Contrib. Astron. Obs. Skalnaté Pleso **49**, 278 – 286, (2019)

Surface inhomogeneities of the eclipsing binary ER Vul

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Received: November 2, 2018; Accepted: January 24, 2019

Abstract. We performed Doppler imaging of the eclipsing binary ER Vul using time-series mid-resolution (R $\sim$ 13500) spectra of the system. The spectra were acquired via the echelle spectrograph attached to the 0.4m Kreiken Telescope at the Ankara University Kreiken Observatory. We applied Least-Squares Deconvolution (LSD) technique in order to enhance SNRs of the velocity profiles to better resolve the spot signatures. We determined the mass ratio, q, as 0.949(19) and masses of the primary and secondary components as 1.108 (33) and 1.052 (34), respectively. The reconstructed images of both components show that cool spots are preferably located at high latitudes. We also investigated the chromospheric activity behaviour with the help of the spectral synthesis method. Both photospheric and chromospheric activity variations along with the orbital phase are in accordance with each other.

Key words: stars: activity – binaries: eclipsing – stars: imaging.

1. Introduction

RS CVn-type systems have remarkable significance in better understanding the dynamo mechanism working in close binary stars due to their strong magnetic activity. One of them, ER Vul, is a short-period RS CVn-type eclipsing binary system that has several activity-related studies in the literature after its classification by Hall (1976). The variability in the light curves of the system outside eclipses was attributed to the cool spot activity on both components (Olah et al., 1994; Ekmekçi et al., 2002; Wilson & Raichur, 2011; Pop & Vamoş, 2013). The activity of both components of ER Vul was confirmed by Çakırlı et al. (2003), who also revealed that the secondary star is more active than the primary one using the equivalent width (hereafter EQW) variations of H_α excess emission with the help of the spectral subtraction method. Using the high resolution spectroscopic data obtained from the Canada-France Hawaii Telescope (CFHT), Shkolnik et al. (2005) determined some orbital parameters of the system from radial velocity measurements and investigated the activity behaviour with the help of the Ca II emissions. They mentioned that the emissions are consequences of the activity of both components as well as a broad stream flowing toward the secondary. The Doppler images of the system obtained by Piskunov (1996) and Piskunov et al. (2001) showed large temperature difference as well as the presence of a hot spot at sub-stellar points on both components. Piskunov (2008) revealed a non-axisymmetric dynamo action by analyzing the Doppler images of ER Vul. The most recent Doppler imaging study of the system was carried out by Xiang et al. (2015) using the code DoTS. They mentioned that the active regions were almost found in the hemisphere facing the other component, while they found no remarkable concentration of spots at the sub-stellar points.

In this work, we analyzed the mid resolution time-series spectroscopic data of the short-period RS CVn-type eclipsing binary ER Vul via the Doppler imaging and spectral synthesis methods in order to study the activity behaviour and determine some orbital parameters of the system. In addition to the long-term star-spot activity of ER Vul, we also presented the performance of a small telescope (D=0.4m) equipped with a mid-resolution spectrograph in point of image reconstruction of such active binary systems.

2. Observations and data reduction

The mid-resolution time series spectra of ER Vul were obtained between 1 and 19 July 2018, using the Shelyak *eShel* spectrograph attached to the 0.4m Kreiken Telescope at the Ankara University Kreiken Observatory. We obtained seventeen spectra of the system with an average resolution of R ∼13500 that cover the wavelength range between 4340 Å and 7400 Å. The data was taken using the exposure time of 3600 seconds that gives SNR values between 58 and 99. We also observed three slowly rotating and non-active template stars HD 143761 (G0V), HD 32147 (K3V) and HD 139777 (G1.5V) that are required by Doppler imaging (photospheres of the primary and secondary components and the spot temperature) and spectral synthesis methods (photospheres of the primary and secondary components). The data reduction as well as the wavelength calibration procedures were carried out with the help of the AudeLA software (Klotz et al., 2012). The normalization of the spectra was performed using our own code that was developed in Python.

