The eclipsing binary star RZ Cassiopeiae

II. Spectroscopic monitoring in 2006[★]

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ABSTRACT

Aims. We test the hypothesis that the oEA star RZ Cas has undergone a transient phase of rapid mass-transfer in 2000/2001.

Methods. We analyze a time series of high-resolution spectra of RZ Cas obtained in 2001 and in 2006 for radial velocity (RV) and line profile variations. Improved orbital solutions are determined using the method of differential corrections. In the RV residuals, after subtracting the orbital solution and low-frequency variations, we search for non-radial pulsations in the high-frequency domain and for an amplitude modulation of the pulsation modes. We model the observed line profiles using a new computer program based on the method of spectroscopic eclipse mapping and investigate the line intensity residuals and the Rossiter-McLaughlin effect.

Results. Between 2001 and 2006, the derived orbital solutions show an increase of the orbital period of the order of 2 seconds that is compatible to the photometrically obtained results. RZ Cas changed its pulsation pattern again. We find at least three pulsation frequencies where one is observed for the first time. All three frequencies show amplitude modulations that are correlated with the position of the star in its orbit. The amplitude amplification around primary minimum is much stronger than in 2001. The modeling of line profiles gives hints to a much more complex and inhomogeneous circumbinary gas density distribution in 2001 compared to 2006. The Rossiter-McLaughlin effect is strongly asymmetric in 2001 and almost normal in 2006.

Conclusions. The findings support the assumption that a rapid mass-transfer episode occurred in RZ Cas in 2000/2001.

Key words. stars: binaries: eclipsing – stars: variables: delta Sct – stars: fundamental parameters – lines: profiles

1. Introduction

The A3 V + K0 IV eclipsing binary RZ Cas is an active, semi-detached Algol-type system showing complex features in its light-curve and radial velocities (RVs). Its orbital period is of 1.1952572 d and the primary minimum is a partial eclipse (Narusawa et al. 1994). The primary component was discovered as a 22.4 min period oscillating star by Ohshima et al. (1998, 2001). RZ Cas is a member of the recently-established group of oEA stars (oscillating EA stars, Mkrtichian et al. 2005). These are Algol-type systems with mass-transfer where the mass-accreting primary (gainer) lies inside the instability strip and shows δ Sct-type non-radial pulsations (NRP). In recent years, the number of known oEA stars has increased to 22 (Mkrtichian et al. 2007b; Pigulski & Michalska 2007). RZ Cas is one of the brightest oEA stars ($m_V = 6.27$, luminosity ratio between secondary and primary of 0.122). Its brightness implies that the oscillating primary of RZ Cas is one of the most promising targets for asteroseismologic studies. RZ Cas is the most-well studied oEA star that has extensive spectroscopic data available (Lehmann & Mkrtichian 2004, hereafter referred to as Paper I).

In Paper I we showed, based on time series of high-resolution spectra taken at TLS in 2001, that the star exhibits a strongly asymmetric rotation effect (anomalous Rossiter-McLaughlin

effect, RME) in its RVs, possibly caused by the large density gradient in the circumstellar environment that is expected close to the primary minimum from 3D-hydrodynamic simulations (Paper I; Mkrtichian et al. 2007a).

In the residuals of the orbital solution we detected short-term RV oscillations. Whereas the photometrically observed oscillations were dominated by mono-periodic pulsations at a frequency of 64.19 c d^{-1} until the year 2000 (Ohshima et al. 1998, 2001; Rodriguez et al. 2002, 2004; Mkrtichian et al. 2007b), we found in the spectra from 2001 a multi-periodic behavior with two dominant frequencies of 56.600 and 64.189 c d^{-1} . This change of the pulsation pattern was also photometrically detected by Mkrtichian et al. (2003) who found the same two frequencies from the 2001 photometric campaign, together with a decrease of the pulsation amplitude of the main mode by an order of magnitude down to 1–2 mmag.

The observed amplitude modulation of the short-term RV variations with the orbital period has its maximum close to primary minimum. As mentioned above, it can be explained by screening effects during the eclipse itself and by the effects of the gas density gradient close to primary minimum.

The absolute elements of the RZ Cas system and its components were determined by Maxted et al. (1994). These elements have been recently revised by Mkrtichian et al. (2007b) using the Wilson-Devinney code (WD) in its 2003 version (Wilson & Devinney 1971) with the *uvby* light curves from

[★] Based on observations obtained at the 2-m Alfred Jensch telescope at the Thüringer Landessternwarte (TLS) Tautenburg.

Table 1. Journal of observations. N is the number of obtained spectra.

