Spectroscopic long-term monitoring of RZ Cas

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Abstract

RZ Cas is an active, short-period Algol-type system where the primary component shows Delta Scuti-like pulsations. We investigate hundreds of high-resolution spectra taken with the 2-m telescope of the Thüringer Landessternwarte Tautenburg and with the HERMES spectrograph at the Mercator Telescope at La Palma over a time span of 16 years. We use a newly developed program package to analyse the radial velocity (RV) and line profile variations (LPV). Main tasks are to disentangle the line profiles and RVs of the components as well as pulsation from orbital motion. The main goal is to correlate the variations of orbital period, $v\sin i$ or differential rotation, and the occurrence, amplitudes, and frequencies of different pulsation modes with each other and with the occurrence of episodes of rapid mass transfer. Preliminary results are presented.

1 Introduction

RZ Cas belongs to the oscillating Eclipsing Algol-type (oEA) stars. This group of stars was defined in the early 2000s (Mkrtchian et al., 2002) as active, semi-detached, eclipsing binaries of Algol-type, in which the mass-accreting primary is a A–F type main sequence star that shows series of Algol-type, in which the mass-accreting primary is a A–F type main sequence star that shows Delta Scuti-like pulsations. Research on stars of this class is interesting, for at least three reasons. First, due to the ongoing mass transfer, it is possible to study stellar evolution on short timescales. Second, because of the observed changes in oscillation patterns, the changes in the outer layers of the mass gaining primary can be investigated asteroseismologically. And third, principles of the interaction between the magnetic activity cycle of the mass-losing secondary, the episodes of mass transfer and the excitation of pulsation modes in the primary can be inferred (Tkachenko et al., 2009).

Being a bright ($V=6.26$) star, RZ Cas has been studied for a long time. Its light-curves and radial velocities (RVs) with complex structures point towards a complex distribution of circumstellar-binary matter, a hot spot on the primary and a dark one on the secondary, and a gas stream transferring circumstellar/-binary material, a hot spot on the primary and a dark one on the secondary, and a gas stream transferring matter from secondary to primary component (e.g. Lehmann & Mkrtchian, 2004; Tkachenko et al., 2009, and references therein). Its spectral type is A3 V + K0 IV and it is a short period ($P\sim 1.19526$ d) binary. Spectroscopic measurements revealed a different behaviour between a transient episode of stronger mass transfer in 2001 and a quiet phase in 2006. This concerns changes in orbital period, pulsation patterns, and distribution of circumstellar material (Lehmann & Mkrtchian, 2008; Tkachenko et al., 2009). Analogue findings are known from photometry taken over decades (Mkrtchian et al., 2018).

In our project, we investigate hundreds (see Tab. 1) of high-resolution spectra taken with the 2-m telescope of the Thüringer Landessternwarte Tautenburg and with the HERMES spectrograph at the Mercator Telescope at La Palma over a time span of 16 years. Our main goal is to correlate the variations of orbital period, $v\sin i$ or differential rotation, and the occurrence, amplitudes, and frequencies of different pulsation modes with each other and with the occurrence of episodes of rapid mass transfer.

Here, we present two newly developed methods and preliminary results of their application to our data. First, LSDbinary, which is a new approach to the classical Least-Squares Deconvolution (LSD) method. Further, a Python-based extension to the pixel-by-pixel method of the FAMIAS program (Zima, 2008) which adds the functionality of an automated frequency search as well as a fit function that allows to also optimise the frequencies and therefore to calculate uncertainties for them.

2 LSDbinary

SB2 stars in eclipsing binaries provide the clue to the determination of important stellar parameters like absolute masses and effective temperatures. For absolute masses, we need to derive the RVs of the components. For spectrum and line profile analysis, we first need to disentangle the observed composite spectra to obtain the spectra of the components. For semi-detached binaries like the Algol-type ones, the analysis is complicated by the non-spherical shape of the stars and non-Keplerian effects in orbital motion.

