the UVB (300–550 nm), the visible (VIS; 500–1020 nm), and the NIR (1000–2480 nm). Observations of DQ Tau were performed with the narrow slits of 0.5″, 0.4″, and 0.4″ in the UVB, VIS, and NIR, respectively, leading to spectral resolutions of \(R \sim 9700, 18,400\), and 11,600, respectively. The exposure time in each epoch was 1220 s, 840 s, and 1200 s in the three arms, respectively.

The data are publicly available in the ESO archive.4,5 We downloaded data reduced with the VLT/X-Shooter pipeline, consisting of extracted, wavelength-calibrated, and flux-calibrated one-dimensional spectra in tabular format, following the established standard for ESO science data products.

We performed the telluric correction of the VIS and NIR bands using the molecfit tool v3.0.3 (Kausch et al. 2015). This included correction for molecular bands as \(\text{O}_2\) and \(\text{H}_2\text{O}\) lines in VIS (Erick et al. 1998; Newnham & Ballard 1998), where strong residuals remained even after telluric correction. We computed the signal-to-noise ratio (S/N) for the spectra after discarding the noisy parts where atmospheric transmission is very low, between the \(JHK\) bands. The S/N of the spectra depends on the wavelength and on the actual seeing and airmass, being on average higher in the NIR (\(~203\)) than in the VIS (\(~132\)) and in the UVB (\(~68\)). Further details about the observations are reported in Table 1, where the mean seeing, airmass, and S/N values for each epoch are listed. Table 1 also shows the barycentric velocity correction \(\beta\), computed using the software BARYCORPY (Kanodia & Wright 2018). We applied the appropriate correction to each spectrum.

In order to flux calibrate our spectra, we collected multifilter photometry for DQ Tau from the literature (Muzerolle et al. 2019) and data archives (ASAS-SN; Shappee et al. 2014; Kochanek et al. 2017). The light curves of DQ Tau are plotted in Figure 1, along with the epochs when the X-Shooter spectra were taken. We used \(BVIJK\) photometry from Figure 1 for the flux calibration. For the first four epochs, we simply interpolated the available photometry for the exact observing times of the spectra. For Epoch 5, only ASAS-SN \(V\)-band photometry is available. So we fitted the linear relation between each band and the \(V\)-band photometry. Then we applied this relation to the \(V\)-band, finding the putative \(B\), \(I\), \(J\), \(H\), and

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4 http://archive.eso.org/wdb/wdb/adp/phase3_main/query
5 http://archive.eso.org/scopeportal/home
K-band photometry. Lastly, no photometry in any band is available for Epochs 6, 7, and 8. To flux calibrate these spectra, we computed the phases, listed in Table 1, of these epochs from the orbital parameters provided by Czekala et al. (2016), and we used the averaged data of the V-band for previous periods at the same phase. Then we applied the fitted relation already used for Epoch 5 to estimate the B-, I-, J-, H-, and K-band photometry.

We then convert our photometry from magnitudes to fluxes, by using Bessel zero fluxes. We linearly interpolated the fluxes for all the wavelength ranges to flux calibrate the spectra wavelength by wavelength.

The achieved flux calibration of the X-Shooter spectra is shown in Appendix A, in Figure 13, epoch by epoch, and in Figure 14, for all the epochs.

3. Analysis

3.1. Spectral Type and Extinction

We performed the spectral typing of DQ Tau by comparing our spectra to a grid of empirical templates from G4 to M9.5 (Manara et al. 2013) that has typical steps of one spectral subclass for spectral types G and K and 0.5 spectral subclass for M-type stars. For the comparison, we used only those observed spectra in which the two components were not resolved, so that the overall system can be treated as a single star, which means Epoch 3 (see Table 2). We reddened the templates, and shifted their fluxes to that of DQ Tau in two windows of Δλ = 5 nm: one around λ = 570 nm, the other around λ = 1230 nm. By varying the template and the extinction, and matching the shape of the overall spectrum and the molecular features of our data with those of the templates, we find that the best-fitting spectral type for the DQ Tau system is M0, in agreement with the literature (Herbig 1977; Herczeg & Hillenbrand 2014; Czekala et al. 2016), with $A_V = 1.7$ mag. After having computed the veiling (see Section 3.3), we checked this spectral type by correcting the spectra for the veiling. Our best fit is still the M0 type with $A_V = 1.7$ mag. This is not surprising, because the veiling is low in the VIS, and increases only in the NIR, where we expect the IR excess (see Figure 4).

We computed the extinction toward DQ Tau for Epoch 3 in an independent way as well, with the help of the color–color diagram shown in Figure 2, for the same reasons described above. We evaluated the needed extinction to shift the position of the DQ Tau system on the CTT locus (Meyer et al. 1997), by using the extinction law of Cardelli et al. (1989) and $R_V = 3.1$. The resultant extinction we found was $A_V = 1.72 \pm 0.26$ mag, in agreement with the literature (e.g., Tofflemire et al. 2017) and with our spectral typing. We adopt this latter value as the

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**Figure 1.** The light curve of DQ Tau. The epochs of the X-Shooter observations are marked with the black point-dashed lines. The epochs of periastron passage are marked with the blue lines. Note that Epoch 2 and Epoch 7 correspond to periastron passages. Light curves are obtained from ASAS-SN data or from Muzerolle et al. (2019) photometry, as described in the legend.