Date	JD	N	Date	JD	N
2005/12/13	2 453 717	21			
2006/01/08	2 453 744	101	2006/05/08	2 453 864	36
2006/01/09	2 453 745	123	2006/05/09	2 453 865	37
2006/01/10	2 453 746	128	2006/05/10	2 453 866	52

1999 (Rodriguez et al. 2004) and the RVs from 2001 presented in Paper I.

In 2006 we continued the spectroscopic monitoring of the star with the aim to look for further timely variations of the effects observed so far such as the changing pulsation pattern, the order of the amplitude modulation of the NRP modes, the asymmetry of the RME, and its correlations. Furthermore we test a first version of a program for the spectroscopic modeling of eclipsing binaries by using the 951 spectra obtained in 2001 (Paper I) and the 498 new spectra from 2006 and compare the results with those obtained photometrically.

2. Observations and data reduction

In Table 1 we provide the journal of new observations. 498 spectra of RZ Cas were obtained in total, in one night in December 2005, in three consecutive nights in January, and in three consecutive nights in May 2006. All spectra were taken with the coude-echelle-spectrograph attached to the 2-m telescope at the Thüringer Landessternwarte Tautenburg. The typical exposure time was 300 s, the spectral resolution 30 000, and spectra have a signal-to-noise (SN) between 60 and 120 (85 typical).

Spectroscopic reduction was completed using standard MIDAS packages. It included bias and stray-light subtraction, filtering of cosmic rays, flat-fielding, optimized extraction of echelle orders and wavelength calibration using a Th-Ar lamp. Instrumental shifts were compensated for by using a large number of telluric O₂ lines.

RVs were measured from the centroids (Gaussian fits) of the cross-correlation function between spectrum and template calculated from the wavelength range from 4915 Å (end of H β red wing) to 5670 Å (where stronger telluric lines occur). Starting with one arbitrary spectrum as the template, we shifted and added all spectra according to the obtained RVs to build a new template of high SN and repeated this procedure. The finally achieved internal accuracy was approximately 40 m s⁻¹. RVs computed using cross-correlation are on a relative scale. They have been calibrated by using 20 metallic lines of Fe, Mg, Ca, and Si to obtain absolute RVs. Due to the large value of $v \sin i$ for RZ Cas (71 km s⁻¹ for the primary and 83 km s⁻¹ for the secondary) the accuracy of this absolute calibration is ± 1.2 km s⁻¹.

3. Orbital solutions

3.1. Primary orbit

For the derivation of the orbital elements we used a computer program based on the method of differential corrections (Schlesinger 1909) that we extended to include also linear variations of the orbital elements with time. RVs close to primary minimum, where the values are distorted by the RME (see Figs. 1 and 2), were excluded from the analysis.

Starting with the assumption of circular orbits we derived orbital elements separately (columns S_{2001a} and S_{2006} in Table 2)

Table 2. Orbital elements derived from the two data sets separately.

Element	S_{2001a}	S_{2001b}	S_{2006}
P (d)	1.194946(57)	1.194946(55)	1.1952946(48)
K (km s ⁻¹)	71.481(1)	73.1 (fixed)	70.643(60)
T (2 452 193+)	0.38475(22)	0.98203(23)	0.38475(22)
γ (km s ⁻¹)	-44.293(68)	-45.1 (fixed)	-44.484(46)
rms (km s ⁻¹)	1.695	1.695	0.763

for the two periods of observations. Table 2 lists the derived orbital periods P , RV semi-amplitudes K , times of primary minimum T , γ -velocities, and the rms of the residuals. Errors in units of the last two digits are shown in parentheses. The errors listed for γ do not include the uncertainty of the absolute RV values. Figures 1 and 2 show the observed and calculated RVs. Comparing the solutions S_{2001a} and S_{2006} , we see that the RVs from 2006 yield a much more precise value of the orbital period and that the rms is smaller by a factor of two. Moreover, from Fig. 1 we see that there are stronger local deviations of the 2001 data from the calculated orbital curve outside the eclipse phases, in particular close to secondary eclipse and close to the phase gap close to RV minimum. To check if our solution is influenced by this phase gap we adjusted and fixed the RV semi-amplitude K to the observed values about the RV minima and maxima although our results remain unchanged. We obtained a more accurate solution only after allowing the γ -velocity to vary (Fig. 3). As in case of S_{2001a} , the upper half circle is reproduced well although there are larger deviations in the lower circle. The new solution (S_{2001b} in Table 2) has the same rms as obtained for S_{2001a} and both solutions yield the same orbital period. We finally accept the solution S_{2001a} because of the tight constraints on γ and K and the strong deviations of γ and measurements of T from all other solutions. We assume that local deviations from a sinusoid are caused by physical reasons like the inhomogeneously distributed circumbinary matter rather than by a wrong fit due to phase gaps.

