The component star masses in RW Tri

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ABSTRACT

We use time-resolved spectra of the cataclysmic variable RW Tri in the I and K bands to determine the orbital velocity of the secondary star using skew-mapping and cross-correlation techniques respectively. We find radial velocity amplitudes of 250 ± 47 km s$^{-1}$ in the I band, and 221 ± 29 km s$^{-1}$ in the K band. We also determine the rotational velocity of the secondary star using the K-band data and find a $V_{rot} \sin i$ of 120 ± 20 km s$^{-1}$. A combination of these results coupled with an estimate of the effect of heating on the secondary star suggests a mass ratio $M_2/M_1$ in the range 0.6–1.1; the mass ratio range with no correction for heating is 0.5–0.8. These lead to most likely estimates of the primary and secondary star masses in the range 0.4–0.7 and 0.3–0.4 M$_\odot$ respectively. Further refinement of the stellar masses is hampered by uncertain knowledge of the white dwarf orbital velocity, and we discuss evidence that at least some estimates of the white dwarf velocity are contaminated by non-orbital components.

Key words: techniques: radial velocities – binaries: eclipsing – stars: individual: RW Tri – novae, cataclysmic variables – infrared: stars.

1 INTRODUCTION

RW Tri is an eclipsing nova-like cataclysmic variable (CV) system with an orbital period of 5 h 34 min. Nova-like systems contain a non-magnetic white dwarf primary and a late-type (K–M) secondary star that fills its Roche lobe, transferring mass to the white dwarf via an accretion disc.

Since first being observed as an eclipsing variable (Protitch 1937), multi-wavelength studies of RW Tri have provided much insight into the system, but have yet to yield an accurate measurement of the masses of the two component stars. By observing the velocities of the component stars, their masses can be calculated using Kepler’s laws. A number of authors have attempted to measure the radial velocity of the white dwarf (e.g. Kaitchuck, Honeycutt & Schlegel 1983; Still, Dhillon & Jones 1995; Mason 2002), but thus far little work has been done on the secondary star.

Measurement of the secondary star velocity is hampered by the large contrast in optical brightness between it and the accretion disc. Weak secondary star absorption features were detected in the I-band spectrum of RW Tri by Friend et al. (1988), and later used by Smith, Cameron & Tucknott (1993) to estimate the secondary star velocity as $\sim$250 km s$^{-1}$ using a ‘skew-mapping’ technique (cf. Smith, Dhillon & Marsh 1998). Dhillon et al. (2000) have detected secondary star features in low-resolution K-band spectra of RW Tri. The relative contribution of the secondary star is higher in the K band and the equivalent width of the absorption features greater as a consequence.

In this paper we report phase-resolved spectral observations of RW Tri in the K band, covering the binary orbit. We use these observations to determine the radial velocity of the secondary star in RW Tri. We also re-analyse the original I-band spectra of Smith et al. (1993). Based on these results we revisit the mass ratio and the masses of the component stars in RW Tri and discuss their implications.

2 I-BAND DATA

We have re-analysed the RW Tri near-I-band data of Smith et al. (1993) using the back-projection routines in the software package MOLLY written by Tom Marsh (see also Vande Putte et al. 2002), combined with a Monte Carlo error analysis. We use the method of ‘skew-mapping’ (Smith et al. 1993) in which the orbital phase-resolved data are corrected for a trial orbital velocity amplitude and phase, and compared with the spectrum of a standard ‘template’ star. The degree of correlation between the summed corrected spectrum and the template is computed for a grid of velocity amplitudes and phases to produce the skew map. This method is useful when the spectral features of the secondary are too weak to produce significant cross-correlation peaks using individual spectra.

The I-band spectra were obtained using the Isaac Newton Telescope (INT) on La Palma, and the 831R grating, giving a wavelength coverage of 7700–8300 Å. This range includes the Na I absorption doublet feature (λλ 8183.3, 8194.8 Å) that is expected in the...
Table 1. Template stars from Martin (1988).

| Name  | Colour index | Spectral type |
|-------|--------------|---------------|
| Gl 653 | 0.49         | K5            |
| Gl 717 | 0.54         | K7            |
| Gl 673 | 0.60         | K7            |
| Gl 488 | 0.67         | M0            |
| Gl 383 | 0.70         | M0            |
| Gl 281 | 0.71         | M0            |
| Gl 908 | 0.87         | M1.5          |

A range of skew maps with total systemic velocities (RW Tri + template) from \(-50\) to \(50\) km s\(^{-1}\), were produced for each template. A mask between 7760 and 7800 Å was used to remove the accretion disc absorption feature of neutral oxygen at 7774 Å (Friend et al. 1988). The skew map with the strongest peak was found using the M0 template Gl 281, with a RW Tri systemic velocity of \(-13\) km s\(^{-1}\) and secondary velocity amplitude of 250 km s\(^{-1}\). Patterson (1984) estimated the secondary star of RW Tri to be of spectral type M0, based on the empirical zero-age main-sequence (ZAMS) mass–radius relation. Our result is also consistent with the statistical prediction of K9–M1–M2 stars of spectral type K7–M2 were observed over the two nights (Table 2). Bright A-type stars of known broad-band magnitudes and arc spectra were also observed through both nights, enabling us to flux- and wavelength-calibrate respectively. The bright A stars also allowed us to remove telluric lines.

