Ultra-High Gravity Darkening in the oEA Star RZ Cas

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We report on first results obtained in the framework of a larger study of oEA stars, i.e. Algol-type systems with oscillating components. We investigate an extended time series of high-resolution spectra of the oEA star RZ Cas taken in 2006. By comparing our model calculations with the observations, we try to determine the system and atmospheric parameters of RZ Cas. Starting values were obtained from uvby photometry and from an analysis of the mean out-of-eclipse spectra by means of the KOREL program. The fine tuning of the model was done using the modified SHELLSPEC code. With SHELLSPEC we determined an unusual large gravity darkening exponent of 0.5 for the secondary of RZ Cas. This value is far above the theoretical limit given by the Von Zeipel law but in good agreement with those obtained by Unno et al. in 1994. We attribute the large value to different large star spots on the front and back sides of the secondary with respect to the primary that exist in the result of mass-outflow from the donor to the gainer.

Introduction

The new class of oEA stars was introduced by Mkrtichian et al. [1, 2] and means mass-accreting, eclipsing, Algol-type systems with oscillating primary components. The existence of this new class of δ Sct-like pulsators was realized very recently and its members are outstanding objects for asteroseismic investigations. The co-existence of mass-transfer and oscillations allows to study stellar evolution on a short timescale and to investigate the changing structure of the outer layers of the primary which is reflected by the change in oscillation modes. During eclipse phases the secondary acts as a periodic spatial filter that produces specific amplitude and phase changes in brightness and line profiles depending on the oscillation mode's quantum numbers. This so-called spatial filtration effect can be used to identify the pulsation modes.

RZ Cas (A3 V+K0 IV) is an oEA star with an orbital period of 1.1952595 days. Lehmann & Mkrtichian [3, 4] investigated the star spectroscopically, based on spectra obtained in 2001 and 2006. They found that the star was in a transient phase of rapid mass-transfer in 2001 whereas in 2006 it was in a relatively quiet phase. This conclusion is based on the following observational facts: First, the Rossiter effect for the primary which distorts its orbital curve during the eclipses was strongly asymmetric in 2001 whereas in 2006 it was almost symmetric. The different behaviour is attributed to a different strong density gradient in the circumbinary gas distribution seen during primary minimum. Second, the assumption is supported by the observed change in the orbital period of about 2 seconds between the two epochs of observations and by the changed pulsation pattern. In 2001, authors observed only two pulsation frequencies f_1=64.27 d and f_2=56.76 d whereas in 2006 f_1 and a new frequency, f_3=62.41 d, dominate the pulsation spectrum. And third, the radial velocity (RV) amplitude modulation of the non-radial pulsation modes with orbital phase is much stronger in 2006 (Fig. 1). The enhancement of the oscillation amplitudes during primary eclipse comes from the above mentioned spatial filtration effect. It is damped by the much denser, attenuating, circumstellar gas distribution in 2001 whereas in 2006 the pulsations could be seen nearly undamped. Authors did a first spectroscopic modelling of the line profile variations based on very simple assumptions [4]. The aim of our present work is to improve this modelling by considering, in a first step, non-spherical star configurations based on Roche geometry and the gravity darkening of the secondary.

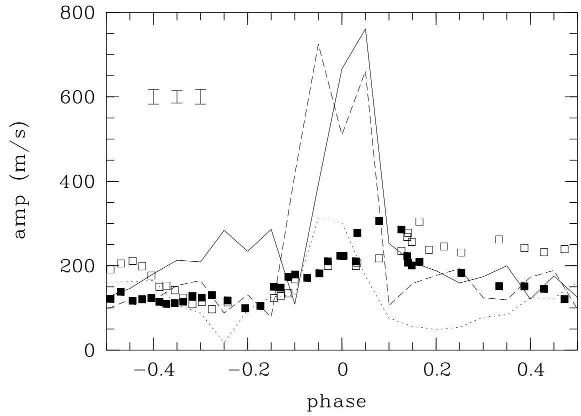

Figure 1: Amplitudes of RV variations due to different pulsation modes, folded with the orbital period. Phase zero corresponds to primary, phase 0.5 to secondary minimum. In 2001: f_1 = filled squares, f_2 = open squares, f_3 is not present. In 2006: f_1 = solid line, f_2 = dashed line, f_3 = dotted line.

Observations

Time series of high-resolution spectra were obtained with the Coude-Echelle-Spectrograph at the 2-m telescope at the Thüringer Landessternwarte Tautenburg in 12 runs in 2001 (951 spectra) and in 8 runs in 2006 (512 spectra). All spectra have a resolution of 32 000 and cover the wavelength range from 4 760 Å to 7 400 Å . Our present analysis is based on 498 spectra of good S/N (60-120) from 2006.