Orbital solution S_{2006} yields the most accurate value of the orbital period. Its accuracy is comparable to that of the most precise value of 1.1952572(6) d obtained by Narusawa et al. (1994) from the photometric times of minima calculated from the measurements by Nakamura (1991). The values of the orbital period given by S_{2001a} , S_{2006} , and by Narusawa et al. (1994) differ significantly within its limits of errors. We obtain a difference of 30 s between the spectroscopic orbits from 2006 and 2001. Such a large difference is unreliable and much larger than the maximum deviations of approximately one to two seconds that are observed from the times of minima so far (Mkrtichian et al. 2007b). We therefore assume that the orbital period that is derived from the 2001 data alone is falsified by the distortions in the orbital curve. The difference in orbital period between our S_{2006} solution and the value derived by Narusawa is of 3.2 ± 0.5 s and quite compatible to the order of RZ Cas period changes observed in the past (see Sect. 7.1 for a discussion).

In a next step we derived a common solution from all spectra from 2001 and 2006 (S_1 in Table 3). Except for the RV amplitude, this solution is almost identical to S_{2006} . Also this fact speaks against a drastic period change of 30 s between 2001 and 2006 and supports our assumption that the period derived from the 2001 data alone is uncertain.

To search for a period change based on both data sets we allowed for a linear variation of P and K . This can be done regardless of the question if the period changes occur in steps or continuously since the time span of the two data sets is short

Fig. 1. RVs from 2001 folded with the orbital period. *Top:* measured RVs. Solid curve: orbital solution S_{2001a} . *Bottom:* orbital residuals. Dashed lines indicate γ -velocity and phase of primary minimum.

Fig. 2. As Fig. 1 for the RVs from 2006 (solution S_{2006}).

Fig. 3. As Fig. 1 showing orbital solution S_{2001b} .

compared to the total time span from 2001 to 2006, the result will give a measure for the total period change between the two epochs. Derived elements are listed in Table 3 as solution S_2 . The period increased by 0.37 s yr^{-1} and the RV half-amplitude decreased by $135 \text{ m s}^{-1} \text{ yr}^{-1}$. The total amounts of the changes during the effective period length of observations of 4.33 yr is of 1.6 s in P and of -0.585 km s^{-1} in K . In the common solution, the influence of the distortions in the orbital RV curve from 2001 is distinctly reduced and the derived orbital period change is of the order of the photometrically observed changes. We did not

Table 3. Orbital elements derived from all data. In case of S_2 , T is the reference time for the given P and K .

Element		S_1	S_2
P	(d)	1.19525988(26)	1.1952410(77)
dP/dt	(s yr $^{-1}$)	...	0.37(16)
K	(km s $^{-1}$)	71.050(60)	71.311(78)
dK/dt	(km s $^{-1}$ yr $^{-1}$)	...	-0.135(27)
T	(2 452 193+)	0.38477(22)	0.38482(20)
γ	(km s $^{-1}$)	-44.129(46)	-44.207(49)
rms	(km s $^{-1}$)	1.508	1.493

expect different RV half-amplitudes, however. A discussion will be given in Sect. 7.

The orbital curve corresponding to S_2 can hardly be distinguished by eye from the curves shown in Figs. 1 and 2; the local deviations from the 2001 observations are practically the same as shown in Fig. 1. From Figs. 1 and 2 it can be seen that the RME observed in 2006 is almost normal whereas in 2001 a strong asymmetry is observed.

Spectroscopic orbits of RZ Cas have been derived by Horak (1952), Duerbeck & Hänel (1978), and Maxted et al. (1994). Our solutions from Paper I and the solutions of Duerbeck & Hänel (1978) both constrain the non-circularity of the orbit. In Paper I we reconciled the small measurement of eccentricity, 0.03, with the influence of the inhomogeneously distributed circumbinary matter. Here we readress the possibility that the orbit is non-circular. Our results for both datasets provide similar eccentricities as before, but completely different longitudes of periastron. If we allow in the common solution for non-circular orbits and for apsidal motion we obtain an unlikely rate of apsidal motion of 33° yr^{-1} . And, it is not possible to fit any local deviations in a better way by using non-circular orbits. Thus we believe that any non-circularity calculated using our RVs is simulated by low-frequency variations due to changes in the stellar environment of RZ Cas and that solution S_2 provides the most adequate results.

3.2. Secondary orbit

Due to the large value of $v \sin i$, the faintness of the companion, and the large orbital RV amplitude we detected only five unblended lines of Fe and Ca of the secondary. Only one of these lines, the Fe I 4957 Å line, provided a sufficiently high SN to investigate the fundamental system parameters. Results are described in Sect. 6.