3 K-BAND DATA

The secondary star only contributes \(\sim 10\) per cent of the flux in the \(I\) band, compared with an estimated \(\sim 65\) per cent in the \(K\) band (Dhillon et al. 2000), so we would expect to see secondary star absorption features more easily at longer wavelengths. Absorption features caused by the secondary star have been observed in the \(K\)-band spectrum of RW Tri by Dhillon et al. (2000) at low spectral resolution, which motivated us to investigate whether we could use these features to measure the secondary star velocity directly using a standard cross-correlation technique.

3.1 Observations

Observations of RW Tri were made in the \(K\) band on 2000 August 6 and 7 using the Cooled Grating Spectrometer (CGS4) on the United Kingdom Infra-Red Telescope (UKIRT). The 150 line mm\(^{-1}\) grating gives us a spectral resolution of 100 km s\(^{-1}\) at 2.2 μm, and a wavelength range of 2.200 to 2.275 μm, enabling us to observe both the Na I and Ca I absorption lines recorded by Dhillon et al. (2000) in RW Tri. The telescope was nodded up and down the slit taking spectra at different detector positions to facilitate the removal of sky background. Summing the data from the telescope nodding positions gave a total exposure time of 600 s for each RW Tri spectrum. This exposure time is equivalent to 0.03 orbital cycles which is short enough to prevent any significant smearing because of orbital effects.

A total of 35 spectra were taken of RW Tri over the two nights: 15 spectra on the first night, and 20 spectra on the second. 10 template stars in the range of spectral type K7–M2 were observed over the two nights (Table 2). Bright A-type stars of known broad-band magnitudes and arc spectra were also observed through both nights, enabling us to flux- and wavelength-calibrate respectively. The bright A stars also allowed us to remove telluric lines.

3.2 Data reduction

Real-time data reduction was undertaken at the telescope using the ORAC-DR package developed at the Joint Astronomy Centre. Bad pixels were masked and a flat-field was applied to remove pixel-to-pixel variations across the array, and a bias frame was subtracted. As a result of nodding the telescope along the slit, the night sky spectrum could be accurately removed and the spectra co-added.

Bad pixels were found close to the Na I doublet feature at 22 063 and 22 101 Å on night 1, and 22 078 and 22 116 Å on night 2.
The difference between the apparent wavelengths of the bad pixels between the nights is due to a slight shift in the grating angle. These bad pixels were removed by interpolation.

Further data reduction was carried out using the FIGARO package. Spectra were extracted, and wavelength-calibrated using the rest wavelength of arc spectra, and telluric lines were removed using the observations of A stars. The resulting RW Tri and template spectra were flux-calibrated using the A stars, and then smoothed and re-binned on to a linear wavelength scale. The ephemeris of Robinson et al. (1991) was used to phase the data.

Fig. 2 shows the normalized template spectra in order of spectral type. The Na I doublet and Ca I triplet absorption features can be clearly seen, showing the quality of the data. There are no large differences in the depths of the Ca I and Na I lines between the different spectral types in this wavelength band, making it hard to distinguish between them. Fig. 3 shows the individual spectra of RW Tri distributed in orbital phase. The Na I and Ca I absorption features appear to shift from spectrum to spectrum on each night. These features will be discussed further in Section 3.4. RW Tri was brighter on the second night. Fig. 4 shows the average spectrum of RW Tri for each night with the scaled M0 template Gl 281.

3.3 The secondary star velocity

The velocity of the secondary star in RW Tri was investigated by cross-correlating the spectra of RW Tri with template spectra. Both sets of spectra were normalized in the same way as described for the I-band data (Section 2), and re-binned on to the same wavelength scale. Each RW Tri spectrum was cross-correlated with each template spectrum in turn. The position of the cross-correlation peak was then plotted against orbital phase to produce the velocity curve of the secondary star. As in skew-mapping (Section 2), the spectral template that yields the strongest cross-correlation peaks is the best fit to the data. All the cross-correlation templates gave similar peak values, which is what we expect as there is little variation in the relative strengths of the Na I and Ca I lines over the range of late-type stars that we used (cf. Fig. 2). The best-fitting radial velocity curve of the average cross-correlation lags using all the template data is illustrated in Fig. 5.

This velocity curve can be parametrized as

\[ V = \gamma + K \sin(2\pi(\Phi - \Phi_0)), \]

where \( V \) is the radial velocity, \( \gamma \) is the systemic velocity, \( K \) is the orbital velocity amplitude, \( \Phi \) is the binary orbital phase defined by the ephemeris of Robinson et al. (1991), and \( \Phi_0 \) is the orbital phase of blue to red zero crossing (inferior conjunction of the secondary star). A sinusoidal curve was fitted to the velocity data using the Levenberg–Marquardt algorithm in IDL; by minimizing the reduced chi-squared and considering the 68.3 per cent (1σ) confidence level, a best-fitting velocity and error were calculated. This gives \( K_2 = 221 \pm 29 \text{ km s}^{-1}, \gamma = 17 \pm 20 \text{ km s}^{-1} \) and \( \Phi_0 = -0.040 \pm 0.020 \) orbital phase. The results derived from individual template stars are listed in Table 3. These are all consistent within the errors, and consistent with the mean values listed above.

In Fig. 6 we plot the velocity-corrected average spectrum of RW Tri for each night, along with the scaled M0 template Gl 281. We can clearly see the Na I doublet and Ca I triplet in both nights. These features are broadened compared with the template spectra, owing to the rotational velocity of the secondary star.