| Epoch | $\phi$ | $RV_1$ (km s$^{-1}$) | $RV_2$ (km s$^{-1}$) | $\log(\ell_{acc}/\ell_\odot)$ | $\log(M_{acc}/M_\odot/yr)$ | Number of Detected Lines |
|-------|-------|----------------------|----------------------|-----------------------------|-----------------------------|-------------------------|
| 1     | 0.90  | $-6.11 \pm 0.27$     | $42.70 \pm 0.42$     | $-0.144 \pm 0.032$          | $-7.313 \pm 0.032$          | 37                      |
| 2     | 0.96  | $4.56 \pm 0.37$      | $38.19 \pm 0.44$     | $-0.138 \pm 0.039$          | $-7.307 \pm 0.039$          | 36                      |
| 3     | 0.62  | $22.08 \pm 0.14$     | $22.08 \pm 0.14$     | $-1.380 \pm 0.034$          | $-8.549 \pm 0.034$          | 20                      |
| 4     | 0.74  | $6.38 \pm 0.40$      | $27.08 \pm 0.48$     | $-1.093 \pm 0.032$          | $-8.262 \pm 0.032$          | 25                      |
| 5     | 0.89  | $-4.82 \pm 0.73$     | $43.28 \pm 0.26$     | $-0.423 \pm 0.031$          | $-7.592 \pm 0.031$          | 37                      |
| 6     | 0.08  | $34.83 \pm 0.52$     | $-1.24 \pm 0.68$     | $-0.744 \pm 0.035$          | $-7.913 \pm 0.035$          | 28                      |
| 7     | 0.98  | $9.79 \pm 1.82$      | $23.78 \pm 0.14$     | $-0.508 \pm 0.024$          | $-7.678 \pm 0.024$          | 34                      |
| 8     | 0.04  | $6.33 \pm 0.33$      | $38.25 \pm 0.83$     | $-0.793 \pm 0.046$          | $-7.962 \pm 0.046$          | 34                      |

**Note.** The orbital phase ($\phi$) is computed with respect to the nearest previous periastron, assuming the parameters from Czekala et al. (2016).
interstellar extinction and $A_V = 0$ for the circumstellar extinction because in Kóspál et al. (2018), the dips due to circumstellar extinction only cause very small changes, and only for 4.85 days in total, which corresponds to 6% of the time, suggesting that all the extinction of DQ Tau is basically due to the interstellar medium.

### 3.2. Radial Velocity

The RV of the DQ Tau components was measured using the SAPHIRES code\footnote{https://github.com/tofflemire/saphires}, which determines the relative broadening functions (BFs). For a complete description of the code, we direct the reader to Tofflemire et al. (2019). To compute the BFs and RVs, high-resolution empirical templates of non-accreting Class III spectra were used (Manara et al. 2013). As a first step, we found the best-fit template spectrum that matches DQ Tau by determining the BFs among the various spectral types ranging from K7 to M3.5. We used only the VIS and NIR spectra, where the continuum and absorption lines are detected with higher S/N than in the UVB. Among the various spectral types in both VIS and NIR, the BF obtained by using the M0 template (TYC 7760-283-1) showed the best fit with our spectra. To measure the RVs, we only utilized the VIS, because of its higher resolution and relatively well-corrected telluric absorption features. In addition to having the best BFs, the M0 template shows the smallest uncertainties of RVs for all the observed epochs among all the different spectral types. Consequently, we adopted the M0 template to measure the RVs of DQ Tau. We note that the M0 template is also compatible with the spectral type we obtained in Section 3.1.

The RV of the M0 template spectrum was measured by fitting the BFs with a synthetic spectrum ($T_{\text{eff}} = 3750$ K, log $g = 1$, and solar abundance; Coelho et al. 2005). We obtained $RV = 6.26 \pm 1.52$ km s$^{-1}$. The barycentric velocity of the template spectrum was computed by using barycorrpy (Kanodia & Wright 2018) as 2.74 km s$^{-1}$. The template spectrum was therefore shifted by RV and barycentric velocity. The resultant velocity-corrected spectrum was used to measure the RVs of DQ Tau.

The RVs of DQ Tau were computed by considering 22 fitting regions with about 100 Å wavelength intervals for each epoch. We excluded wavelength ranges where emission lines and strong residuals from telluric absorption lines were present. The mean and standard deviation values are adopted as the RV and its uncertainty, respectively. In most epochs, the BFs were double-peaked, so we could fit separately the RVs of the two components in all epochs, except for Epoch 3. For Epoch 3, the BF is single-peaked, so the RVs of the two stars must be identical within the uncertainties; as such, for this epoch, we give the same value for both stars in Table 2, where the results are listed. These values are plotted in Figure 3.

The top panel in Figure 3 shows the RVs we measured and those from Czekala et al. (2016). To calculate the orbital phase, we adopted the orbital solutions from Czekala et al. (2016), also shown in the figure as solid lines. The phase coverage of our eight measurements is not sufficient to determine a Keplerian solution independently, but our results agree with those from Czekala et al. (2016). There is a slight offset between the absolute values of our RVs and those from Czekala et al. (2016), but as shown in the bottom panel of Figure 3, the RV differences of the two components are well consistent with previous studies (Czekala et al. 2016;
3.3. Veiling