Using information from many lines in a stellar spectrum to construct an averaged line profile of high S/N is the idea behind the Least-Squares Deconvolution (LSD) technique that was developed by Donati & Collier Cameron (1997) for research on magnetic polarization features in stellar spectra. Applying this technique to composite spectra of SB2 stars and to calculate fully separated LSD profiles of the components is the aim of LSDbinary, a method developed by Tsymbal et al. (2019). As in the classical approach, the method is based on line masks but it uses two different masks for the two stars, corresponding to their spectral types. Synthetic spectra are used to determine the deviations caused by the underlying simplifications like assuming identical line profiles and linear addition in blends and to apply correspond-

| year       | 2001 | 2006 | 2008 | 2009 | 2013 | 2014 | 2015 | 2016 |
|------------|------|------|------|------|------|------|------|------|
| BJD number | 743  | 465  | 54   | 166  | 653  | 631  | 804  | 468  |

Table 1: Number of observations per epoch used for oscillation frequencies search. BJD gives the mean BJD 2450000+.
Figure 1: LSD profiles of primary (left) and secondary (right) component of RZ Cas from spectra taken during primary eclipse around zero orbital phase.

Figure 2: RVs of primary and secondary component of RZ Cas measured in 2013 (black dots) and fitted using PHOEBE (solid lines) with (green) and without (blue) assuming a cool spot on the secondary component.

The main output of the calculations in our case are the separated LSD profiles for primary and secondary component (Fig. 1) as well as precise RVs (Fig. 2). As can be seen from Fig. 1, the line profiles do not only shift according to orbital motion but the profiles of the primary component also change their shapes due to the Rossiter-McLaughlin effect (RME) during primary eclipse. As will be described in Sect. 4, the calculated profiles also show the impact of stellar pulsations and, probably, of stellar spots.

3 Period changes

We used the RVs derived from different epochs to look for changes in the orbital period of RZ Cas. The time coverage of the RVs from single epochs was not sufficient to find differences between different epochs, however. That is why we used the RVs from pairs of neighbouring epochs which are separated by one year or more. In this way we calculated the orbital parameters for the mean BJD of each pair, allowing for a linear change of the orbital period and extrapolated the period values to the mean BJD of the single epochs.

Figure 3 shows the results. The values of period change extrapolated from neighbouring pairs of epochs agree well. Figure 4 compares the O—C residuals obtained from a common solution, based on a period that fits the RVs from all epochs best, with the residuals obtained when calculating different periods for different epochs as described before. In the latter case, the sum of squares is reduced by 50%.
4 Automated search for LPV frequencies

We applied the pixel-by-pixel method of the FAMIAS program (Zima, 2008) to search for short-term oscillations in the computed LSD profiles of the primary component of RZ Cas. This method also allows to detect high-degree \( l \)-modes from LPV. We only used profiles taken out of primary eclipse and shifted them in RV according to the derived orbital solutions.

The FAMIAS program works in a two-staged process and is illustrated in Fig. 5. First, a two-dimensional Fourier spectrum is computed by calculating one-dimensional spectra for every dispersion bin of a time series of profiles (see upper panel) and then the mean Fourier spectrum for all bins (red line in the lower panel). The frequency at the maximum peak of this mean Fourier spectrum is then taken as the first found frequency. The second step is a least-squares fit followed by pre-whitening of the data. Every bin is fitted individually by the sum of determined frequency contributions where the amplitudes and phases are re-determined but the frequencies are kept at the values determined in the first step. After fitting, each individual model is subtracted from its corresponding bin and the procedure begins anew with the residuals as input data (see blue line in the lower panel of Fig. 5, which is the mean Fourier spectrum after subtracting the first frequency).

This procedure has two main disadvantages. First, it requires an enormous effort in interactive work with the FAMIAS GUI when dealing with many frequencies. Secondly, as the least-squares fit of the pixel-by-pixel method does no frequency optimisation, no frequency errors can be estimated. But uncertainty estimations for the frequencies are necessary, if significant changes in the frequency pattern between different epochs shall be monitored.

We developed a Python based extension to the FAMIAS program, which tackles both of these issues. First, it performs a fully automated frequency search based on the priorly described procedure. However, after finding a new frequency, this frequency is added and all other frequencies found so far are checked for their values and significance again, where we use significance criteria similar to the S/N>4 criterion from Breger et al. (1993). The second step is a least-squares fit to the data that also optimises the frequencies. Contrary to FAMIAS, we are not fitting the bins individually but altogether in one fit which was made possible due to a careful construction of the vector of residuals and the Jacobian matrix. The uncertainties of the frequencies are then calculated from the correlation matrix of the fit. For further details we refer to an upcoming paper.

The application to our data set yielded two groups of frequencies (see Fig. 5): There are low frequencies extending up to about 15 cd\(^{-1}\) and a group in the high-frequency domain between about 55-75 cd\(^{-1}\). The latter is shown in Fig. 6 as found with our automated search in different years of observation. The size of the diamonds correspond to their integrated amplitude.

