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Magnetic activity under tidal influences in the 2+2 hierarchical quadruple system V815 Herculis

Zs. Kővári[1,2], K. G. Strassmeier[3], L. Kriskovics[1,2], K. Oláh[1,2], T. Borkovits[1,4,5], B. Seli[1,2], K. Vida[1,2] and Á. Radványi[6]

[1]Konkoly Observatory, HUN-REN Research Centre for Astronomy and Earth Sciences, Budapest, Hungary
email: kovari@konkoly.hu

[2]CSFK, MTA Centre of Excellence, Budapest, Hungary

[3]Leibniz–Institute for Astrophysics, Potsdam, Germany

[4]Baja Astronomical Observatory of University of Szeged, Baja, Hungary

[5]HUN-REN-SZTE Stellar Astrophysics Research Group, Baja, Hungary

[6]Moholy–Nagy University of Art and Design Budapest, Hungary

Abstract. Tidal forces in close binaries and multiple systems that contain magnetically active component are supposed to influence the operation of magnetic dynamo. Through synchronization the tidal effect of a close companion helps maintain fast rotation, thus supporting an efficient dynamo. At the same time, it can also suppress the differential rotation of the convection zone, or even force the formation of active longitudes at certain phases fixed to the orbit. V815 Her is a four-star system consisting of two close binaries orbiting each other, one of which contains an active G-type main-sequence star. Therefore, the system offers an excellent opportunity to investigate the influence of gravitational effects on solar-type magnetic activity using different methods.

Keywords. close binaries, stellar magnetic activity, starspots, Doppler imaging, differential rotation

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1. V815 Her: a single-lined multiple system with a chromospherically active primary

V815 Her is a single-lined multiple star system with a G5-6 V type active primary component. It has long been known that the G star features cool spots on its surface. The photometric behavior of the system is dominated by the magnetic activity of the primary component, as shown by the long-term photometric data in Figure 1. For the period analysis we used our Time Frequency Analyzer package TiFrAn (Kolláth and Oláh 2009) with Choi–Williams distribution kernel. Several long-term brightness changes can be attributed to the chromospheric activity of the G star. The century-long archival data from Digital Access to a Sky Century @ Harvard (DASCH) database supplemented with photoelectric data from Jetsu et al. (2000) reveals a slowly increasing cycle with steady amplitude around ∼6.5 years, two other cycles of about ∼9.1 and ∼13 years, while the longest feature points towards a timescale around ∼24-26 years with weakening amplitude (see the bottom panel of Fig. 1). The cycle lengths of ∼13 and ∼26 years are perhaps harmonics of ∼6.5 years.

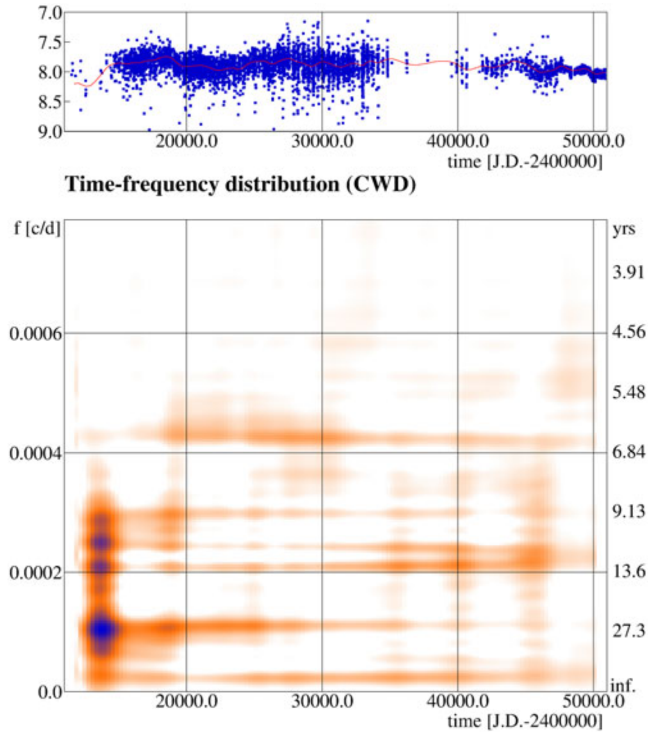

Figure 1. Long-term photometry and time-frequency analysis of V815 Her.

The rapidly rotating ($P_{\rm rot} = 1.8$ d) G star (=V815 Her Aa) together with an unseen, but probably late M-dwarf component (=V815 Her Ab) form the close binary subsystem V815 Her A with $P_{\rm orb} = 1.8$ d, i.e. orbiting synchronously. The binary was also known to have a distant companion with an orbital period of about 5.7 years (Fekel et al. 2005).