In order to subtract the chromospheric and photospheric contribution from the DQ Tau spectra, we first evaluated the veiling of the source. We first normalized the observed spectra ($F_{\nu,\text{obs}}$) and the template spectrum ($F_{\nu,\text{temp},0}$), then applied a veiling $V$ to the template:

$$F_{\nu,\text{temp, veiled}} = \frac{F_{\nu,\text{temp},0} + V}{1 + V}.$$  

We call the $V$ parameter *continuum veiling* in accordance with the usual practice in the literature (Basri & Batalha 1990), while acknowledging that line veiling may contribute to the measured value. It was suggested that emission lines may cause additional veiling (on top of the veiling caused by continuum emission) by Folha & Emerson (1999). Dodin & Lamzin (2012) wrote that narrow emission lines in the postshock region contribute to the veiling of the photospheric absorption lines, and concluded that this contribution is most significant for moderately accreting CTTs. Therefore, this could potentially be important for DQ Tau. Rei et al. (2018) studied high-resolution spectra of three T Tauri stars and found strongly line-dependent veiling: the veiling was larger if measured from stronger photospheric lines, and lower or absent from weaker lines. They concluded that the best estimate for the true value of the continuum veiling can be obtained by measuring the weakest photospheric lines with equivalent widths (EWs) down to 10 mÅ, and that lines with EW above 100 mÅ may already suffer from line veiling.

To find out if line veiling is significant in DQ Tau, we checked the EWs of the photospheric absorption lines we used for our veiling calculation. We found that all of these lines have EWs < 100 mÅ in epochs 1, 2, and 5, and only one to eight lines have EWs > 100 mÅ in the other epochs. We found no correlation between the measured veiling and the EWs in any of the epochs. Because we used only lines with EWs < 100 mÅ for our veiling calculations (with a few exceptions), according to Rei et al. (2018), our results should give the best possible estimate of the true level of the continuum veiling. As we see no dependence of the veiling on EW, we can conclude that in the EW range we used for our calculations, line veiling is negligible. For each epoch, we measured the veiling by studying suitable wavelength ranges around the absorption lines, which are sensitive to the veiling itself. We varied the veiling values between 0 and 3, in steps of 0.01, and computed the $\chi^2$ between the veiled template $F_{\nu,\text{temp, veiled}}$ and the DQ Tau spectrum $F_{\nu,\text{obs}}$, choosing the veiling value that minimizes the $\chi^2$. In the following analysis, we use the same veiling for the two components, assuming that in each epoch the primary and the secondary both suffer the same veiling. This is not necessarily true, but the limited spectral resolution of X-Shooter, compared to the relatively narrow photospheric absorption lines, and the rather low S/N of the individual absorption lines did not allow us to measure the veiling separately for the two components. Figure 4 shows the veiling values measured in 5 nm wide wavelength ranges for selected absorption lines. We discarded the portions of the spectra where strong residuals of telluric absorption were present. To better outline the general trend of how the veiling varies with wavelength and time, we calculated the median values of the measured veiling values in 200 nm wide bins. We plotted these median values in black in Figure 4, which reveals two main trends: (i) in Epochs 2, 3, 4, 6, 7, and 8, the veiling is almost constant in the UVB and VIS bands, and it increases in the NIR; and (ii) in Epochs 1 and 5, the veiling is constant only in the VIS band, while it increases toward both shorter and longer wavelengths.

![Figure 4. Veiling as a function of the wavelength for each epoch. The blue dots are the results of the analysis, and the black dots correspond to the median values in 200 nm wide bins.](image-url)
In Figure 5, we show the median veiling as a function of the orbital phase. This figure shows that the veiling varies significantly with the orbital phase, being larger immediately before the periastron both in the NIR and VIS, and with the orbit, being larger for Epochs 1 and 2, which belong to the same orbit, than for other epochs, which belong to a subsequent orbit.

Figure 5. Median veiling values in the optical (top) and NIR (bottom) wavelength ranges. The different colors indicate the different epochs. Uncertainties smaller than the symbol size are not presented.

4. Accretion in DQ Tau

The DQ Tau spectra display several emission lines that trace the accretion process. The strengths of these lines vary with the orbital phase, and they can be used to calculate the accretion luminosity and the mass accretion rate of the system. In the following, we describe in detail the various steps of this procedure, and the relative analysis we performed.

4.1. Correction for Photospheric and Chromospheric Contributions

The observed accretion lines of DQ Tau are contaminated by the photospheric and chromospheric contributions of each component. According to the spectral typing and the RV analysis, the DQ Tau system is consistently described by two M0 stars. Under the assumption that stars of the same spectral type have similar chromospheric contributions, we fitted both components with the same template, as described below.

For this procedure, we used normalized spectra. The normalization of the spectra was performed considering wavelength ranges of 5 nm. For each wavelength range, we computed the median value of the spectrum, discarding the strong emission lines. We then fitted these median values with a polynomial of second order, and divided the spectra by the fitted line.

For each epoch, we normalized two spectra of the TYC 7760-283-1 star, an M0 Class III (Manara et al. 2013) also known as V1249 Cen, with each being shifted to the RV computed in Section 3.2. Then we summed the two spectra and normalized them again. Hence, we veiled the new template using the values estimated in Section 3.3. We subtracted the flux of this template from each line of the normalized DQ Tau spectra that traces the accretion, so that the remaining emission lines were completely due to the accretion process.

