SPECTROSCOPIC ANALYSIS OF OSCILLATING ALGOL-TYPE SYSTEMS

A. Tkachenko[1], H. Lehmann[1], V. Tsymbal[2], D. Mkrtichian[3]

[1] Thueringer Landessternwarte Tautenburg, D-07778 Tautenburg, Germany
[2] Tavrian National University, Simferopol, Ukraine
[3] Crimean Astrophysical Observatory, 98409 Nauchny, Ukraine

ABSTRACT. We analyze time-series of high-resolution spectra of RZ Cas, one of the brightest Algol-type stars where the primary shows δ Sct-like oscillations. Our inverstigation uses a variety of methods like the KOREL program to derive the orbital solution and to decompose the spectra of the binary components, the SynthV program to derive the elemental abundances of both components from the mean, decomposed spectra, and finally the newly developed Shellspec07_inverse program to compute optimized stellar parameters from the composite line profiles observed at different orbital phases including the eclipse mapping.

Spectra of RZ Cas have been taken at two different epochs. In 2006, the system can be well modeled without including any Algol-typical effects like a gas stream or an accretion annulus into the calculations. We have only to assume that the secondary of RZ Cas shows a large dark spot on its surface pointing toward the primary, presumably originating from a cooling mechanism by the enthalpy transport via the inner Lagrangian point. The O-C residuals of our solution based on the spectra from 2001 show a complex distribution of circumbinary matter, however, pointing to the occurrence of an episode of rapid mass transfer. This assumption is supported by the deduced change of the orbital period of RZ Cas of 2 seconds between the two epochs of observations.

Numerical simulations of the spatial filtration effect that occures during the primary eclipse showed that this effect can be used for an identification of the excited non-radial pulsation modes in terms of l and m numbers.

Key words: Stars: binary: eclipsing; Stars: variables: Algols; Stars: individual: RZ Cas.

1. Introduction

Algol-type systems are interacting, eclipsing binaries consisting of a more massive, main-sequence primary component of spectral type A-B and a less massive, evolved F-K companion of luminosity class III-IV. The fact that the evolved component in the system is the less massive one completely contradicts our knowledge about stellar evolution and is called the Algol paradox. It was solved by realizing that currently less massive star initially was the more massive one but during the evolution of the system it filled its Roche-lobe and transferred a significant part of material to the companion. Algol-type systems are well known to show complex light curves effected by accretion disks, gaseous streams, and star-spots on the surface of the cool, evolved component indicating the occurrence of mass-transfer episodes and magnetic activity of the secondary component in the system.

The group of oEA stars was introduced by Mkrtichian et al. (2002) and means mass-accreting, eclipsing Algol-type systems with oscillating primary components. The stars lie in the instability strip showing δ Scuti-type pulsations. There are only about 40 such objects known so far. The co-existence of mass-transfer and oscillations of the primary components makes these objects to be of great interest for asteroseismic investigations. First, the occurrence of rapid mass-transfer episodes allows to study the evolution of the systems on a short time scale. Second, due to the change of the excited oscillation modes during phases of rapid mass-transfer, the changing structure of the outer layers of the mass-accreting primary can be investigated by asteroseismic methods. And third, the secondary acts as a spatial filter during the primary eclipse phases producing specific amplitude modulations of the excited oscillation modes which helps to identify these modes in terms of l and m numbers. Moreover, since oEA stars are eclipsing binaries, their atmospheric and system parameters can be determined with high accuracy from combined spectroscopic and photometric data which is very important for the subsequent construction of an asteroseismic model of the primary.

RZ Cas (A3 V+K0 IV) is a short-period (P=$1^d.1953$) Algol-type system and one of the best studied oEA stars. Narusawa et al. (1994) report that a partial eclipse during primary minimum is observed. Olson (1982) and Varricatt et al. (1998) find evidence of circumstellar matter surrounding the primary component. Based on extended photometric investigations, Rodriguez et al. (2004) assume the existence of a gas stream between the components and the formation of a hot spot on the surface of the primary where the gas stream impacts its photosphere. Ohshima et al. (1998, 2001) detect the short-period light variability of the system for the first time. The authors find that the primary of RZ Cas is a mono-periodic pulsator with a dominant frequency of 64.2 $c\,d^{-1}$. Later on, this conclusion is confirmed by Mkrtichian et al. (2003) and by Rodriguez et al. (2004).