4. Low-frequency RV variations

In addition to RME the orbital RV curve of RZ Cas is distorted by low frequency contributions presumably due to changing inhomogeneities in the circumstellar environment. To detect high-frequency RV variations due to pulsations, we cleaned the data for both orbital and low-frequency RV variations of timescales similar to the orbital period and its first harmonics. We did not perform a period search to remove these variations but fitted cubic splines to the RV residuals of orbital solution S_2 to remove separately trends in each of the runs. We estimate that the spline fits cover a frequency range that does not exceed 10 d^{-1} in maximum. Figure 4 shows the resulting spline fits folded with the orbital period. It can be seen that orbital solution S_2 provides a very precise alignment of the distortions due to the RME at

Fig. 4. RV spline fits of low-frequency distortions folded with the orbital period. Dashed: observations in 2001. Solid: observations in 2006.

the phase of primary minimum. The RME amplitude in 2006 is distinctly lower than in 2001.

5. High-frequency RV variations

5.1. Period search

After filtering all low-frequency variations, we analyzed the residuals to detect a wide range of frequencies. Frequency search was completed by successive pre-whitening of the data for the found periodic variations using the program PERIOD04 (Lenz & Breger 2005). In each step the frequencies, amplitudes, and phases of all contributions found so far have been optimized simultaneously.

Figure 5 shows the periodograms for the different steps of pre-whitening (to reduce the amount of graphical output we omitted a large number of local minima in the figure). Table 4 lists the results. Here we term the strongest mode found in the 2006 data f_1 since it was also the main mode in the early photometric detections (note that in Paper I the designations of f_1 and f_2 are interchanged). The errors of the parameters have been calculated by PERIOD04 using the Monte Carlo simulation method. The last column provides the signal-to-noise calculated from the amplitude and its error. The strongest contribution is found for $f_1 = 64.27$ c/d. Frequency $f_3 = 62.41$ c/d is the second strongest component. It is observed for the first time spectroscopically. Close to f_2 we find two peaks of almost the same amplitude, at a frequency of 56.76 c/d⁻¹ and at its 1 d alias frequency. After subtracting the 56.76 c/d⁻¹ contribution both peaks disappear. The amplitude of the f_2 mode is distinctly lower than the amplitudes of f_1 and f_3 . Frequencies listed in Table 4 as f_4 and f_5 are spurious contributions that were found in the residuals after subtracting f_1 to f_3 . Its peak strengths are comparable with that at high frequencies close to the Nyquist frequency of 119 c/d and the calculated SN is very low. The detection of the frequencies f_4 and f_5 requires confirmation using additional observations.

5.2. Amplitude modulation

From the spectroscopic investigations in 2001 (Paper I) we know that an amplitude modulation of the pulsation modes occurred that is correlated with the position of the star in its orbit. We searched for such a correlation in the new data. To enhance the SN we built overlapping orbital phase bins from all runs in 2006. Each bin has a width of $\Delta\phi = 0.2$ in orbital phase. 20 such phase bins cover the full orbital period in steps of 0.05. We determined the amplitudes of the three pulsation modes from each phase bin using a three frequencies model.

Figure 6 shows the results and compares them with those obtained in 2001. As observed in 2001 (Paper I), the orbital amplitude modulation in the out-of-eclipse phases is quite weak. For each mode we register now a sharp-peaked RV amplitude

Fig. 5. Periodograms for different steps of successive pre-whitening. Highest peaks are found for f_1 , f_3 , and f_2 . Bottom panel: residuals after subtracting the contributions of f_1 to f_3 .

Table 4. Results of frequency search in the RZ Cas RVs.

	Frequency (c d ⁻¹)	Amplitude (m s ⁻¹)	Phase	SN
f_1	64.27025(25)	203(16)	0.781(11)	12.7
f_2	56.76104(55)	94(16)	0.538(24)	5.9
f_3	62.40619(36)	145(17)	0.845(15)	8.5
f_4	64.58751(61)	84(17)	0.530(26)	4.9
f_5	51.25156(76)	69(17)	0.811(32)	4.1

amplification at primary minimum. This remarkable effect is caused by the periodic spatial filter effect arising during the partial eclipse of the disk of the non-radially pulsating primary. The effect was predicted for oEA stars by Mkrtichian et al. (2002). It was found for the first time in photometric data and modeled for RZ Cas by Gamarova et al. (2003). In our spectroscopic data from 2006 we observe an amplification of the f_1 , f_2 , and f_3 modes of 6.6, 6.3, and 9.1 times, respectively. *This is the first spectroscopic detection of the periodic spatial filter effect.* The shape of the f_3 mode RV amplitude variation during primary minimum is double-peaked. Due to the poor resolution in phase in our analysis we do not exclude that this is the case for the two other modes as well.