4.2. Measuring Emission Line Fluxes

After we subtracted the photospheric and chromospheric contributions of the binary components for each epoch, we calculated the fluxes of the accretion tracer emission lines in the following way. First, we fitted a linear curve to the local continuum in a wavelength range of $\Delta \lambda = 2$ nm, centered on the emission line wavelength $\lambda_0$. We slightly modified this range, if needed, taking the one most suitable for each line; for example, by avoiding other emission lines, if present, or telluric absorption lines. The line flux was determined by subtracting
the local continuum from the spectra and integrating it over the line. We computed the noise of the line by multiplying the standard deviation of the local continuum (rms) for the wavelength element between two pixels $\Delta \lambda$, and multiplying this by the square root of the number of pixels within the wavelength range ($N_{\text{pix}}$). We considered a line to be detected when its $S/N > 3$. For those lines that were detected in at least one epoch, we estimated the upper limits in the other epochs as three times the noise:

$$F_{\text{line}}^\text{upp} = 3 \times (\sqrt{N_{\text{pix}}} \times \text{RMS} \times \Delta \lambda).$$ (2)

The results are shown in Table 3.

4.3. Accretion Luminosity and Mass Accretion Rate

In order to estimate the accretion luminosity of DQ Tau, we used the most recent empirical relations between the lines that trace accretion ($L_{\text{line}}$) and the accretion luminosity itself (Alcalá et al. 2017):

$$\log (L_{\text{acc}}/L_{\odot}) = a_{\text{line}} \log (L_{\text{line}}/L_{\odot}) + b_{\text{line}},$$ (3)

where $a_{\text{line}}$ and $b_{\text{line}}$ are coefficients that vary with the line, and $L_{\text{line}} = 4\pi d^2 F_{\text{line}}$ is the luminosity of the line. The error on $L_{\text{line}}$ was computed by using the error propagation formula, considering the error on the distance and the error on the line flux. The error on $F_{\text{line}}$ was computed in the same way, considering the error on $L_{\text{line}}$ and the error on the $a$, $b$ coefficients. We estimated the accretion luminosity for every line from Table 3, and used the mean weighted value of $L_{\text{acc}}$ derived from these lines as the best estimate for $L_{\text{acc}}$ for each epoch. The errors on $L_{\text{acc}}$ are computed by dividing the standard deviation of $L_{\text{acc}}$ computed for every line detected by the square root of the number of used lines. The results are shown in Table 2.

We computed the mass accretion rate $\dot{M}_{\text{acc}}$ using the relation:

$$\dot{M}_{\text{acc}} \sim \left(1 - \frac{R_*}{R_{\text{in}}} \right)^{-1} \frac{L_{\text{acc}} R_*}{GM_*},$$ (4)

where $R_{\text{in}}$ is the inner disk radius, which we assume to be $R_{\text{in}} \sim 5R_*$. (Hartmann et al. 1998), and $M_* = 1.52 M_\odot$ and $R_* = 2.58 R_\odot$ are the mass and radius, respectively, for the overall system derived by Czekala et al. (2016) and scaled to $d = 195$ pc. We note that if we use the mass and radius of a single star, given that the two components of DQ Tau are almost equal ($M_2/M_1 = 0.93 \pm 0.05$), the factor of two will be in both the numerator and the denominator in Equation (4), not affecting the final results. The error on $\dot{M}_{\text{acc}}$ is computed as for $L_{\text{acc}}$. Given that $\dot{M}_{\text{acc}}$ is proportional to $L_{\text{acc}}$, the error for each epoch is the same for both $L_{\text{acc}}$ and $\dot{M}_{\text{acc}}$. Indeed, because we are interested in the variability of $\dot{M}_{\text{acc}}$, we have taken into account only the error due to the accretion variability, considering the stellar parameters to be fixed. The results are listed in Table 2. However, the absolute values of the mass accretion rate are also affected by the uncertainties on the stellar parameters, and we will do this when comparing our results to other works. In this latter case, the error results in 0.45 dex.

Both $L_{\text{acc}}$ and $\dot{M}_{\text{acc}}$ are shown as a function of orbital phase in Figure 6. We see that Epochs 3 and 4, the measurements taken closest to the apastron, show the smallest $L_{\text{acc}}$ and $\dot{M}_{\text{acc}}$. On the contrary, the epochs between $\phi = 0.8$–1.0 show significantly elevated accretion rates. Our results—that the accretion depends on the orbital phase and is highest near periastron—support previous observational and numerical results in the literature for DQ Tau and for eccentric binary systems in general (e.g., Basri et al. 1997; Mathieu et al. 1997; Günther & Kley 2002; Salter et al. 2010; D’Orazio et al. 2013; Farris et al. 2014; Muñoz & Lai 2016; Tofflemire et al. 2017; Kospál et al. 2018; Muzerolle et al. 2019). This is in agreement with the hypothesis that the accretion flow of DQ Tau can be explained by the “pulsed accretion model” (Artymowicz & Lubow 1996), according to which the accretion is highly modulated by the binary’s orbital motion, peaking during periastron passages.

It is worth considering the system’s geometry when interpreting the line flux variations because, in theory, these can be caused by rotational modulation as well (e.g., Kurosawa et al. 2008; Kurosawa & Romanova 2013; Romanova & Owocki 2016). The inclination of the rotational axis of the stars in the DQ Tau binary is not known. If we assume that the stars’ equator is coplanar with the disk, then the DQ Tau system is viewed nearly pole-on ($i = 20^\circ$?), therefore we do not expect significant rotational modulation. For instance, the numerical simulations by Kurosawa et al. (2008) suggest that the EWs of the emission lines only change by up to a factor of 1.5 for $i = 10^\circ$ and up to a factor of 2.5 for high-inclination ($i = 60^\circ$–80$^\circ$) models, while we observe significantly larger variations in DQ Tau, despite its low inclination. Moreover, the line variations observed in DQ Tau are periodic with the orbital period of the binary, not with the rotational period of the stars. The ratio between the system’s orbital period ($15.80158 \pm 0.00066$ days) and its rotational period ($3.017 \pm 0.004$ days) is $5.2375 \pm 0.0069$, which is far from any possible low-order resonances (Kospál et al. 2018). Therefore, we can exclude with high confidence the axial rotation of the components being synchronized with the orbital motion, and changes that are periodic with the rotational period cannot be confused with changes that are periodic with the binary’s orbital period. In conclusion, the observed line flux variations are unlikely to be explained by rotational modulation.