3.4 Orbital modulation of secondary star absorption features

To search for variations in the strength of the absorption features with orbital phase, we compare the depth of the strongest features in the velocity-corrected spectrum of RW Tri with the values observed in the the template star spectrum. We consider the combined regions around the Na I absorption feature \( \lambda \lambda 22010-22140 \) Å and the Ca I absorption feature \( \lambda \lambda 22570-22700 \) Å, and mask out the rest of the spectrum. Fig. 7 shows a plot of the ratio of RW Tri versus...
Figure 3. The left-hand plot shows the smoothed normalized RW Tri spectra of the first night, and the right-hand plot shows the smoothed normalized RW Tri spectra of the second night. The orbital phase is printed on the right-hand axes of both plots. The dashed lines in both plots represent the rest wavelengths of the Na I doublet (left) and Ca I triplet (right) as in Fig. 2. Each spectrum is vertically offset by 0.1 normalized flux from its neighbour.

Template star absorption feature deficit through the orbital cycle. There is some evidence that the secondary features are strongest near phase zero and weaker near phase 0.5. Taken at face value, this suggests that the centroid of the secondary features is shifted to the hemisphere of the secondary that faces away from the disc. Although the effect is marginal, it is in accordance with what we expect from heating effects. The best sinusoidal fit to the data has an amplitude of $0.27 \pm 0.18$ (solid line in Fig. 7). This sinusoidal fit to the data implies that the secondary star contributes $\sim 39$ per cent of the $K$-band flux at phase 0.0, while at phase 0.5 this is reduced to $\sim 15$ per cent. Hence the absorption in the hemisphere of the secondary star nearest to the primary star is $\sim 0.4$ times the strength of the absorption in the hemisphere facing away from the primary.

Averaged over orbital phase, these results suggest that the secondary star contributes $29 \pm 13$ per cent of the $K$-band flux. This is considerably different from the $65 \pm 5$ per cent estimated by Dhillon et al. (2000). The American Association of Variable Star Observers (AAVSO) quick-look light curves of RW Tri at the time of our UKIRT observations show that RW Tri was at a magnitude of $V \sim 13$, but during the observations of Dhillon et al. (2000) RW
of the secondary star can be estimated by artificially broadening the secondary star as it orbits the white dwarf. The rotational velocity be due to broadening caused by the rotation of the (phase-locked) significantly broader than in the template spectra. This is likely to

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3.5 Secondary star rotational velocity

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| Table 3. Secondary star orbital parameters derived from individual template stars. |
|---------------------------------|-------------------|-------------------|------------------|
| Template | $K_2$ (km s$^{-1}$) | $\gamma$ (km s$^{-1}$) | $\Phi_0$ (orbital phase) |
| Gl 397 | 229 ± 47 | −6 ± 28 | −0.044 ± 0.031 |
| Gl 3478 | 218 ± 92 | 18 ± 65 | −0.037 ± 0.068 |
| Gl 334 | 218 ± 38 | 10 ± 27 | −0.042 ± 0.027 |
| Gl 182 | 217 ± 51 | 21 ± 36 | −0.041 ± 0.037 |
| Gl 281 | 223 ± 10 | 28 ± 6 | −0.039 ± 0.007 |
| Gl 383 | 220 ± 4 | 36 ± 3 | −0.042 ± 0.003 |
| Gl 212 | 219 ± 90 | 39 ± 64 | −0.041 ± 0.064 |
| Gl 390 | 221 ± 59 | 0 ± 37 | −0.042 ± 0.037 |
| Gl 382 | 222 ± 5 | 14 ± 8 | −0.042 ± 0.008 |
| Gl 393 | 217 ± 38 | 17 ± 27 | −0.041 ± 0.026 |

after masking out strong absorption features. Each template was then artificially broadened in the velocity range $V_{rot} \sin i = 10$–200 km s$^{-1}$ in steps of 10 km s$^{-1}$, assuming partial limb darkening [linear limb darkening coefficient =0.5 (North et al. 2000)]. These broadened template spectra were then compared with the orbital velocity corrected RW Tri spectra on each night. Residual spectra were produced by subtracting a constant times the shifted broadened template from each RW Tri spectrum; the constant was adjusted to minimize the scatter on each residual spectrum. A boxcar average smoothing was applied to the residual spectrum to eliminate any large-scale structure. The reduced chi-squared ($\chi^2$) was calculated between each residual and smoothed spectrum in the wavelength regions containing the NaI absorption feature (22 040 to 22 108 Å) and the Ca I absorption feature (22 614 to 22 689 Å). The average results can be seen in Fig. 8 where we plot night 1 and night 2 separately, and also combined.

The best fits (minimum $\chi^2$) for nights 1 and 2 are obtained with $V_{rot} \sin i \sim 90$ and $\sim 140$ km s$^{-1}$ respectively (Fig. 8). Based on the $\chi^2$ distribution in Fig. 8, we estimate a mean $V_{rot} \sin i = 120 \pm 20$ km s$^{-1}$. All template stars gave the same order of chi-squared values, confirming again that the data are not template-sensitive in this wavelength band. The minimum $\chi^2$ values had a range over all the templates of $V_{rot} \sin i$ from 80 to 100 km s$^{-1}$ for night 1, and

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4 DISCUSSION

To calculate the masses of the two component stars in the system we can use the mass ratio \( q \),

\[
q = \frac{K_1}{K_2} = \frac{M_2}{M_1}, \tag{2}
\]

where \( K_1 \) and \( K_2 \) are the radial velocity amplitudes of the primary and secondary stars respectively, and \( M_1 \) and \( M_2 \) are the primary and secondary masses respectively.