We used the signal enhancing Least-Squares Deconvolution (LSD) technique by Donati et al. (1997) to better resolve the spot signatures on both components during Doppler imaging process. The linelist required by the LSD technique was obtained from the Vienna Atomic Line Database (Kupka et al., 1999), considering log g and $T_{\rm eff}$ of ER Vul. We obtained the SNR values of LSD profiles between 1500 and 1900. Considering the resolving power of the spectral data, we set the increment per pixel to 10 km s^{-1} during the calculation of LSD profiles.

3. Analysis

3.1. Orbital solution and Doppler imaging

We determined the RVs of both components of ER Vul by fitting synthetic rotation profiles to the LSD profiles (see Şenavcı et al., 2018, for more details). An example of a fitted LSD profile is given in Fig. 1. The radial velocity analysis of ER Vul was performed using the `rvfit` code developed by Iglesias-Marzoa et al. (2015). The RV data together with the model are also plotted in Fig. 1, while the parameters obtained from the RV analysis are given in Table 1.

We used the Doppler imaging code `DoTS` (Collier Cameron, 1997) to reveal the spot pattern on the surfaces of both components of ER Vul. The code is based on two temperature model to mimic the spotted and unspotted photosphere and uses the Maximum-Entropy Method (MEM) to find the best fitting spot distribution across the stellar surface by means of a spot filling factor. The LSD profiles and best fit models are shown in Fig. 2, while the surface reconstructions of the primary and the secondary components are in Fig. 3.

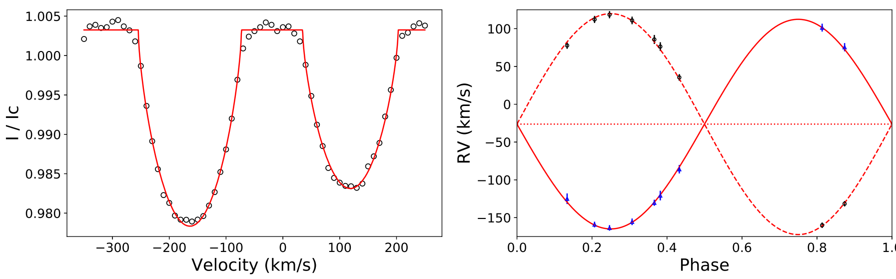

Figure 1. Left panel: An example of LSD profile (open circles) at phase 0.247 and the theoretical fit (red solid line) used in RV determination. Right panel: RV curve of ER Vul. The open blue triangles and open black circles represent the RV data of primary and secondary components of ER Vul, respectively. The solid and dashed red lines belong to the RV fit to the data.

3.2. Spectral subtraction

We also investigated the chromospheric activity behavior of ER Vul with the help of the spectral subtraction technique that was first suggested by Barden (1985). In this context, we determined the EQWs of the H_α excess emission for each spectrum considering the flux contribution from both components depending on the orbital phase and hence the eclipses. The details of the code used concerning the spectral subtraction process can be found in the study by Şenavcı

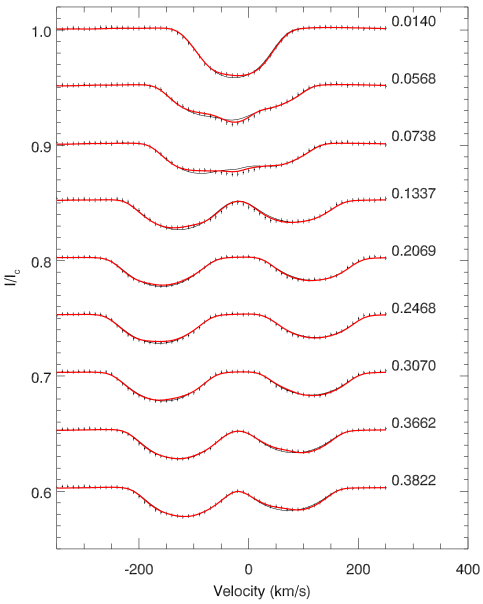

Figure 2. Phase-ordered LSD profiles of ER Vul. Black solid lines represent the synthetic velocity profiles generated using the system parameters, while the red solid lines show the maximum entropy regularized models of ER Vul.