6. A first spectroscopic solution of the RZ Cas system

6.1. The model

We used a new computer program that models the composite line profiles of eclipsing binaries including eclipse mapping. In its preliminary stage the program makes very simple assumptions about the intrinsic stellar line profiles. It assumes a fixed luminosity ratio of the components taken from the light curve analysis and scales the intrinsic profiles to fit the observations after an integration over the visible stellar disks. It further assumes spherical star configurations. We describe our program in Lehmann & Mkrtichian (2007). In spite of the aforementioned assumptions the program delivers global stellar parameters that are in good agreement with those derived photometrically with WD. Advantages of our simple model are that it is directly sensitive to spectroscopic parameters such as orbital RV half-amplitude K and $v \sin i$ and that it considers the position angles ψ_i of the rotation axes of both components in the observers plane. The RME is very sensitive to this parameter. The non-considered effects in

Fig. 6. Amplitudes of RV variations folded with the orbital period. Curves: observations from 2006. Solid: f_1 . Dotted: f_2 . Dashed: f_3 . Error bars: from left to right for f_1 to f_3 . Squares: observations from 2001. Filled squares: f_1 . Open squares: f_2 .

Algol-type stars such as the accretion annulus of the gainer and gaseous streams in the circumbinary environment can be studied in the line intensity O–C values in an extracted form.

6.2. Application

Table 5 describes the two data sets from 2001 and 2006. It lists the total number of spectra in the corresponding year, the mean signal-to-noise, the mean number of spectra per orbital phase bin, and the orbital period calculated from solution S_2 . We took all spectra with $SN > 60$ into account. The mean orbital period was calculated from orbital solution S_2 for the data from 2001 and 2006 separately. For the analysis we used the Fe I 4957 Å doublet that is sufficiently strong and most unblended by other lines. Time series of spectra from 2001 and from 2006 were binned into 150 orbital phase bins each by averaging the spectra falling into the same bin. The resulting Fe I 4957 Å line profiles were rebinned to the RV scale and arranged in a 2D frame (orbital phase – RV plane) as shown in the left panels of Fig. 7. Each of the 150 columns in Fig. 7 represents one Fe I 4957 Å line profile that was built from all profiles that have been observed at the corresponding orbital phase. In the case of the spectra from 2006, we obtain full phase coverage in this way. The observations from 2001 show some phase gaps (black vertical stripes in Fig. 7).

The interesting S-shaped enhancement in line strength that can be seen during primary minimum can be explained by the combined effect of the variations of depth, width, and position of the lines of the rotating primary during the screening of its visible disk by the secondary. Intensities are normalized to the common continuum consisting of the contributions from both stars. During primary eclipse, the dominating light of the primary is attenuated and thus the relative absorption line strength is enhanced. The lines of the primary get sharper and wavelength-shifted at the beginning and the end of the eclipse where one hemisphere of the rotating primary is covered by the secondary. During mid-eclipse, this asymmetry is removed and we see a symmetric broadening arising from the non-eclipsed surface region close to the pole. This picture is valid for a partial eclipse and for a system where the primary is more luminous than the secondary. From the line shapes during eclipse we obtain detailed information about stellar and atmospheric parameters (eclipse mapping).

Table 5. Characteristic data of the two data sets.

Epoch	N_{spec}	SN	N_{bin}	P_{orb} (d)	Phase gaps
2001	951	200	6	1.1952410	yes
2006	498	85	4	1.1952595	no

Table 6. Parameters taken from the WD solution.

Parameter	Primary	Secondary
$M(M_{\odot})$	2.054(14)	0.706(6)
$R(R_{\odot})$	1.593(7)	1.931
$\log g$	4.347(11)	3.716
T (K)	8550(100)	4590
$L(L_{\odot})$	12.15(58)	1.48
X	0.661 ^a	0.646 ^a
F	1.22 ^b	1.00 ^b
$a(R_{\odot})$	6.641(13)	
$j(^{\circ})$	82.622(36)	

^a Fixed, ^b Assumed.

Table 7. Spectroscopic solutions.

Parameter	WD		2001-calc		2006-calc	
	prim	s	prim	s	prim	s
X	0.661	0.636	0.62	0.66	0.59	0.60
K (km s ⁻¹)	71	207	71.5	198	71	206
$v \sin i$ (km s ⁻¹)	82	82	78	100	71	83
ψ (°)	–	–	83.1	90	90	90
j (°)	82.622		80.1		83.1	
a_1/R_1	1.067		1.068		1.067	
R_2/R_1	1.212		1.217		1.215	
S (%)	6.34 ₂₀₀₁ /6.85 ₂₀₀₆		5.65		4.78	