Looking in more detail at Figure 6, we note that, when detected, the He I at 501.6 nm and He I–Fe I blend at 492 nm give accretion rates that are systematically larger than the other lines. On the contrary, the Paschen series usually provide lower accretion rates, especially in Epochs 3, 4, 6, and 8. The final errors on the $\log L_{\text{acc}}$ values of individual lines are in the range of 0.17 to 0.73, having a typical uncertainty of 0.33 dex in $L_{\text{acc}}$. Figure 6 shows that the observed differences in accretion luminosity often exceed these, hinting at a physical reason behind the differences, i.e., that different lines trace the different parts of the accretion flow with different physical conditions. We will discuss this point in detail in Section 4.8. We note that the same lines are not detected in all epochs. To minimize the effects of these uncertainties, we calculated the mean weighted value as the best estimate for the accretion rate.

4.4. Comparing the Continuum Veiling and the Mass Accretion Rate

The continuum veiling values plotted in Figure 5 and the accretion rates plotted in Figure 6 show a similar trend with the orbital phase. Both the veiling and accretion rates increase close to periastron. Epochs 1 and 2 display the maximal veiling and maximal accretion rate as well during our monitoring. In the
### Table 3
Observed Fluxes of Accretion Tracers after Subtracting the Photospheric and Chromospheric Contributions

| Element | $\lambda$ (nm) | $f^\text{line}_{\text{full}}$ (in units of cm$^{-2}$ s$^{-1}$) |
|---------|----------------|----------------------------------|
| H3(Hα)  | 656.28         | 382.554 ± 0.523                  |
| H4(Hβ)  | 486.13         | 42.697 ± 0.148                   |
| H5(Hγ)  | 434.05         | 15.843 ± 0.445                   |
| H6(Hδ)  | 410.17         | 9.645 ± 0.103                    |
| H7(Hε)  | 397.91         | 10.882 ± 0.069                   |
| H8      | 388.90         | 4.905 ± 0.131                    |
| H9      | 383.54         | 4.542 ± 0.197                    |
| H10     | 379.79         | 3.479 ± 0.102                    |
| H11     | 377.06         | 2.541 ± 0.114                    |
| H12     | 375.02         | 1.756 ± 0.101                    |
| H13     | 373.44         | 1.863 ± 0.125                    |
| H14     | 372.19         | 1.780 ± 0.102                    |
| Pa5(δPa) | 1281.81      | 69.714 ± 0.717                   |
| Pa6(Paγ) | 1093.81      | 10.938 ± 0.212                   |
| Pa7(δPa) | 1004.94      | 33.388 ± 0.821                   |
| Pa9     | 922.90         | 20.552 ± 0.327                   |
| Pa10    | 901.49         | 19.005 ± 0.239                   |
| Br7(Brγ) | 2166.12    | 21.706 ± 0.586                   |
| He I    | 402.62         | 0.490 ± 0.027                    |
| He I    | 447.15         | 1.635 ± 0.242                    |
| He I    | 471.31         | 0.312 ± 0.045                    |
| He I Fe I | 492.19      | 7.896 ± 0.099                    |
| He I    | 501.57         | 7.864 ± 0.114                    |
| He I    | 587.56         | 7.670 ± 0.359                    |
| He I    | 667.82         | 4.419 ± 0.203                    |
| He I    | 706.52         | 2.732 ± 0.256                    |
| He I    | 468.58         | 0.366 ± 0.054                    |
| Ca II (K) | 393.37     | 8.177 ± 0.158                    |
| Ca II (H) | 396.85     | 10.67 ± 0.056                    |
| Ca II   | 489.80         | 46.784 ± 0.239                   |
| Ca II   | 854.21         | 42.254 ± 0.127                   |
| Ca II   | 866.21         | 39.072 ± 0.221                   |
| Na I    | 589.00         | 2.162 ± 0.219                    |
| Na I    | 589.59         | 1.260 ± 0.288                    |
| O I     | 777.31         | 8.276 ± 0.275                    |
| O I     | 844.64         | 19.353 ± 0.649                   |

Note. Reported flux values are not dereddened.
following, we want to compare our results for DQ Tau with other sources in Taurus, to verify whether this relation between the mass accretion rate and the continuum veiling is peculiar to DQ Tau or general for the Taurus star-forming region. For this purpose, we plot in Figure 7 the mass accretion rate as a function of the median veiling in the VIS for a sample in Taurus (the black filled dots; Muzerolle et al. 1998, rescaled to 195 pc) and for DQ Tau (the red filled dots). We note that the log $M_{\text{acc}}$ of DQ Tau increases almost linearly with the continuum veiling. The figure shows that the data points for DQ Tau match the general trend outlined in Muzerolle et al. (1998).