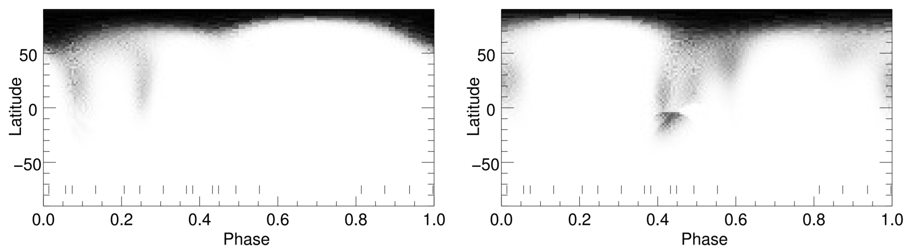

Figure 3. The Mercator projection of reconstructed image for the primary (left panel) and the secondary (right panel) component of the ER Vul system.

et al. (2018). An example of H_α excess emission obtained for two different orbital phases using spectral subtraction is shown in Fig. 4.

4. Discussion and conclusion

We have presented an activity investigation of both components of the RS CVn type eclipsing binary ER Vul, using time-series mid-resolution spectra of the

Table 1. Some physical parameters of ER Vul and comparisons from the literature.

Parameter	Value	Reference
$q = M_2/M_1$	0.949 ±0.019	This Study
	0.960 ±0.050	a
K_1 (km s^{-1})	138.67 ±2.06	This Study
	139.30 ±4.60	a
	135.20 ±0.63	b
K_2 (km s^{-1})	146.13 ±1.90	This Study
	144.30 ±5.20	a
	142.82 ±0.76	b
i [°]	66.63	c
V_γ [km s^{-1}]	-26.26 ±1.24	This Study
	-28.30 ±3.30	a
$T_0(HJD)$	2445220.40964	This Study
$P(d)$	0.698095	This Study
$T_{\mathrm{eff},1}(K)$	6000	c
$T_{\mathrm{eff},2}(K)$	5750	c
$a(R_\odot)$	4.28 ±0.04	This Study
M_1 ($M_\odot$)	1.108 ±0.033	This Study
M_2 ($M_\odot$)	1.052 ±0.034	This Study

Note: Reference: a. Çakırlı et al. (2003), b. Shkolnik et al. (2005), c. Harmanec et al. (2004).

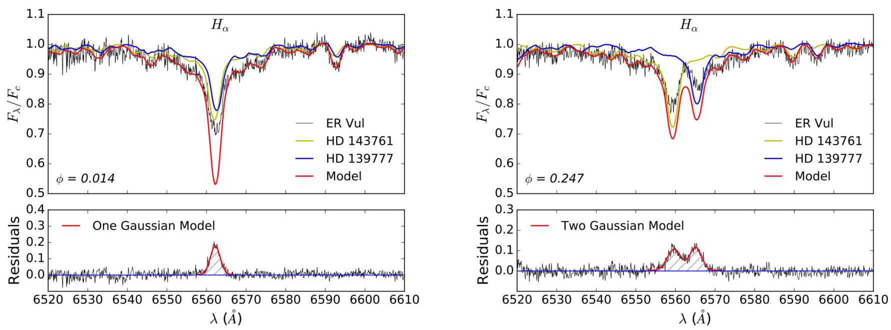

Figure 4. The spectral subtraction of the H_α line obtained at phases 0.014 (left panel) and 0.247 (right panel) of ER Vul. The yellow and blue solid lines show the spectra of the primary and secondary components, respectively, while the red solid line represents the total flux. The bottom panels show the residuals from the fit as well as the area of excess emission.