2. V815 Her B: an eclipsing binary subsystem formed by two M type dwarfs

Until our discovery, it was not known that the distant third body V815 Her B is actually itself an eclipsing close binary, whose members Ba+Bb are late M dwarfs (most probably M1+M5). In other words, the V815 Her system is essentially a 2+2 hierarchical quadruple. Figure 2 shows the *TESS* light curve of the primary and secondary minima of the V815 Her B eclipsing binary subsystem as an example. The light curve extracted from *TESS* Sector 53 observations is folded with the 0.52-day orbital period of the subsystem. The orbital solution without assuming surface inhomogeneities are drawn with grey line, while the model drawn with red line fits also the light curve variations arising from stellar spots on the surface of one or both M dwarf components.

3. Doppler imaging and differential rotation of V815 Her Aa

We performed a Doppler imaging study for the G star in order to reconstruct its spotted surface. For this we used 545 high-resolution optical spectra taken during a 9-month long observing run in 2018. The spectroscopic observations were carried out with the 1.2-m STELLA-II telescope of the STELLA robotic observatory (Strassmeier et al. 2010) at the Izaña Observatory in Tenerife, Spain. From the spectra we created 19 independent Doppler images in time series (adopted stellar parameters are listed in Table 1).

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Table 1. Astrophysical parameters for V815 Her Aa.

Spectral type	G6 V
Gaia distance [pc]	32.087 ± 0.127
$V_{\rm br}$ [mag]	7.56
$(B-V)$ [mag]	0.71
$M_{\rm bol}$ [mag]	4.90 ± 0.03
Luminosity [$L_\odot$]	0.87 ± 0.03
$T_{\rm eff}$ [K]	5582±63
$\log g$ (in cgs)	4.27±0.04
$v \sin i$ [kms^{-1}]	30.0 ± 1.5
$P_{\rm rot} = P_{\rm orb}$ [d]	1.80983433
Inclination [°]	75 ± 5
Radius [$R_\odot$]	1.1 ± 0.1
Mass [$M_\odot$]	$\lesssim$1.0
Microturbulence [kms^{-1}]	1.14 ± 0.19
Macroturbulence [kms^{-1}]	4.2
Metallicity [Fe/H]	0.06± 0.03
Age [Myr]	~30

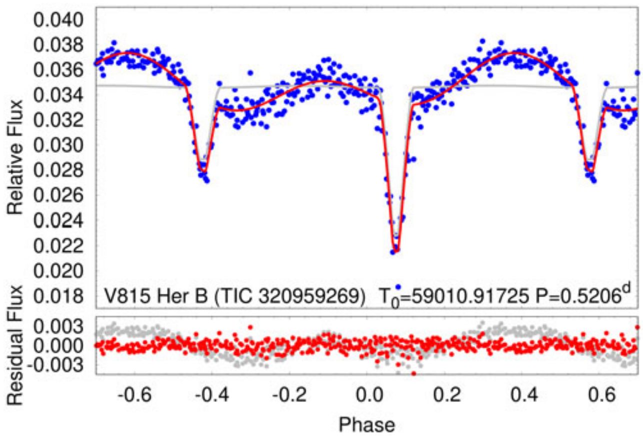

Figure 2. Cleaned and folded *TESS* Sector 53 light curve (blue) for V815 Her B with the orbital solution (grey) and the fitted spot model (red). Below are the residuals.

For the image reconstruction we used the state-of-the-art Doppler imaging code *iMap* (Carroll et al. 2012). The images follow each other at intervals of 11 days on average. As an example, in Figure 3 we show three surface maps, the 8th, the 9th and the 10th from the time series which indicate a constantly changing surface structure on a time scale of a few weeks. The rotational phases are calculated using the orbital period from Fekel et al. (2005) according to the following equation:

$$HJD = 2450204.5802 + 1.80983433 \times E. \quad (1)$$

The latitude dependent surface rotation can usually be inferred from the cross-correlation of two successive Doppler images. Here we use ACCORD (Kővári et al. 2012, 2015), a technique which enables the averaging of latitudinal cross-correlations in the case of a sufficient number of pairs of Doppler images not too distant in time, this way suppressing the effect of randomness and amplifying the correlation pattern attributed to surface differential rotation. In the left panel of Figure 4 we plot the average cross-correlation function map from 18 individual cross-correlations (i.e. for each consecutive image pairs). The figure indicates how much longitude shift occurs at a given latitude due