The most extended spectroscopic investigation of the RZ Cas system is carried out by Lehmann & Mkrtichian (2004, 2008) based on two data sets taken in 2001 and 2006. The authors derive an orbital solution based on both data sets and find that the Rossiter effect (Rossiter 1924) observed in the radial velocities of the primary in 2001 is highly asymmetric whereas almost symmetric in 2006. They also report that the star changed its pulsation pattern twice: first, in 2001, it changed from mono- to multi-periodic behaviour with two dominant frequencies of 56.76 $c\,d^{-1}$ and 64.27 $c\,d^{-1}$, and second, in 2006, when the third additional oscillation mode with the frequency of 62.41 $c\,d^{-1}$ is detected. These facts, together with the observed increase of the orbital period of about two seconds between 2001 and 2006, the authors attribute to the occurrence of a rapid mass-transfer episode in 2001.

In this paper we present a detailed spectroscopic analysis of the RZ Cas system using variety of methods. This, in particular, includes the newly developed computer program Shellspec07_inverse that is used for the fine-tuning of stellar and system parameters of RZ Cas based on the observed composite line profiles (Sect. 2). In Sect. 3 we represent our main results, while Section 4 is devoted to future prospects.

2. Methods

We used the Shellspec07 code developed by Budaj & Richards (2004) as the basic engine for our program. This code does not solve the inverse problem of finding stellar and system parameters but serves for the computation of composite synthetic line profiles of interacting binaries based on a priori known input parameters. Mass-transfer typical phenomena like an accretion disk or a gas stream can be taken into account and are assumed to be optically thin. The stars are considered to emit either black-body radiation or their own intrinsic spectra while the effects of limb and gravity darkening are roughly approximated by analytical laws.

Our newly developed Fortran 90 code Shellspec07_inverse uses the core of the Shellspec07 program and is designed for an accurate estimation of stellar and system parameters of binary stars based on extended spectroscopic observations. According to this task, new input and output routines and a graphical representation of the results have been implemented in the program. The program can work in two different modes, optimizing the stellar and system parameters either based on the original, observed spectra or on spectra that have been averaged into a certain number of orbital phase bins.

With respect to the shape and position of the local continuum, Shellspec07_inverse is free of any approximations and provides an accurate normalization of the computed spectra, in contrast to the Shellspec07 code which assumes the continuum to be a straight line between the outermost points of the considered spectral range. This is a poor approximation for two reasons. First, it is not for sure that the outermost points will be a part of the local continuum. And second, the shape of the continuum may significantly deviate from a straight line, especially for the broad Balmer lines. Instead, we compute both the line and continuum fluxes which makes the normalization of the synthetic spectrum to be a trivial task.

As mentioned at the beginning of this section, Shellspec07 uses analytical laws to take the effects of limb and gravity darkening into account. In the case of limb darkening, the program uses a linear law assuming that the center-to-limb variation of intensity can be described by a constant limb darkening coefficient independent of line depth. In reality this is not the case and we solve the problem by computing intrinsic stellar line profiles for nine different values of the angle θ between the line-of-sight and the normal to the stellar surface and interpolate according to the desired position on the stellar disk. In a similar way, to count for the temperature variation over the stellar surface due to the effect of gravity darkening, we compute intrinsic line profiles for each point on the stellar surface for exactly the required temperature.

For the non-linear optimization we use the Levenberg-Marquardt algorithm (Levenberg 1944; Marquardt 1963), an iterative technique that determines the minimum of a χ^2 merit function realized as the sum of squares of non-linear functions. We use a modified, fast version of the algorithm (a detailed description can be found in Piskunov & Kochukhov 2002). For more details with respect to the program description see Tkachenko et al. (2009)

3. Results

We used KOREL (Hadrava 2004), a Fourier transform based program, to derive the orbital solution and to compute the mean, decomposed spectra of the components of the binary. Assuming circular orbits,

Table 1: Orbital elements of RZ Cas derived with KOREL and by Lehmann & Mkrtichian (2008).

	2001	2006	
P	1.19501(15)	1.195232(20)	d
K_1	71.55(26)	71.72(25)	$\mathrm{km\,s^{-1}}$
K_2	200.50(69)	201.91(60)	$\mathrm{km\,s^{-1}}$
q	0.3569(25)	0.3552(23)	
T	2193.39011(59)	3866.746(75)	