6.3. Results

Optimum model parameters were achieved from the minimization of the line intensity O–C values as shown in the right panels of Fig. 7. We started with the parameters taken from the WD solution without a hot spot (Mkrtichian et al. 2007b) as listed in Table 6. X is the linear limb darkening coefficient, F the rotation-orbit synchronization ratio, a the semi-major axis of the relative orbit, and j the orbital inclination. From the parameters in Table 6 we calculated our model parameters as provided in Table 7 in columns WD. Table 7 lists the linear limb darkening coefficients X , RV semi-amplitudes K , $v \sin i$, position angles of the rotation axes ψ , orbital inclination j , and, in units of the radius of the primary, the radius of the primary orbit a_1/R_1 and the radius of the secondary R_2/R_1 . S is the reduction in the sum of squares in % obtained from each model: it is $S = \sigma^2/\sigma_0^2$ where σ^2 is the variance of the residuals and σ_0^2 is the variance of the observations. The luminosity ratio $L_2/L_1 = 0.1218$ was taken from the WD solution and fixed.

Our model has 13 free parameters in total, the 11 parameters listed in Table 7 plus the intrinsic line depths of the two stars. In the first step we fixed all model parameters to the WD values and computed only optimized intrinsic line profiles and the corresponding reduction in the sum of squares. To reduce the number of free parameters, we then optimized the parameters that determine the line profiles outside the eclipses, namely X , K , $v \sin i$, and the intrinsic line depths using only the out-of-eclipse data. Minimization of the residuals was completed by optimizing the single parameters repeatedly in alternating order. After finding the optimized values, the parameters were fixed and the

Fig. 7. Time series of Fe I 4957 Å line profiles folded with the orbital period (note that zero orbital phase refers here to the extrema of the orbital RV curves). From left to right: observed and calculated profiles, O–C values. *Top:* spectra from 2001. *Bottom:* spectra from 2006.

remaining parameters ψ , j , a_1/R_1 , and R_2/R_1 were optimized based on the entire data set including the eclipse phases.

The residuals of our final solution are shown in the right panels of Fig. 7. For the spectra from 2006 one can see that, except for a larger region surrounding the secondary minimum, almost all structures from the lines of both components have been removed. The “bright” feature at the position of the secondary close to Min. II means that the observed lines are weaker in this region than predicted by our model that was calculated in the final step only from the data outside this region. The dark vertical strip centered at Min. I originates from very weak neighboring lines that cannot be seen in the original spectra. All other weak vertical features result from the different SN due to the different number of single spectra in the different rotation-phase bins.

7. Discussion

7.1. The orbit

Our orbital solutions yield different values of the orbital period based on the spectra taken in 2001 and 2006 and a significantly different value of the orbital period derived from the spectra taken in 2006 compared to Narusawa’s period (Narusawa et al. 1994). According to our solution S_2 , the orbital period increased from 2001 to 2006 by 1.6 s. This result is in agreement with the photometric findings from the analysis of the observed times of minima. Figure 8 shows the O–C values derived from a compilation of observed times of minima from literature (see also Mkrtichian et al. 2007b). O–C values are based on the period of 1.1952572 d as provided by Narusawa. For the calculation we converted all reported times of minima into heliocentric Julian Ephemeris Dates based on Terrestrial Time (see Bastian 2000).

We observe a constant orbital period shortly before the year 1998. In 1998 a break point occurred followed by a decrease of the orbital period and an abrupt increase from 2000/2001 on. From the different slopes in Fig. 8 we calculate an increase of the orbital period between years 2001 and 2006 of about 1.4 s.

Fig. 8. O–C values from the times of minima versus heliocentric Julian Ephemeris Date.

Because of the uncertainty in the period derived from our spectra in 2001, our spectroscopic finding cannot be stated as a confirmation of this photometrically-detected period change. Only the accurate period derived using spectra obtained in 2006 allows a direct comparison with photometric periods to be made. Narusawa’s period is based on the observations by Nakamura (Nakamura et al. 1991) from November 1990. Compared to his value of $P = 1.1952572(6)$ d, our period from solution S_{2006} shows an increase by 3.2 ± 0.5 d. Period changes of RZ Cas of a number of seconds have been repeatedly observed. Narusawa et al. (1994) reported an increase in the orbital period by 1.5 s between 1988 and 1990. A detailed analysis of the time of minima observations will be given in a forthcoming paper.