4.1 Primary star velocity measurements

There have been a number of different estimates of \( K_1 \) based on measurements of the optical emission lines in RW Tri, and these have yielded a range of values. Doppler maps of RW Tri (Kaitchuck et al. 1983) indicate that the He II \( \lambda 4686 \) Å emission arises from the inner accretion disc region. He I \( \lambda 4471 \) Å emission is found further out in the accretion disc, and H\( \beta \) and H\( \gamma \) emission originates from the outer regions of the accretion disc and the inner face of the secondary star.

Still et al. (1995) measured the emission-line centroids and obtained \( K_1 \) values of \( 208 \pm 8 \) km s\(^{-1} \) from H\( \beta \), \( 223 \pm 11 \) km s\(^{-1} \) from H\( \alpha \), and \( 216 \pm 9 \) km s\(^{-1} \) from He II (\( \lambda 4686 \) Å). The He I measurement of Still et al. (1995) is consistent with the \( 197 \pm 20 \) km s\(^{-1} \) measured by Kaitchuck et al. (1983), who also found a \( K_1 \) velocity of \( \approx 170 \pm 20 \) km s\(^{-1} \) for He I. Still et al. (1995) also used the convolution technique of Schneider & Young (1980) to measure the wings of the H\( \beta \), H\( \gamma \) and He II emission lines. The line wings, which come from high-velocity gas in the inner disc, are in principle more likely to reflect the motion of the white dwarf than the line cores. The latter may well be contaminated by emission from the secondary star, the accretion stream and the bright-spot. However, Still et al. found that the measured velocities for the emission-line wings in RW Tri were inconsistent with the velocities obtained from Doppler maps. These inconsistencies could be due to absorption affecting the wings of the accretion disc emission lines.

Recently, Hubble Space Telescope (HST) data have been used to measure the velocity of narrow absorption features in the ultraviolet. Mason et al. (in preparation) detected velocity shifts in the ultraviolet absorption lines and found that they had the same orbital phase as that expected for the white dwarf. The lines appear to originate in a layer above the inner accretion disc, and their motion may therefore mirror that of the white dwarf. By cross-correlating the average spectrum through the orbital cycle they find \( K_1 = 296 \pm 5 \) km s\(^{-1} \).

4.2 Effects on the secondary star radial velocity amplitude

The apparent value of \( K_2 \) may be modified by heating, line-quenching and line contamination (Friend et al. 1990). Heating of the secondary star occurs because of hard photons from the accretion disc. Line quenching occurs because of the ionization of the absorption lines by flux from the disc. Both irradiation and line quenching can deplete the absorption-line strength on the surface of the secondary star that faces the accretion disc, and shift the apparent centroid of the absorption-line region to the hemisphere facing away from the disc. This would lead to an overestimate of the \( K_2 \) value. The magnitude of this effect may be reduced, however, if the accretion disc has a thick rim which shields the secondary. This appears to be the case in RW Tri (Mason, Drew & Knigge 1997). Line contamination may occur because of weak disc features. This could lead to variations in the line strengths of the absorption through the orbit.

To account for these effects, Wade & Horne (1988) estimated the likely correction required for the radial velocity amplitude of the secondary star. This ‘\( K \)-correction’ is given by

\[
\Delta K = \frac{\Delta R}{a_2} K_2 = f R_2 \frac{R_2}{a_2} K_2, \tag{3}
\]

where \( a_2 \) is the semi-major axis of the secondary star, \( R_2 \) is the radius of the secondary star, and \( f \) is a correction factor that depends on the geometry of the system. The correction factor can be estimated by comparing the observed and theoretical velocities of the secondary star.

Figure 7. The total flux deficit in the NaI and Ca I RW Tri secondary star absorption features, expressed as an equivalent width, divided by the corresponding equivalent width in the template star Gl 281 (which has the highest quality spectrum among the templates measured, and is the best match to RW Tri in the \( i \) band). We corrected for the orbital velocity shift of RW Tri in forming these numbers. Night 1 is represented by asterisks, and night 2 is represented by triangles. The solid line represents the best-fitting sinusoidal curve to the data.

Figure 8. Plot of \( \chi^2 \) obtained using the average of all templates after artificially broadening by \( V_{rot} \sin i \) in the range 10–200 km s\(^{-1} \). This shows that the minimum \( \chi^2 \)s for night 1 (asterisks), night 2 (triangles) and the average of the two nights (dashed line) are 90, 140 and 120 km s\(^{-1} \) respectively.

130 to 150 km s\(^{-1} \) for night 2. We confirmed that the intrinsic \( V_{rot} \sin i \) of each template was consistent with 0 km s\(^{-1} \), by cross-correlating the templates against each other.

The analysis of the orbital radial velocity was not changed significantly when we broadened the template lines by 120 km s\(^{-1} \). This is because rotational broadening affects the profile of the absorption lines, but not the position of the line centroids which govern the cross-correlation peak positions.
where $\Delta R$ is the displacement between the effective centre and the centre of mass of the secondary star, $R_2$ is the secondary star radius, $|f| < 1$ is a weighting factor representing the strength of the absorption feature, and $a_2$ is the distance of the centre of mass of the secondary star from the centre of mass of the system, given by

$$a_2 = \frac{a}{1 + q},$$

(4)

where $a$ is the separation of the component stars and $q$ is the mass ratio ($q = M_2/M_1$).