4.5. Comparing DQ Tau with Single Accretors

During periastron, the DQ Tau components are known to approach each other to within $8R_c \sim 13R_c$, which means that their magnetospheres merge (Salter et al. 2010). This may mean that single circumstellar disks, if present, would be disrupted by the magnetosphere during periastron, and, eventually, the accretion columns can generate directly from the CBD to the stars. Therefore, in terms of the magnetospheric accretion scenario, the DQ Tau system can probably be considered as a single star when the system is close to (or at) periastron. To verify this, we compared DQ Tau with the most recent CTT surveys in Lupus, Chamaeleon I, NGC1333, and Taurus (Alcalá et al. 2019; Manara et al. 2019; Alcalá et al. 2021; Fiorellino et al. 2021, respectively) in Figure 8. We plotted the DQ Tau $L_{\text{acc}}$ and $M_{\text{acc}}$ total values for the two stars together, at a place that corresponds to the total luminosity and mass of the two stars, respectively. We find that, in general, the accretion rates of DQ Tau (the red filled diamonds) are in agreement with the typical ranges of values for single CTTs with the same stellar luminosity and mass. While $L_{\text{acc}}$ perfectly matches the CTT distributions in the $\log L_{\text{acc}} - \log L_*$ relationship.
of DQ Tau lies in the lower part of the $-\log \log \text{acc}$ diagram. In particular, the $M_{\text{acc}}$ is compatible with the $M_{\text{acc}}$ distribution of the $\sim2$ Myr star-forming regions Chamaeleon I and Lupus for all the epochs. Thus, our results show that DQ Tau is accreting at a rate compatible with single stars with similar stellar parameters, even when it is accreting less, near apastron. This result seems to confirm the hypothesis that we can study the $M_{\text{acc}}$ on DQ Tau as if it were a single star.

4.6. Accretion Variability over the Binary Orbit

To study the accretion variability over the binary orbit, we compare our $M_{\text{acc}}$ estimates with previous results from the literature, after scaling them to the distance we adopt of 195 pc. We plot in Figure 9 the mass accretion rate as a function of the orbital phase. As described in Section 4.3, we used spectroscopic data and empirical relations between $F_{\text{line}}$ and $L_{\text{acc}}$ to compute $M_{\text{acc}}$. Our results are shown with the red filled circles. The same approach was used by Muzerolle et al. (2019), but only for Pa$\beta$ and Br$\gamma$ lines. We computed the mean values of these two $M_{\text{acc}}$ estimates, plotting the results as blue filled squares. In a different approach, Kóspál et al. (2018) and Tofflemire et al. (2017) provided the $M_{\text{acc}}$ of the DQ Tau source from photometry data, using an empirical relation between the luminosity excess in the $U$-band and the accretion luminosity (Gullbring et al. 1998). The black solid and gray dashed lines are the histograms from Kóspál et al. (2018) and Tofflemire et al. (2017), respectively, where the peaks correspond to the mean values for the same phases of several periods. Figure 9 shows that the trend with respect to the phase between the samples is the same, so $M_{\text{acc}}$ is larger near periastron in every sample, but the results obtained from photometry are about a factor of two smaller than the $M_{\text{acc}}$ computed from emission lines. This difference can be explained by both the different method used and the fact that the histograms show the average values of tens of orbits, while our results and the results of Muzerolle et al. (2019) are computed in a specific phase. The $M_{\text{acc}}$ values in the four samples were computed by using different techniques and different data at different wavelengths, in different orbits. Moreover, all the methods are based on empirical relations that, therefore, are affected by large uncertainties. Considering all these differences, it is actually a significant result that the trend shown in this figure is the same for each sample, strengthening the pulsed accretion theory for the DQ Tau system.

4.7. Accretion in Binary Systems

An important aspect of accretion in close, eccentric binary systems like DQ Tau is the absence of single circumstellar disks, and the presence of a CBD around the two stars, from which the material flows to one or both components. To test this scenario, we compared the line-observed accretion variability in DQ Tau with the results from theoretical simulations of binary systems provided by Günther & Kley.
that the only reason why the emitted in the postshock gas part of the inner disk. On the contrary, Paschen lines are mostly thought to be emitted by the preshock gas, in the outermost regions. Because the main accretor changes with the orbital phase, sometimes we see “new” material (Balmer series), which is going to accrete a certain component, while “old” material (Paschen series) is accreting on the other component. 

In general, narrow components are usually formed in the postshock region, close to the stellar surface, while broad components are usually formed in the preshock region (Hartmann et al. 2016). We should also remember that the actual accretion flows are not homogeneous in density or temperature, so they could be explained as a superposition of accretion columns (Hartmann et al. 2016). This means that, in principle, different elements with different densities and temperatures develop different accretion columns. This may explain why using different lines gives different accretion rates. Averaging the different values provides the mean value of the accretion flow in the overall inner disk. Focusing only on a certain line provides a different estimate, tracing accretion from a specific region, under specific physical conditions.