Our orbital solutions show a decrease in the RV semi-amplitudes. From solution S_2 (Table 3) we calculate a total decrease of K_1 by 0.6 km s^{-1} between 2001 and 2006. The spectroscopic solution (Table 7) confirms this decrease and provides an increase in the K_2 of the secondary of 8 km s^{-1} . A simple

consideration shows that the observed values of the changes of orbital period and RV semi-amplitudes are not compatible with each other in the context of pure mass-transfer effects. When the mass is completely transferred from the secondary to the gainer, we have $dM_1 = -dM_2 = dM$ and the relative changes of the orbital period and the semi-major axis are calculated using

$$\begin{aligned}\frac{dP}{P} &= 3 \frac{M_1 - M_2}{M_1 M_2} dM \\ \frac{da}{a} &= 2 \frac{M_1 - M_2}{M_1 M_2} dM\end{aligned}\quad (1)$$

(for a derivation see e.g. van den Heuvel in Shore et al. 1994). From Eq. (1) we calculate the time derivatives, based on the observed values of the mass ratio $q = 0.356$ and the relative period change $\dot{P}/P = 3.58 \times 10^{-6} \text{ yr}^{-1}$:

$$\begin{aligned}\frac{\dot{M}}{M_2} &= \frac{1}{3} \frac{1}{1-q} \frac{\dot{P}}{P} = 1.85 \times 10^{-6} \text{ yr}^{-1} \\ \frac{\dot{a}}{a} &= \frac{2}{3} \frac{\dot{P}}{P} = 2.4 \times 10^{-6} \text{ yr}^{-1}.\end{aligned}\quad (2)$$

We then derive, with $K_{1,2} = 2\pi a_{1,2} \sin j / P$ for a circular orbit, for the RV semi-amplitudes

$$\frac{\dot{K}_i}{K_i} = -\frac{1}{3} \frac{\dot{P}}{P} = -1.2 \times 10^{-6} \text{ yr}^{-1}.\quad (3)$$

Assuming the mass of the secondary to be 0.71 solar masses and inserting the measured RV semi-amplitudes we obtain $\dot{M} = 1.3 \times 10^{-6} M_\odot \text{ yr}^{-1}$, $\dot{K}_1 = -0.08 \text{ m s}^{-1} \text{ yr}^{-1}$, and $\dot{K}_2 = -0.24 \text{ m s}^{-1} \text{ yr}^{-1}$. We see that the observed period change of 1.6 s in 4.33 years requires a transferred mass of more than $6 \times 10^{-6} M_\odot$ and that the corresponding changes in the RV semi-amplitudes are small, lying below the limits of our measurements.

The most obvious explanation seems to be that the derived differences in RV semi-amplitudes are caused by distortions in the orbital curve, due to the influence of inhomogeneously distributed circumbinary matter, an assumption that is supported by other observations as discussed below.

7.2. Pulsations

From 1997 to 2000 RZ Cas demonstrated dominant mono-periodic photometric oscillations with frequency $f_1 = 64.27 \text{ c d}^{-1}$ (Rodriguez et al. 2004) whereas in the dual-mode oscillations observed in the spectroscopic data in 2001 (Paper I) f_1 was the second strongest component. Frequency f_1 is now the strongest mode, followed by $f_3 = 62.41 \text{ c d}^{-1}$ which is observed for the first time spectroscopically. This mode was detected for the first time in the photometric data observed in January 2003 with an amplitude of $1.62 \pm 0.17 \text{ mmag}$ (Mkrtichian et al. 2007b). $f_2 = 56.76 \text{ c d}^{-1}$ was the strongest mode during the two weeks long spectroscopic observations in 2001. Its amplitude is now distinctly lower than the amplitudes of f_1 and f_3 .

The shape of the RV amplitude modulation of the pulsation modes with the position in orbit is not much different in 2006 compared to 2001 for out-of-eclipse phases, but completely different for the phase of primary minimum. The reason for this different behavior is the same as for the observed orbital RV amplitude and orbital period variations and the changes in the pulsation spectrum – the occurrence of a high mass-transfer episode in the RZ Cas system shortly before and during 2001 and low mass-transfer rates in the years after 2001, as suggested already by Mkrtichian et al. (2003, 2005, 2007b). The higher

mass-transfer in 2001 resulted in a dense circumstellar gas envelope that suppressed the periodic spatial filter effect during primary eclipse. Examples of 3D hydrodynamical calculations by Mkrtichian et al. (2007a, b) predicted that for high mass-transfer rates the suppression will be strongest at the descending branch of primary minimum at phases -0.2 to 0.0 , and will have only minor influence at the ascending branch, in good agreement with the observed behavior of the RV amplitudes in 2001 (Fig. 6).

A detailed analysis of the amplification due to the periodic spatial filter effect and its use for the identification of the pulsation modes in RZ Cas is in preparation and will be given in a forthcoming paper.

7.3. Line profile modeling

It is not possible to use the luminosity ratio as a free parameter in our model because we then need constraints on the ratio of the intrinsic line strengths (e.g. from adapted model atmospheres). It is surprising, however, that in principle we can confirm the WD solution with such a simple model. We derive same values of K , j , a , and R_2/R_1 . The differences in the limb darkening coefficients are certainly caused by the non-spherical, Roche-lobe filling secondary and higher effects such as gravity brightening and reflected light.