To estimate the $K$-correction, we use $f = 4/5\pi \sim 0.25$ where the front hemisphere of the secondary star has $\sim 0.4$ of the absorption of the back hemisphere. This is based on the measured change in the amplitude of the absorption features with orbital phase (Section 3.4). Each hemisphere is assumed to have uniform absorption, and we relate $R_2/a$ to the mass ratio $q$ using

$$\frac{R_2}{a} = \frac{0.49q^{2/3}}{0.6q^{2/3} + \ln(1 + q^{1/3})}$$

(5)

(Eggleton 1983).

### 4.3 Mass ratio theory

Consider the conservative mass transfer equation,

$$\frac{\dot{R}_L}{R_L} = \frac{2J}{f} + \frac{2(-M_2)}{M_2} \left( \frac{5}{6} - q \right),$$

(6)

where $R_L$ is the radius of the Roche lobe, $J$ is the orbital angular momentum, and $-M_2$ is the instantaneous mass transfer rate (Frank, King & Raine 1992).

When $q(= M_2/M_1) < 5/6$ then $\dot{R}_L > 0$, so the Roche lobe expands, reducing the mass transfer, and the system is stable. In order to sustain long-lived mass transfer the secondary star must expand in size relative to the Roche lobe, otherwise the lobes detach from the star and mass transfer stops. Evolution of the secondary star is one possibility, but for the secondary to evolve within the age of the Galaxy, it must be spectral type G0 or earlier (Patterson 1984). Most CV secondaries have spectral types later than G0, so a more likely solution for stable mass transfer is angular momentum loss arising from gravitational radiation and/or magnetic braking. The loss of angular momentum shrinks the binary system, therefore enabling sustained mass transfer to occur.

When $q > 5/6$ then $\dot{R}_L < 0$, and the Roche lobe shrinks. Mass transfer will therefore increase, and the system will become unstable unless the secondary star can contract rapidly enough to keep its radius smaller than the radius of the Roche lobe. If the secondary star obeys the main-sequence mass–radius relation $R_2 \propto M_2$, and the radius of the star responds to changes in its mass on a thermal time-scale, equation (6) becomes

$$\frac{J}{f} = \frac{-M_2}{M_2} \left( \frac{4}{3} - q \right),$$

(7)

yielding a critical upper mass ratio ($q_{\text{crit}}$). When $q > 4/3$ the secondary star will not shrink rapidly enough to keep pace with the Roche lobe. There will be a spontaneous overflow and mass transfer becomes unstable.

The secondary star in a CV is a late-type low-mass star with a deep convective envelope, and therefore loses mass on a dynamical time-scale governed by the adiabatic response of the star. Considering a complete polytrope with a polytropic index of $n = 3/2$ (Hjellming & Webbink 1987), the mass–radius relation for the secondary star becomes $R_2 \propto M_2^{-1/3}$, and hence equation (6) becomes

$$\frac{J}{f} = \frac{-M_2}{M_2} \left( \frac{2}{3} - q \right),$$

(8)

producing a lower mass ratio limit ($q_{\text{ad,lc}}$). When $q > 2/3$ the star cannot remain within its Roche lobe in hydrostatic equilibrium, and mass transfer occurs on dynamical time-scales. When $q < 2/3$, the star becomes stable on a dynamical time-scale and mass transfer occurs because of the slow expansion of the star via nuclear evolution or angular momentum loss causing the Roche lobe to contract.

The secondary star in RW Tri may not be fully convective so the true adiabatic mass ratio will be higher. In the case where the secondary star has a convective envelope, but a radiative core, the mass–radius relation becomes $R_2 \propto M_2^{1/3}$, leading to a mass ratio of $q_{\text{ad,rc}} = 1$ for the adiabatic response (Hjellming & Webbink 1987).

### 4.4 Mass ratio

We first calculate the mass ratio of RW Tri using the various estimates of the component star radial velocity amplitudes. The most reliable estimate for the secondary star velocity is from the $K$-band data because there is not enough detail in the $J$-band data to be sure that they are not affected by telluric lines and background emission etc. When combined with the $K$-band secondary star velocity (221 \pm 29 km s$^{-1}$), the various estimates of the primary star velocity amplitude discussed in Section 4.1 lead to a range of mass ratios of 0.8–1.3 as expressed in Table 4 (column 4).

The $K_1$ velocity values that a priori are most likely to reflect the motion of the white dwarf are the ultraviolet absorption lines of Mason et al. (in preparation), and the He II emission lines of Still et al. (1995), because they both originate in regions close to the white dwarf. These velocities therefore give us a ‘most likely’ mass ratio in the range 1.0–1.3. To consider the effects of the ‘$K$-correction’ on our most likely mass ratio range, we use equations (3) and (5), and $f \sim 0.25$ with $q = 1.0–1.3$, which corresponds to a range in $\Delta K$ of $\sim$19 to $\sim$24 per cent. Thus, after applying the most likely value for the secondary star heating, the value of $K_2$ in RW Tri is $\sim$178 km s$^{-1}$, implying a revised mass ratio, $q$, in the range 1.2–1.7 (Table 4, column 5).