The five frequencies found in the high-frequency domain are \( f_1 = 62.4 \) cd\(^{-1}\), \( f_2 = 64.2 \) cd\(^{-1}\), \( f_3 = 64.9 \) cd\(^{-1}\), \( f_4 = 65.6 \) cd\(^{-1}\), and \( f_5 = 70.2 \) cd\(^{-1}\) (mean values). All frequencies and corresponding amplitudes show timely variations. The separation of the 'triplet' \( f_2, f_3, f_4 \) (Fig. 7) is 0.71 cd\(^{-1}\) corresponding to a period of 1.41 d, which is distinctly larger than the orbital period of 1.19526 d.

In the low-frequency regime, we found the peaks with highest amplitudes very close to the orbital frequency and its multiples (up to five harmonics). We suspect that they might come from spots on the primary or from circumprimary/-binary material. At present stage, also an imperfect subtrac-
tation related zero points in the Fourier power spectra. Fig-
S/N of the spectra, we could determine two to four stellar ro-
5 Rotation velocity
We used the Fourier method (see e.g. Smith & Gray, 1976) to measure \( v \sin i \) from the LSD profiles. Depending on the S/N of the spectra, we could determine two to four stellar rotation related zero points in the Fourier power spectra. Figure 8 shows the resulting \( v \sin i \) values for one epoch as an example. A strong variation with orbital phase can be seen. We assume that this variation comes from Algol-typical effects like inhomogeneous circumpri-
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a qualitative picture of the pulsational behaviour of RZ Cas. We see from Fig. 6 that different pulsation modes are excited in different epochs. Moreover, mode amplitudes and frequen-
auxiliary text

6 Conclusions
The LSBDinary program, firstly tested on the short pe-
and mass ratio, and masses of the components. A cool, spot-like region on the companion pointing towards the primary component was already found in Tkachenko et al. (2009). Also a hot spot on the primary has an impact on the RVs, modifying them in orbital phases \(-0.1..0.0\), i.e. during the ingress of primary eclipse. PHOEBE assumes Roche geometry of the components and thus handles the non-spherical shape of the companion well. We are about to also include spots into our model using PHOEBE scripter, trying to optimize their parameters and finally to derive accurate orbital solutions.

Because of the mentioned problems, we here only show a qualitative picture of the pulsational behaviour of RZ Cas. We see from Fig. 6 that different pulsation modes are excited in different epochs. Moreover, mode amplitudes and frequencies change. Modes \( f_2 \) and \( f_3 \) are present in most of the epochs. \( f_2 \) is well-known from photometry. It was the dominating mode in 1997 (Ohshima et al., 1998), 1999 (Rodríguez et al., 2002), and 2001 (Mkrtichian et al., 2003) and is most probably a sectorial \( l = 2, m = \pm 1 \) mode as it was shown by Mkrtichian et al. (2018). Also \( f_1 \) was found in the photometric data, e.g. in 1997 (Ohshima et al., 2001), 1999 (Rodríguez et al., 2004), or 2003 (Mkrtichian et al., 2018). There is one further frequency of 56.6 cd\(^{-1}\) found in several epochs in photometry (see Mkrtichian et al., 2018, for a comprehensive overview). It was also detected in our RVs from 2001 and 2006 (Lehmann & Mkrtichian, 2004, 2008) but could not be found from the LPV analysis. Instead, we detect three completely new frequencies, namely \( f_4, f_3 \) and \( f_5 \). Moreover, the amplitude of \( f_4 \) or \( f_5 \) dominates the LPV variations in some of the years (see Fig. 6).

Complete and improved results on orbital solutions, de-
solution from changes due to orbital motion (RV) and eclipses (LPV and RV). The main problem in determining the orbital solution from the RVs is actually the presence of spots on the stellar surfaces that strongly influences the determination of separation, mass ratio, and masses of the components. The main problem in determining the orbital solution from the RVs is actually the presence of spots on the stellar surfaces that strongly influences the determination of separation, mass ratio, and masses of the components.

Figure 8: Values of \( v \sin i \) versus out-of-eclipse phases, measured from the LSD profiles observed in 2016 (black) and from the same profiles corrected for low-frequency variations (red).

Figure 9: Mean values of \( v \sin i \) derived from different epochs of observation.
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