Results

Lehmann & Mkrtichian [4] tried to model the observed line profile variations of RZ Cas using a simple approach that assumed spherical configurations of both stars and did not consider effects like gravity darkening, accretion disk or gas streams. Results obtained from the spectra from 2006 showed that such a simple model provides system parameter values comparable to those derived with the Wilson-Deviney code from photometry and a smooth O-C value distribution for all orbital phases except for a region around secondary minimum where the calculated line profiles were too strong. The latter finding was interpreted as the attenuation effect caused by an accretion annulus around the primary. On the other hand, results obtained from the spectra taken in 2001, where rapid mass-transfer took place, clearly showed that in this case the observed line profile variations cannot be explained by the simple model.

We reinvestigate the system now by using the modern code SHELLSPEC written by Budaj [6] for the synthesis of composite line profiles of binary systems. Effects like gravity darkening, accretion disk and gas stream can be taken into account. The program uses intrinsic line profiles for both components which we calculated with the SynthV code written by Tsymbal [9]. Atmosphere models for the hot primary have been calculated with the LLmodels code by Shulyak et al. [10] while for the cool secondary MARCS atmosphere models were used. Starting values for the system parameters like distance, separation, orbital inclination, radii and masses were taken from the Wilson-Devinney solution based on uvby-photometry and from the RV-analysis (Lehmann & Mkrtichian [3, 4]). Starting values for atmospheric parameters like $T_{\rm eff}$, $\log g$, and $v \sin i$ as well as the elemental abundances were derived from an analysis of the mean disentangled spectra of the components that were derived by means of the KOREL program (Hadrava [5]). Using SHELLSPEC, we fine-tuned the masses (RV amplitudes), orbital inclination (Rossiter effect), $T_{\rm eff}$ (line depths), $v \sin i$ and limb darkening coefficients (line widths and shapes) and tried to adjust the gravity darkening exponent for the secondary. The Roche geometry of the secondary is calculated by the program based on given masses, radius of the primary, separation, and orbital period.

Figure 2 illustrates one spectroscopic solution obtained from the spectra taken in 2006. It shows the observed and calculated time-series of Fe I 4957 Å composite line profiles. For the calculations we averaged the observed spectra into 100 orbital phase bins. Averaged line profiles are shown along the ordinate of the 2D images. The abscissa gives the orbital phase, phase zero corresponds to the phase of largest RV-separation. The S-shaped distortion of the line profiles during primary minimum is caused by the Rossiter effect as mentioned above.

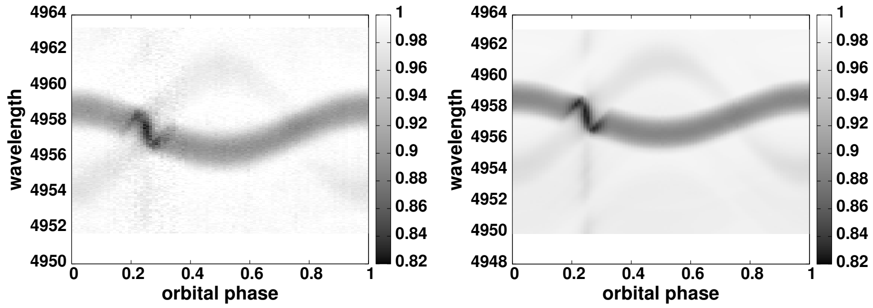

Figure 2: Observed in 2006 (left) and calculated (right) time series of rotation phase binned Fe I 4957 Å profiles. Phase 0.25 corresponds to primary, phase 0.75 to secondary minimum.

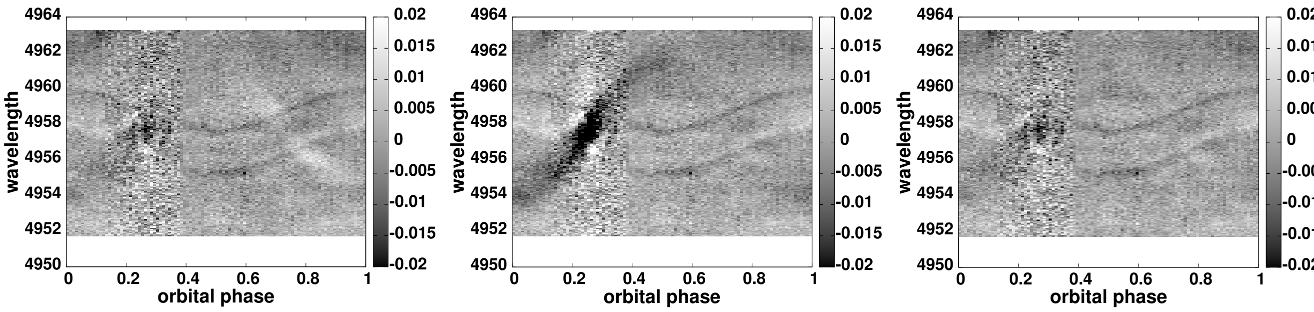

Figure 3: O-C values based on different gravity darkening exponents. From left to right: $\beta = 0.1$ overall, $\beta = 0.5$ overall, and $\beta = 0.5$ for the star's hemisphere towards the primary and $\beta = 0.1$ for the opposite side.