Alternatively, we can calculate the mass ratio of RW Tri using the rotational broadening of the secondary star, independently of $K_1$. Assuming that the secondary star rotates in phase with the binary orbit, we use

$$\frac{K_2}{V_{\text{rot}} \sin i} = \left( 1 + q \left( \frac{R_2}{a} \right) \right)^{-1},$$

(9)

where $R_2/a$ is found using equation (5). The results are shown in Fig. 9 where the solid line represents the $K_2$ values implied by $V_{\text{rot}} \sin i = 120$ km s$^{-1}$ (from Section 3.6) as a function of mass.

### Table 4. Mass ratio results using our best estimate of the secondary star velocity, with a combination of white dwarf velocities.

| Feature | $K_1$ (km s$^{-1}$) | $K_2$ (km s$^{-1}$) | $q_{\text{using}}$ | $q_{\text{using}}$ |
|---------|---------------------|---------------------|---------------------|---------------------|
| UV      | 296 $\pm$ 5         | 221 $\pm$ 29        | 1.34 $\pm$ 0.18     | 1.66 $\pm$ 0.27    |
| Hα      | 223 $\pm$ 11        | 221 $\pm$ 29        | 1.01 $\pm$ 0.14     | 1.25 $\pm$ 0.21    |
| Hβ      | 216 $\pm$ 9         | 221 $\pm$ 29        | 0.98 $\pm$ 0.14     | 1.21 $\pm$ 0.20    |
| Hε      | 208 $\pm$ 8         | 221 $\pm$ 29        | 0.94 $\pm$ 0.13     | 1.17 $\pm$ 0.20    |
| Hδ      | 170 $\pm$ 20        | 221 $\pm$ 29        | 0.77 $\pm$ 0.14     | 0.96 $\pm$ 0.19    |
Fig. 9. Radial velocity of the secondary star ($K_2$) versus a range of mass ratios ($q = M_2/M_1$). The solid curved line represents $K_2$ calculated using $V_{\text{rot}} \sin i = 120$ km s$^{-1}$, and equations (9) and (5). The dotted curved lines represent $K_2$ using $V_{\text{rot}} \sin i = 120 \pm 20$ km s$^{-1}$. The dashed straight lines represent the variation of $K$-corrected $K_2 = 221$ km s$^{-1}$ (Section 4.2) as a function of mass ratios, when $\Delta K = 0$ and 24 per cent. The horizontal bars labelled ‘He ii’ and ‘UV’ represent the mass ratio ranges of He ii and ultraviolet respectively, using $\Delta K = 0$ and 24 per cent from Table 4.

ratio between $q = 0.2$ and 2.0. The dotted lines show the effects of changing $V_{\text{rot}} \sin i$ by $\pm 20$ km s$^{-1}$. The dashed lines in Fig. 9 represent the $K$-corrected secondary star velocity as a function of the mass ratio, for the cases $\Delta K = 0$ and 24 per cent. We find a self-consistent value of $q$ in the range 0.5–0.8 when no correction for possible heating effects is applied ($\Delta K = 0$ per cent). This does not agree with the mass ratio range derived for either He ii or ultraviolet $K_1$ velocities, which are indicated in Fig. 9. When $\Delta K = 24$ per cent, the allowed mass ratio range is $q = 0.6$–1.1 (Fig. 9), and again does not overlap with either the He ii or ultraviolet range.

This can be more clearly seen in Fig. 10 where the derived values of $q$ are expressed as a function of $\Delta K$. The solid black line in Fig. 10 shows the mass ratio at which the $K_2$ value implied by $V_{\text{rot}} \sin i = 120$ km s$^{-1}$ equals the $K$-corrected value of $K_2$ (adopting an observed value of $K_2$ of 221 km s$^{-1}$). Again the dotted lines indicate the effect of changing $V_{\text{rot}} \sin i$ by $\pm 20$ km s$^{-1}$. The dashed and thick solid lines represent the mass ratio derived using the He ii and ultraviolet line estimates of $K_1$ in combination with the $K$-corrected value of $K_2$, as a function of $\Delta K$. Fig. 10 shows that $V_{\text{rot}} \sin i$ is consistent with the He ii-based mass ratio range only for $\Delta K > 34$ per cent, and higher still for the ultraviolet-based $K_1$ value (cf. our best estimate of $\Delta K \sim 24$ per cent). This is greater than the we find in Section 4.2, suggesting that velocities found using the ultraviolet and He ii emission lines may contain non-orbital components.

4.5 Masses

Using the Roche lobe geometry, a relationship between the mass ratio ($q$), orbital inclination angle ($i$) and eclipse duration was derived by Chanan, Middleditch & Nelson (1976) and also by Horne (1993). Because the temperature of the accretion disc increases towards its centre, the ultraviolet emission of the disc will be more concentrated around the white dwarf than the optical emission. Thus an eclipse width at half-light measured in the ultraviolet is likely to be a better approximation to the white dwarf eclipse duration than one measured in the optical band. Using the relationships of Chanan et al. (1976) and Horne (1993), the mass ratio, and the eclipse width at half-light of 0.077 $\pm$ 0.002 from the ultraviolet light curves of Mason et al. (1997), a set of inclination angles can be calculated. These inclination angles range from 73° to 79° for mass ratios between 0.5 and 1.1. Hence a range of masses for the primary and secondary stars can be derived using

$$M_1 \sin^3 i = \frac{P_{\text{orb}} K_2}{2 \pi G} (K_1 + K_2)^2$$

and

$$M_2 \sin^3 i = \frac{P_{\text{orb}} K_1}{2 \pi G} (K_1 + K_2)^2.$$  

The results derived using the ultraviolet and He ii $K_1$ velocities are shown in Fig. 11. Using the ultraviolet measurement, both the uncorrected and $K$-corrected mass ratios lie above the critical value of 4/3 (Section 4.3), in the region of the diagram where mass transfer is unstable. The upper mass for the primary star exceeds the Chandrasekhar mass limit of 1.44 M$_\odot$, and the secondary star mass is also very large and inconsistent with that of a main-sequence star. This reinforces our suspicions that the ultraviolet velocities contain a non-orbital component. A reduction of $K_2$ below the $K$-corrected value of 178 km s$^{-1}$ would decrease the secondary mass, but further increase the mass ratio.