system with the help of the Doppler imaging and spectral subtraction techniques. The resolution of the spectral data (R $\sim$ 13500) used in this study may not be sufficient for such Doppler imaging purposes. However, both the high $v \sin i$ value of the system (84 km/s and 78 km/s for the primary and secondary, respectively) and the resolving power allow us to resolve star spots larger than 13 degrees, which can be considered as a good resolution for such a telescope and spectrograph system. The exposure time of 3600 seconds used during the observations corresponds to $\sim$ 6% of the orbital period of ER Vul, which causes the phase smearing phenomenon and hence leads to another limitation for the reconstructed surface images. The effects of phase smearing on the surface reconstruction was investigated in detail in the study by Şenavcı et al. (2018) that includes the Doppler imaging of the RS CVn type SV Cam using the code `DoTS`. They found that the long exposure times do not lead to considerable uncertainties for large spots, while the spot features smaller than 12 degrees that correspond to longest exposure times can be artefacts. In our case, the exposure time of 3600 seconds corresponds to 21.5 degrees (0.06 in orbital phase units). Therefore, we may infer that the spot features smaller than 21.5 degrees may not be reliable, while there is no smaller feature present in the reconstructed maps as seen from Fig. 3. It is clear from Fig. 3 that the primary and secondary components show high latitude spots as well as the extensions from lower latitudes. These distributions of spots for both the primary and secondary are consistent with the results that was obtained by Xiang et al. (2015). The spots location on the hemisphere facing to each other are also compatible with their surface maps.

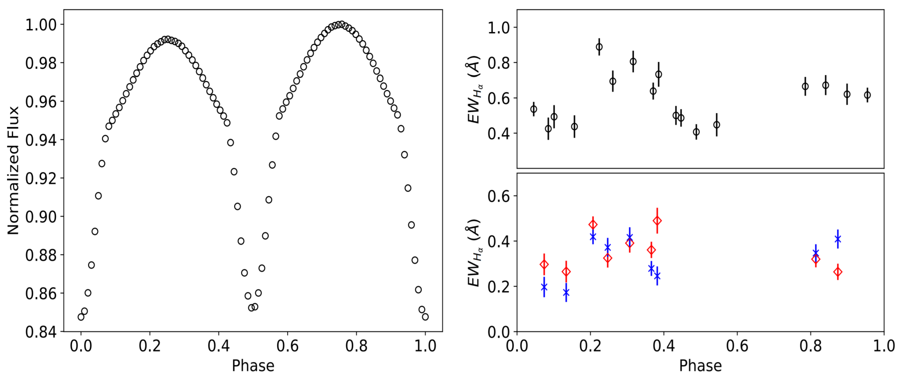

Figure 5. Left panel:The light curve generated by `DoTS` code, using the DI map. Upper right panel: The variation of H_α excess emission coming from both components along with the orbital phase. Lower right panel: The EQW variation of primary (red diamonds) and secondary (blue crosses) component.

As seen from Fig. 5, the EQW variation of the H_α line along with the orbital phase has the highest value at around phase ϕ=0.25, while the minimum excess emission occurs at around phase ϕ=0.50. The lower right panel of Fig. 5 shows the EQW variation of H_α excess emission obtained individually from both components. A similar behaviour can be clearly seen, with a slightly higher emission from the primary. This result is not compatible with the one obtained by Çakırlı et al. (2003), who mentioned that the secondary component is more active. Besides, Gunn & Doyle (1997) also mentioned that the secondary component is more active than the primary, while Newmark (1990) found that the primary is the more active one. Such a behaviour may be a consequence of the interaction between the magnetic fields of both components as suggested by Uchida & Sakurai (1985).

The light curve shown in the left panel of Fig. 5 was generated with the help of the code `DoTS`, using the resultant surface maps of both primary and secondary components obtained from Doppler imaging. The lower light level seen at phase ϕ=0.25 compared to ϕ=0.75 indicates a higher distribution of spots visible at ϕ=0.25. It also confirms the variation of H_α excess emission. This result suggests that both photospheric and chromospheric regions are associated with each other.

Acknowledgements. The authors acknowledge the support by The Scientific and Technological Research Council of Turkey (TÜBİTAK) through the project 1001 - 115F033.

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