From the residuals based on the spectra taken in 2006 (Fig. 3) it can be clearly seen that a model with a gravity darkening exponent of β=0.1 gives a smooth solution in all orbital phases but not around secondary eclipse where we see an attenuation of the lines of the secondary similar to those found by Lehmann & Mkrtichian [4]. Only by using the large value of 0.5 we can fit this region. Such a large value is not compatible to the observed line profiles around primary minimum, however. From the middle panel in Fig. 3 we see that the bright region around secondary minimum disappeared but that the calculated line strengths near to primary minimum are too weak now and a dark region appears there. As it is shown in the right panel of Fig. 3, both regions around primary and secondary minimum can be fitted only if we assume two different gravity darkening exponents for the two hemispheres of the secondary that point towards (β=0.5) and away (β=0.1) from the primary.

Table 1 lists the finally obtained values for separation, inclination, mass and mass ratio, limb darkening coefficients, $v \sin i$ and gravity darkening exponent. Fixed values taken from previous analysis have been the distance of 71 pc, the orbital period of 1.1952595 d, the radius of the primary of 1.575 $R_\odot$, and the iron abundances of the two stars of ϵ_1=-4.75, ϵ_2=-5.1.

In a next step we applied, without changing any parameter values, the solution found from the spectra from 2006 to the spectra from 2001 (Fig. 4). Dark stripes in the figure indicate phase gaps in the observations. From the O-C values (right panel) it can be seen that the model cannot explain the very different properties of the system in 2001. In particular we see a very strong attenuation of the line of the primary that probably arises from a dense accretion annulus around this star.

Table 1: Parameters obtained from the final SHELLSPEC solution based on the spectra from 2006.

a	j	M_1	M_2/M_1	X_1	X_2	$v \sin i_1$	β_2
6.580 $R_\odot$	83.1°	1.995 $M_\odot$	0.3427	0.59	0.80	68 $\mathrm{km\,s^{-1}}$	0.5/0.1

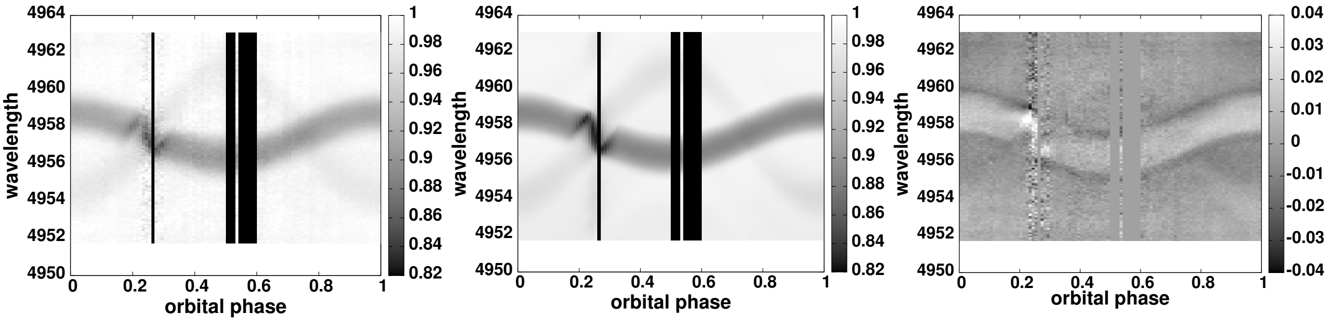

Figure 4: As Fig. 2, but for the spectra from 2001 and calculated with the final parameters obtained from the spectra from 2006.

Conclusions

Our investigation of the oEA star RZ Cas using SHELLSPEC confirmed that the system was in a quiet state during 2006. It can be modelled by assuming two stars where the secondary fills its Roche lobe. We found that the secondary has an inhomogeneous surface brightness distribution that can be successfully modelled by applying a gravity darkening law that assumes two different exponents of 0.5 and 0.1 for the star's hemispheres that point towards and away from the primary, respectively. Whereas the value of β=0.1 is in the range of normal gravity darkening (the Von Zeipel law gives 0.08), the ultra-large value of 0.5 cannot be interpreted in terms of gravity darkening but refers to the existence of a large dark spot of specific origin. This is in agreement with the findings by Unno et al. [11]. Authors investigated 9 semi-detached binary systems and found for the secondary of RZ Cas a gravity darkening exponent of 0.53. They draw the conclusion that in the result of the mass-outflow from the secondary star spots on the front and back sides of the secondary relative to the primary are formed. Our resulting gravity darkening law with two different gravity darkening exponents points to the existence of at least one large dark spot located very close to the innermost point of the secondary with respect to the system. The fact that the derived model is not applicable to the spectra from 2001 is in agreement with the findings by Lehmann & Mkrtichian [4] and with their suggestion of a transient phase of rapid mass-transfer during this period. Further effects caused by the accretion annulus, gas streams and possibly a hot spot have to be included into the model.

Acknowledgement

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