	2001+2006	L&M(2008)	
P	1.195243(19)	1.1952410(77)	d
K_1	72.01(25)	71.311(78)	$\mathrm{km\,s^{-1}}$
K_2	199.03(59)	—	$\mathrm{km\,s^{-1}}$
q	0.3618(23)	—	
T	2193.38931(57)	2193.38482(20)	
$\dot{P}$	0.66(39)	0.37(16)	$\mathrm{s\,y^{-1}}$
$\dot{K}$	−0.104(87	−0.135(27)	$\mathrm{km\,s^{-1}\,y^{-1}}$

we have computed three different orbital solutions: i) based on the spectra from 2001; ii) from 2006; iii) based on the combined 2001 and 2006 data. The results are presented in Table 1, together with those obtained by Lehmann & Mkrtichian (2008). The values of the orbital period derived from the two data sets separately differ significantly. For an additional test, we allowed for a linear trend in the orbital period when computing the orbital solution based on the combined 2001 and 2006 data. The obtained rate of period change of $\dot{P}$=(0.66±0.39) $\mathrm{s\,y^{-1}}$ corresponds to a change of (2.9±1.7) s during the total time span of 5 years. Alternatively, the orbital period change can be estimated from the orbital phase shift between the two data sets obtained when folding the radial velocities (RVs) obtained in the two different epochs with the period observed in 2006. The result is much more accurate than that obtained from the linear trend in the KOREL solution leading to a period change of (2.0±0.1) s between the two epochs.

KOREL also delivers the mean decomposed spectra of the binary components. These spectra are normalized to the common continuum of both stars. We renormalized them to their individual continua and then analyzed them with respect to the basic stellar parameters and individual abundances using the method of synthetic spectra. We used the SynthV code (Tsymbal 1996) for computing the synthetic spectra and the LLmodels program (Shulyak et al. 2004) for the calculation of atmosphere models for the hot primary component. For the cool secondary, MARCS atmosphere models (Gustafsson et al. 2008) have been used, together with an additional molecular line list taken from Kurucz CDs (Kurucz 1995).

For the primary, we obtained $v\sin i$=(66.0±0.5) $\mathrm{km\,s^{-1}}$, ξ_{turb}=(3.0±0.2) $\mathrm{km\,s^{-1}}$, and T_{eff}=(8 850±25) K, with $\log g$ fixed to 4.35. We found that all abundances are close to solar ones except for silicon which is depleted by about −0.4 dex compared to the solar value. The mean error of measurement is 0.03 dex. For the secondary we obtained $v\sin i$=(81±2) $\mathrm{km\,s^{-1}}$ and T_{eff}=(4 800±100) K, with $\log g$ fixed to 3.7. It was not possible to determine the micro-turbulent velocity for this late-type star, however, and thus we fixed it to 2.0 $\mathrm{km\,s^{-1}}$. Our results show that the secondary of RZ Cas has a chemical surface composition close to the solar one, except for iron and chromium which are underabundant by about −0.4 dex and −0.6 dex, accordingly. The mean error of measurement for this cool object with its not so well determined continuum is of about 0.1 dex.

We used the Shellspec07_inverse program for the fine-tuning of the stellar and system parameters of RZ Cas. The starting values of the parameters have been taken from the orbital solutions and the analysis of the disentangled spectra. We started with an investigation of the data from 2006 where no hints to complex structures from a mass-transfer episode have been observed, assuming a spherical configuration of the primary and a Roche-lobe filling secondary. For the gravity darkening exponent of the secondary, we first assumed the value of β=0.08 as predicted by the theory in the case of a star with convective envelope (Lucy 1967). This model resulted in a smooth solution for all orbital phases except for a large region around secondary minimum where the computed line profiles appear to be stronger than the observed ones. We attribute this fact to an attenuation of the light of the secondary which can also be seen in form of a deviation of the RVs from the Keplerian orbital curve in our KOREL solution. Assuming that the observed deviation is an intrinsic property of the secondary, caused by an anomal temperature distribution on its surface, we tried to model this distribution using an unusually large value of β=0.5. This model fits the observed line profiles in the region around secondary minimum well but completely fails at phases close to the primary eclipse, where the calculated line profiles are much too weak. Finally, we divided the stellar surface of the secondary into two regions by using β=0.5 for the hemisphere pointing towards the primary and the normal value of β=0.08 for the opposite side. All spectra obatined around primary and secondary minima can be fitted well with this model. Thus, we conclude that a large dark spot on the surface of the secondary exists, located on the hemisphere that points towards the primary. We stress that an ultra-large value of β=0.5 has no physical meaning and is just used to model the temperature distribution on the surface of the secondary in the region of formation of a cool spot. Table 2 lists the parameters obtained from the final solution, assuming the two-hemispheres model.

In a next step, we applied the derived model to the spectra taken in 2001. The resulting solution indicates strong attenuation of the light of the primary along the full orbit most probably originating from the formation of accretion structures in the system. Our attempt to

Table 2: Parameters of the RZ Cas system derived with Shellpsec07_inverse.