In our analysis, we prefer to analyze narrow lines because they are spectroscopically resolved and formed closer to the stellar surface. In that sense, they provide a better estimate of the amount of material that is going to fall on a certain component. For our purpose, it is also important that the line is not blue- or redshifted. According to the literature (Hartmann et al. 2016, and references therein), the Hα and [O I] lines are usually blueshifted by wind and/or jets, while the Hβ, Paγ, and Na I doublets are usually redshifted with respect to the velocity of the star, by the magnetospheric infall. Some lines might also be both blue- and redshifted: this is the case of He I at 1083.0 nm. Therefore, these lines are not suitable for our purpose. On the contrary, He I at 587.65 nm and the Ca II triplet emission lines usually have a very narrow component and are centered at the stellar velocity, likely tracing the postshocked region, making these lines perfect for our study. Unfortunately, as shown in Figure 11, the He I at λ = 587.65 nm line presents two peaks in only one epoch. For this reason, we decided that, for the epochs in which the main accretor changes by looking at the different lines, we would establish which component accretes the most by examining the Ca II triplet. For Epoch 4, where Ca II is not detected, we assumed that the secondary is the main accretor because we only see a difference at Hα. The Hα line is

4.8. Accretion from Single Stars in the DQ Tau System

The main goal of this work is to determine whether both the components of DQ Tau are accreting during each epoch we observed, and, if so, which one is accreting the most. For this purpose, we need two conditions to be satisfied: (i) the two components are to be spectroscopically resolved; and (ii) the accretion luminosity is not to be too faint, so the lines that trace accretion are detected. With these general rules in mind, we studied the accretion tracer lines for all the epochs in Figure 11 (and in figures in Appendix B), similar to what was done by Tofflemire et al. (2019) for the TWA 3A system.

We identified which source is accreting the most by studying the velocities of the two peaks. We interpret the primary (secondary) to be accreting the most when the highest peak velocity corresponds to the RV of the primary (secondary). Figure 12 shows this result by using red for the primary and blue for the secondary filled circle symbols. When the two peaks, corresponding to the two RVs, are equal, then both components likely accrete at equal rates (the purple filled circles). All the other cases, when it is not possible to provide information on the accretion on single sources from these lines, are marked with a cross. Thus, according to Figure 12, the primary is accreting the most during Epoch 1, at φ = 0.9, and the secondary is accreting the most during Epoch 7, at φ = 0.98. For all other epochs, the main accretor changes, depending on which accretion tracer line is considered.

A plausible interpretation of this change in the main accretor is that different lines are formed in different regions of the accretion column. It has been shown that Balmer series lines are thought to be emitted by the preshock gas, in the outermost part of the inner disk. On the contrary, Paschen lines are mostly emitted in the postshock gas (Alcala et al. 2014; Hartmann et al. 2016, and references therein). Thus, the H I lines we see at the same epoch are tracing the flow that is reaching the shock region (Balmer series; see Appendix B) or the gas that has already been shocked (Paschen series; see Appendix B). In other words, the Paschen lines show the accretion material in a region closer to the stellar surface, while the material traced by the Balmer lines is still farther away from the stellar surface. Thus, looking at the same epoch, but at different lines, in Figure 11, we see emission from the accreting flows in different regions. Because the main accretor changes with the orbital phase, sometimes we see “new” material (Balmer series), which is going to accrete a certain component, while “old” material (Paschen series) is accreting on the other component.
generally strong and broad, and being sensitive to the blueshifting due to the optically thick regime (Hartmann et al. 2016), it is not reliable for this kind of analysis.

Based on these arguments, and looking at Figure 12, we can conclude there is a periodic trend: before the periastron ($\phi = 0.98$), the secondary is accreting the most; then, right
Figure 12. Top: the filled circles show whether the highest peak of the line corresponding to the element in the y-axis in a certain epoch has the radial velocity of the primary (red) or the secondary (blue) component, or whether there are two peaks of the same intensity corresponding to both the RVs (purple). The black crosses highlight the line profiles for which it is not possible to determine which source is accreting the most, either because there is no detection or because the two components are not spectroscopically resolved. Bottom: the coadded mass accretion rate of the two components as a function of the orbital phase, as in Figure 6.
after the periastron ($\phi = 0.04$, Epoch 8), the primary is the main accretor; and in the postshocked region, according to the Paschen series, the accretion is equally distributed between the two components, suggesting that in the future the main accretor will change. Indeed, the primary is still the main accretor at $\phi = 0.08$ (Epoch 6), even if, looking at Pa$\beta$ and Pa$\gamma$, the secondary is already accreting the most. Unfortunately, at $\phi = 0.62$ (Epoch 3), the two components have the same RV, so we are not able to evaluate the accretion on single stars for this epoch. Later, at $\phi = 0.74$ (Epoch 4), the secondary is accreting the most. Then the accretion flows change again, directed toward the primary at $\phi = 0.89$ and 0.90, which are Epochs 5 and 1, respectively. Finally, at $\phi = 0.96$ (Epoch 2), the secondary is still the main accretor, while some lines predict that the primary is going to be the component that will accrete the most, as it is indeed at Epoch 7 ($\phi = 0.98$). We note that the change in the main accretor is not related to the absolute value of the mass accretion rate.

We would like to stress that what we know about the region where a line is produced is based on single stars, whose accretion is driven by a strong magnetic field whose main component is a dipole, and the disk we refer to is the circumstellar disk. DQ Tau is a binary system that can be treated as a single star, with the circumbinary disk acting as the circumstellar disk in a single star, near periastron, when the magnetic field of the two components merges in a dipole magnetic field (Salter et al. 2010). This is all we can say, based on the emission lines. Further insights may be gained from studying the magnetic fields that ultimately determine the path of accretion in the magnetospheric accretion model. Mapping the magnetic fields of stars is possible, e.g., using spectropolarimetric methods, and such a study for DQ Tau is in progress using CFHT/ESPaDOnS spectra (K. Pouilley et al., in preparation).