Comparing the parameters derived using the 2006 data with those of the WD solution derived using the 2001 spectroscopic data (Table 7), we see that there is one obvious difference that leads to different goodness of the fits, namely the values of $v \sin i$ of the primary. The WD solution overestimates this value causing the synchronization factor F in Table 6 to be too large.

The picture of the O–C line intensity residuals in 2006 close to secondary minimum (Fig. 7) is amazing. The attenuation effect caused by the accretion annulus of the primary around secondary minimum can be seen clearly. The effect is very extended, it covers about 1/4 of the orbit of the secondary.

The situation for the data from 2001 is more complex, not only due to gaps in phase coverage that can be handled by the program but because we find in the residuals almost no region that is as smooth as the major part of the 2006 residuals. We end up with a solution where the goodness of the fit is not much better than that based on the WD solution. The main reduction comes from the better fit of the primary eclipse that could be achieved mainly by adjusting the position angle ψ of the rotation axis of the primary. The fact that we had to choose a value different from 90° for this angle does not mean that the axis was not perpendicular to the orbital plane in 2001. The adjustment was necessary to account for the large density gradients of the circumbinary gas streams close to primary minimum as they follow from hydrodynamic calculations. Moreover, Rodriguez et al. (2004) and Mkrtichian et al. (2007b) showed that the WD solution can be significantly improved by assuming the presence of a hot spot on the surface of the primary.

8. Conclusions

Summarizing our results, we have to explain the following observational facts:

- Comparing the spectra taken in 2001 and in 2006, we observe an increase of the orbital period that is confirmed by the light curve analysis.
- Whereas the RME in 2001 was strongly asymmetric we now observe an almost symmetric RME.

- In the line intensity residuals of our spectroscopic solution (Fig. 6) we see in 2006 only one structure about secondary minimum. In contrast, in the 2001 residuals we observe complex structures in all orbital phases.
- The pulsation pattern changed from apparently mono-periodic pulsations with frequency f_1 until the year 2000 to dual-mode pulsations in 2001, accompanied by a decrease of the main mode's amplitude. In 2006 RZ Cas shows three different modes and f_1 is the strongest mode again.
- Compared to 2001, the amplitude modulation of all modes at the phases around primary minimum is drastically enhanced.

All the mentioned facts support the assumption that the star has undergone a transient phase of rapid mass-transfer during the 2000-2001 observations.

Combining the photometric (Mkrtichian et al. 2007b) findings and interpretations with the spectroscopic (Paper I, this paper) ones we get the following complete picture: the abrupt increase of the orbital period in 2000/2001 was accompanied by the change of the pulsation pattern from apparently mono- to multi-periodic. A short time after the beginning of the rapid mass-transfer episode, we observe an asymmetric RME caused by a large density gradient in the circumbinary gas distribution seen at primary minimum. This gradient also gives rise to a corresponding structure in the line intensity residuals about primary minimum. This is compensated by our eclipse-mapping model by allowing an inclination of the rotation axis of the primary that is different from the expected 90° from the orbital plane. We deduce, from the line intensity residuals distribution, a very inhomogeneous distribution of circumbinary matter during all orbital phases. Five years later, in 2006, when the mass-transfer rate returned to low values the distortions introduced by the rapid mass-transfer episode smoothed out to a large degree. The only observable inhomogeneity in the line-intensity residuals is caused by the accretion annulus of the primary. Since there are no larger gas density gradients close to primary minimum the RME is now almost symmetric. The amplitude amplification of the NRP modes during primary eclipse can be seen almost undamped by the circum-primary gas whose density is much lower than in 2001.

The orbital period changes of Algols with late-type secondaries are thought to be caused by the magnetic activity of the cool component that cyclically changes its oblateness and quadrupole moment (Applegate 1992; Lanza & Rodono 1999). The picture of a chromospherically active secondary is supported by findings from X-ray and radio observations. McCluskey & Kondo (1984) reported that RZ Cas was found to be a fairly strong X-ray source by the EINSTEIN observatory. Radio flares are a common phenomenon in Algol-type stars (Richards et al. 2003; Retter et al. 2005). Drake et al. (1986) reported that the radio luminosity and spectrum of RZ Cas is comparable to those of short-period RS CVn stars.

In the case of RZ Cas we have also to explain the simultaneous changes in the pulsation pattern. An adjacent hypothesis is that the magnetic activity of the Roche-lobe filling star initiated first an abrupt period decrease in 1998, followed by a period of rapid mass-transfer and enhanced accretion rate in 2000 or 2001, shortly before the abrupt increase of the orbital period occurred (see also Mkrtichian et al. 2007b). The huge amount of transferred mass and angular momentum increased the orbital period, and affected the pulsation properties of the gainer, in acting on mode coupling and selection mechanisms.

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