Adopting instead the $K_1$ measurement derived from He ii data, we find values of $q$ that broadly lie between $q_{\text{crit}} = 4/3$ and $q_{\text{crit}} = 1$. The masses for the primary and secondary stars lie in the range of 0.8–1.1 and 0.9–1.1 M$_\odot$ respectively. The white dwarf mass is well within the Chandrasekhar mass limit of 1.44 M$_\odot$, and includes the mean primary mass of 0.8 M$_\odot$ for CV systems with $P_{\text{orb}} > 3$ h (Smith & Dhillon 1998). The lower limit for the secondary star mass, however, exceeds the predicted mass of 0.55 M$_\odot$ based on the main-sequence mass–radius relation for an orbital period of 5.25 h (Echevarría 1983).

Given the evidence for a non-orbital component in the ultraviolet absorption line velocities, we cannot be certain that the optical emission-line velocities are not similarly affected. If we forced the secondary star mass to its equivalent main-sequence
The component star masses in RW Tri

5 CONCLUSIONS

$I$-band observations of RW Tri yield a secondary star radial velocity amplitude of $250 \pm 47$ km s$^{-1}$ using the skew-mapping technique. $K$-band observations of RW Tri provide us with a secondary star velocity of $221 \pm 29$ km s$^{-1}$ which is obtained directly from the observations without using complex mapping methods. The two velocities are consistent within the errors.

We estimate the rotational velocity of the secondary star to be $120 \pm 20$ km s$^{-1}$ using the $K$-band UKIRT observations. Combining this velocity with the secondary star radial velocity corrected for non-uniform heating derived from the variation in the absorption-line strengths, we find a mass ratio range of 0.6–1.1, which contains the lower adiabatic response limit of $q_{\text{ad,rc}} = 2/3$. The corrected radial velocity results lead to a mass ratio range of 0.5–0.8.

Combining the radial velocity amplitudes of the secondary star with the radial velocity of the primary determined from He I emission lines in the optical (Still et al. 1995) and narrow absorption lines in the UV (Mason et al., in preparation) yields a range of mass ratios of 1.0–1.3 and 1.2–1.7 respectively, based on a range in the secondary heating correction of $\Delta K = 0–24$ per cent. The ultraviolet mass ratio range lies above the critical mass ratio ($q_{\text{crit}} = 4/3$); this range is also inconsistent with the rotational velocity results, indicating that the ultraviolet velocity very likely includes a non-orbital component. The He I mass ratio range lies between $q_{\text{mass}} = 4/3$ and $q = 5/6$, but is only marginally consistent with the measured secondary rotational velocity, and may also contain a non-orbital component. By combining the data on the rotational broadening of the secondary with its measured orbital velocity, with no assumptions regarding the white dwarf velocity, we find most likely

$0.55 M_\odot$, we would predict a primary star velocity of 152–169 km s$^{-1}$ for $K_2 = 221–178$ km s$^{-1}$. This is closer to the $K_1$ value of $170 \pm 20$ km s$^{-1}$ derived by Kaitchuck et al. (1983) from the He I emission line. The implied mass ratio for a $K_1$ velocity of 170 km s$^{-1}$ is in the range 0.8 ($\Delta K = 0$ per cent) to 1.0 ($\Delta K = 24$ per cent), and is consistent with the rotational velocity of the secondary that we derive (Fig. 10).

Alternatively, we can obtain mass values using the combination of $V_{\text{rot}} \sin i$ and $K_2$ without any assumptions about $K_1$. Using the mass ratio values of 0.6–1.1 for $\Delta K = 24$ per cent and 0.5–0.8 for $\Delta K = 0$ per cent from Section 4.4, and assuming $K_2$ values of 178 and 221 km s$^{-1}$ respectively, the stellar masses can be calculated using equations (2), (10) and (11). Fig. 11 shows the results. The most likely masses of the primary and secondary stars lie in the ranges $0.4–0.7$ and $0.3–0.4 M_\odot$, respectively for the range of $\Delta K = 24–0$ per cent, and better agree with the expected masses for the component stars in a CV. The expected value of $K_1$ based on these results is in the range 120–130 km s$^{-1}$, with an upper limit of approximately 190 km s$^{-1}$.