The fact that the main accreting component changes is, in principle, not in agreement with the numerical simulations that predict that the secondary should always be the dominant accretor in a binary system (e.g., Hayasaki et al. 2007, 2013; Farris et al. 2014; Young & Clarke 2015). These predictions are based on the fact that the angular momentum for the two sources should be the same, and as the secondary is less massive, it is located farther from the center of mass of the system. In other words, the secondary is closer to the CBD, where it should be easier to trap the accreting flow. But, for DQ Tau, because the two components have very similar masses, it is not surprising that the main accretor can change epoch by epoch, and this still satisfies the theoretical basis of the numerical simulations. However, the change in the main accreting component is predicted by both Günther & Kley (2002) and Muñoz & Lai (2016), although the timescale on which such a switch of the main accretor is considered is about 100 orbital periods, while we see the change in the main accretor component three times in less than two orbital periods.

5. Summary and Conclusions

We studied the accretion variability of the young eccentric binary system DQ Tau, by analyzing eight epochs of X-Shooter spectra taken over seven orbital periods. We estimated the RVs, the veiling, the extinction and the spectral type of the DQ Tau system. We subtracted the chromospheric and the photospheric contributions from the observed spectra, to isolate the accretion component. We studied the accretion process of the DQ Tau system, comparing it with single stars, the previous literature on DQ Tau, and other binary systems. We were able to select the main accretor, epoch by epoch, and discuss its variability. Our main conclusions are:

1. DQ Tau is a binary system composed of two early M-type stars (M0), with extinction of $A_V = 1.72 \pm 0.26$ mag, in agreement with the previous literature.
2. We measured the RVs, resolving the RVs of the two DQ Tau components for seven epochs. Our results are in agreement with the Keplerian solutions of Czekala et al. (2016).
3. The veiling changes with orbital phase, time, and wavelength, in a similar way to the accretion variability, confirming its correlation with the mass accretion rate.
4. Our results on the $M_{\text{acc}}$ variability with phase confirm the pulsed accretion model, showing a larger mass accretion rate near periastron, and they are in agreement with the previous results on the DQ Tau mass accretion rate computed using different techniques.
5. The accretion luminosity and the mass accretion rate of DQ Tau are compatible with the $L_{\text{acc}}$ and $M_{\text{acc}}$ of 2–3 Myr old CTTs, following the same relations with respect to the stellar parameters, if we consider the contributions of the two components.
6. The main accretor in the DQ Tau system varies epoch by epoch. This contradicts those simulations that predict that the secondary is always the main accretor in eccentric binary systems. Other simulations predict that the main accretor should change, but on significantly longer timescales than we observe here.

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Facility: ESO-VLT/XSHOOTER.

Software: molecfit (Sméte et al. 2015; Kausch et al. 2015); SAPHIRES https://github.com/tofflemire/saphires; barycorrpy (Kanodia & Wright 2018).

Appendix A

Flux Calibration

In order to check the quality of our flux calibration, we compared the photometry we used (observed or inferred, depending on the epoch) with the synthetic photometry obtained by convolving the spectrum with the filter bandpasses, band by band. Figure 13 shows the general agreement within the observed/inferred and the synthetic photometry, for each epoch.
Figure 13. The X-Shooter flux-calibrated spectra from Epoch 1 (top) to Epoch 8 (bottom) are shown in gray. The yellow circles represent the observed or inferred photometry at each band. The filter bandpasses (lines) and the synthetic photometry (filled squares) obtained from integrating the spectrum over these bandpasses are overlaid.
Figure 14. The DQ Tau smoothed and flux-calibrated spectra.
Appendix B
All the Accretion Lines

We present in this section all the line profiles that trace accretion in DQ Tau (Figures 15–19). The results are summarized in the text, in Figure 12.

Figure 15. The velocity structure of the continuum-normalized H I emission lines, as indicated in the figure, observed by X-Shooter in UVB and VIS. The vertical red and blue dashed lines are the velocities of the two primary and secondary components, respectively. The spectra are ordered from bottom to top by increasing orbital phase, which is labeled adjacent to each spectrum. The line colors mark the epoch, using the same colors as Figure 6.
The velocity structure of the continuum-normalized H I emission lines, as indicated in the figure, observed by X-Shooter in UVB and VIS. The vertical red and blue dashed lines are the velocities of the primary and secondary components, respectively. The spectra are ordered from bottom to top by increasing orbital phase, which is labeled adjacent to each spectrum. The line colors mark the epoch, using the same colors as Figure 6.
Figure 17. The velocity structure of the continuum-normalized H I emission lines, as indicated in the figure, observed by X-Shooter in NIR. The vertical red and blue dashed lines are the velocities of the primary and secondary components, respectively. The spectra are ordered from bottom to top by increasing orbital phase, which is labeled adjacent to each spectrum. The line colors mark the epochs, using the same colors as Figure 6.
Figure 18. The velocity structure of the continuum-normalized He I and He II emission lines, as indicated in the figure, observed by X-Shooter. The vertical red and blue dashed lines are the velocities of the primary and secondary components, respectively. The spectra are ordered from bottom to top by increasing orbital phase, which is labeled adjacent to each spectrum. The line colors mark the epochs, using the same colors as Figure 6.
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Figure 19. The velocity structure of the continuum-normalized Ca II triplet, Na I doublet, and O I emission lines, as indicated in the figure, observed by X-Shooter. The vertical red and blue dashed lines are the velocities of the primary and secondary component, respectively. The spectra are ordered from bottom to top by increasing orbital phase, which is labeled adjacent to each spectrum. The line colors mark the epochs, using the same colors as Figure 6.