T_1 (K)	T_2 (K)	$\log g_1$	$\log g_2$	R_1 ($R_\odot$)	R_2 ($R_\odot$)	M_1 ($M_\odot$)	M_2 ($M_\odot$)	q	a ($R_\odot$)	i (deg)
8907(15)	4797(20)	[4.35]	[3.7]	1.61(1)	1.93	2.01(2)	0.69(1)	0.342(2)	6.59(3)	82.0(3)

model this attenuation by introducing optically thin, circumprimary matter of disk-like structure provided a significantly improved solution inferring that a transient phase of rapid mass-transfer occurred shortly before the observing period in 2001. This is confirmed by the derived orbital period change of (2.0±0.1) s between the two epochs of observations which we interpret in terms of angular momentum transfer between the accelerated rotation of the outer layers of the primary and the orbit.

4. Discussion

There is a unique event that is observed only in the oEA stars called the spatial filtration effect (SPE). It occurs when the secondary is passes in front of the oscillating primary during the primary eclipse phases. This effect causes specific amplitude and phase changes of the excited oscillation modes of the primary, in dependence on the corresponding l and m numbers. To examine whether or not SPE helps to identify the modes and if there are any basic correlations between the pulsation and system parameters, we did a spectroscopic investigation of this effect based on numerical simulations where we considered only the surface velocity field perturbations and neglected the influence of the temperature and projected surface area perturbations on the line profiles. The main conclusion of our study can be summarized as follows:

1. All sectoral modes show an increase of the amplitudes with the inclination of the rotation axis, whereas all modes with odd l, m combinations behave in the opposite way
2. RV amplitudes outside the eclipse decrease with increasing degree l
3. The sectoral modes give rise to a double-peaked amplification feature in the RV curves centered at primary minimum while the zonal and tesseral modes only produce a single peak
4. The amplification of the RV amplitudes is largest if the star is seen nearly equator-on

Our results show that there are two criteria that can be used for a mode identification based on SPE, namely the shape of the RV curve observed during primary eclipse and the amplification factor of the mode under consideration. Moreover, SPE provides an unique possibility to detect non-radial pulsation modes during the eclipse phases although the pulsation amplitudes outside the eclipses may be below the detection limit.

In the future, we plan to implement the effects of surface temperature and area perturbations on the line profiles into the calculations and to derive the parameters of non-radial pulsations together with the stellar and system parameters from the observed time-series of spectra. Since most of the oEA stars are faint objects we want to enhance the signal-to-noise ratio (S/N) of our data by using the least-squares deconvolved technique (Donati et al. 1997) which allows to compute mean line profiles of high S/N from a large number of individual lines present in the spectra.

References

Budaj J., Richards M.T.: 2004, *CoSka,* **34**, 167

Donati J.-F., Semel M., Carter B. D., et al.: 1997, *MNRAS,* **291**, 658

Gustafsson B., Edvardsson B., Eriksson K. et al.: 2008, *A&A,* **486**, 951

Hadrava P.: 2004, *Publ. Astron. Inst. ASCR,* **92**, 15

Kurucz R.L.: 1995, *ASPC,* **78**, 205

Lehmann H., Mkrtichian D.E.: 2004, *A&A,* **413**, 293

Lehmann H., Mkrtichian D.E.: 2008, *A&A,* **480**, 247

Levenberg K.: 1944, *Quart. J. Appl. Math.,* **2**, 164

Lucy L.B.: 1967, *Zs. f. Ap.,* **65**, 89

Marquardt D. W.: 1963, *J. Soc. Indust. Appl. Math.,* **11**, 431

Mkrtichian D.E., Kusakin A.V., Gamarova A.Yu., et al.: 2002, *PASPC,* **259**, 96.

Mkrtichian D. E., Nazarenko V., Gamarova A. Yu., et al.: 2003, *PASPC,* **292**, 113

Narusawa S.-Y., Nakamura Y., Yamasaki A.: 1994, *AJ,* **107**, 1141

Ohshima O., Narusawa S.-Y., Akazawa H., et al.: 1998, *IBVS,* **4581**

Ohshima O., Narusawa S.-Y., Akazawa H., et al.: 2001, *AJ,* **122**, 418

Olson E.C.: 1982, *ApJ,* **259**, 702

Piskunov N., Kochukhov O.: 2002, *A&A,* **381**, 736

Rodriguez E., Garcia J.M., Mkrtichian D.E., et al.: 2004, *MNRAS,* **347**, 1317

Rossiter R.A.: 1924, *ApJ,* **69**, 15

Shulyak D., Tsymbal V., Ryabchikova T., et al.: 2004, *A&A,* **428**, 993

Tkachenko A., Lehmann H., Mkrtichian D. E.: 2009, *A&A,* **504**, 991

Tsymbal V.: 1996, *ASPC,* **108**, 198

Varricatt W.P., Ashok N.M., Chandrasekhar T.: 1998, *AJ,* **116**, 1447