$\frac{\Delta i}{\Delta 1}$ for $K_1 = 296 \pm 5$ km s$^{-1}$ velocity (Mason et al., in preparation), and the middle set of results are obtained using the He II accretion disc emission $K_1 = 216 \pm 9$ velocity (Still et al. 1995). The error bars combine the uncertainties in $K_1$ and $K_2$. The lower set of results show the mass values derived from the $K_2$ measurement combined with $V_{\text{rot}} \sin i = 120 \pm 20$ km s$^{-1}$. The error bars are calculated using the $\pm 20$ km s$^{-1}$ uncertainty on $V_{\text{rot}} \sin i$. The vertical solid line represents the 1.44-M$_\odot$ Chandrasekhar mass limit for white dwarf stars. The two dashed lines represent the locus of masses calculated when $K_2 = 221$ and 178 km s$^{-1}$ respectively with varying $K_1$ values; the tick marks on the two dashed lines mark $K_1$ velocity values of 50, 100, 150, 200, 250 and 300 km s$^{-1}$. The four dotted lines represent the $q_{\text{crit}} = 4/3$ thermal mass transfer limit, $q_{\text{ad,rc}} = 1$ adiabatic response with a radiative core, $q = 5/6$ and $q_{\text{ad,fi}} = 2/3$ fully convective lower adiabatic response limit respectively (Section 4.2).

Figure 11. The masses of the component stars in RW Tri, derived by combining the measurement of $K_2$ with different estimates of $K_1$ (represented as asterisks), and from the combination of $K_2$ with $V_{\text{rot}} \sin i$ (represented by open squares). In each case we show values corrected for the effects of heating of the secondary using $\Delta K \sim 24$ per cent ($K_2 = 178$ km s$^{-1}$ – Section 4.3) and also with no heating correction ($K_2 = 221$ km s$^{-1}$), linked by a straight line. The upper set of results are obtained using the ultraviolet absorption $K_1 = 296 \pm 5$ km s$^{-1}$ velocity (Mason et al., in preparation), and the middle set of results are obtained using the He I accretion disc emission $K_1 = 216 \pm 9$ velocity (Still et al. 1995). The error bars combine the uncertainties in $K_1$ and $K_2$. The lower set of results show the mass values derived from the $K_2$ measurement combined with $V_{\text{rot}} \sin i = 120 \pm 20$ km s$^{-1}$. The error bars are calculated using the $\pm 20$ km s$^{-1}$ uncertainty on $V_{\text{rot}} \sin i$. The vertical solid line represents the 1.44-M$_\odot$ Chandrasekhar mass limit for white dwarf stars. The two dashed lines represent the locus of masses calculated when $K_2 = 221$ and 178 km s$^{-1}$ respectively with varying $K_1$ values; the tick marks on the two dashed lines mark $K_1$ velocity values of 50, 100, 150, 200, 250 and 300 km s$^{-1}$. The four dotted lines represent the $q_{\text{crit}} = 4/3$ thermal mass transfer limit, $q_{\text{ad,rc}} = 1$ adiabatic response with a radiative core, $q = 5/6$ and $q_{\text{ad,fi}} = 2/3$ fully convective lower adiabatic response limit respectively (Section 4.2).
values of the primary and secondary masses that lie in the ranges 0.4–0.7 and 0.3–0.4 $M_\odot$ respectively, depending on the degree of secondary star heating. The most likely value of $K_1$ is predicted to be 120–130 km s$^{-1}$.

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REFERENCES

Chanan G. A., Middleditch J., Nelson J. E., 1976, ApJ, 208, 512
Dhillon V. S., Littlefair S. P., Howell S. B., Ciardi D. R., Harrop-Allin M. K., Marsh T. R., 2000, MNRAS, 314, 826
Echevarría J., 1983, Rev. Mex. Astron. Astrofís., 8, 109
Eggleton P. P., 1983, ApJ, 268, 386
Frank J., King A., Raine D., 1992, Accretion Power in Astrophysics. Cambridge Univ. Press, Cambridge
Friend M. T., Martin J. S., Smith R. C., Jones D. H. P., 1988, MNRAS, 233, 451
Friend M. T., Martin J. S., Smith R. C., Jones D. H. P., 1990, MNRAS, 246, 637
Hjellming M. S., Webbink R. F., 1987, ApJ, 318, 754
Horne K., 1993, in Wheeler C., ed., Accretion Discs in Compact Stellar Systems. World Scientific, Singapore, p. 117
Kaitchuck R. H., Honeycutt R. K., Schlegel E. M., 1983, ApJ, 267, 239
Martin J. S., 1988, DPhil thesis, University of Sussex
Mason K. O., Drew J. E., Knigge C., 1997, MNRAS, 290, L23
North R. C., Marsh T. R., Moran C. K. J., Kolb U., Smith R. C., Stehle R., 2000, MNRAS, 313, 383
Patterson J., 1984, ApJS, 54, 443
Protitch M., 1937, Bull. Astron. Obs. Belgrade, 38, 9
Robinson E. L., Shetrone D., Africano J. L., 1991, AJ, 102, 1176
Schneider D. P., Young P., 1980, ApJ, 240, 871
Smith R. C., Cameron A. C., Tucknott D. S., 1993, in Regev O., Shaviv G., eds, Cataclysmic Variables and Related Physics. IoP Publishing, Bristol, p. 70
Smith D. A., Dhillon V. S., 1998, MNRAS, 301, 767
Smith D. A., Dhillon V. S., Marsh T. R., 1998, MNRAS, 296, 465
Still M. D., Dhillon V. S., Jones D. H. P., 1995, MNRAS, 273, 849
Vande Putte D., Smith R. C., Hawkins N. A., Martin J. S., 2002, MNRAS, submitted
Wade R. A., Horne K., 1988, ApJ, 324, 411

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