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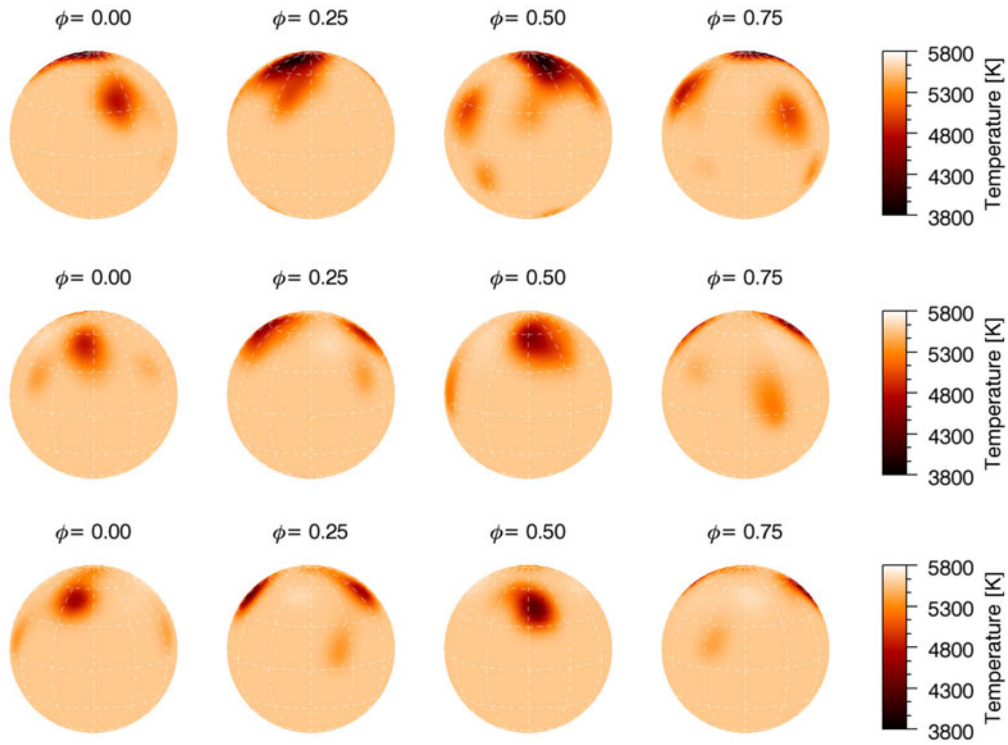

Figure 3. Three time-series Doppler images of V815 Her Aa from 2018.

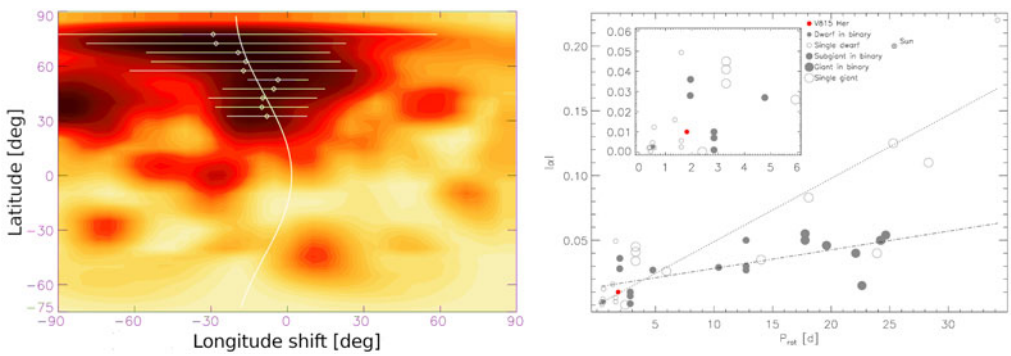

Figure 4. *Left*: The average cross-correlation function map fitted with a solar-type rotation function. *Right*: Surface shear parameter (α) vs. rotation period ($P_{\rm rot}$) graph for active spotted stars.

to surface shear during ~11 days (which is the average time difference between the consecutive Doppler images). The fitted rotation function suggests a weak solar-type surface differential rotation with a dimensionless shear parameter $\alpha = (\Omega_{\rm eq} - \Omega_{\rm pole})/\Omega_{\rm eq} = 0.01$.

In the right panel of Figure 4 we plotted an extended version of the surface shear parameter vs. rotation period graph ($|\alpha|$–$P_{\rm rot}$ graph) for active spotted stars based on Kővári et al. (2017). Open symbols correspond to (effectively) single active stars, grey symbols to active stars in binary (or multiple) systems. Symbol size increases from dwarfs to subgiants to giants. V815 Her Aa is represented by the red dot at $P_{\rm rot}$=1.8 days.

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The dotted and dash-dotted lines denote the linear fits for single stars and stars in binary systems, respectively, with slopes of $|\alpha| \propto 0.0049 P_{\rm rot}$[d] and $|\alpha| \propto 0.0014 P_{\rm rot}$[d]. The difference clearly indicates that binarity does play a role in confining differential rotation of the convective envelope.

4. Summary

From the century-long archival photometric data (DASCH) of V815 Her we found a strong signal of a slowly increasing cycle length around 6.5 years on average, close to the 5.73-yr period of the wide (AB) orbit (see Figure 1). At this point we interpret this slowly changing, ∼6.5-year photometric period as the activity cycle of V815 Her Aa, which is perhaps triggered along the eccentric (e=0.77, see Fekel et al. 2005) wide orbit.

We also demonstrated that V815 Her, previously known as a close binary system with a 'third body' in a wide orbit, and later suspected as a *TESS* planet-host candidate, is actually a 2+2 hierarchical quadruple system of two close binaries, one of which (i.e., V815 Her B) is an eclipsing binary (see Figure 2).

We used high-resolution optical spectra from the STELLA robotic observatory taken during the 2018 observing run to create time-series temperature maps (Doppler images) of the spotted surface of the G component V815 Her Aa. Consecutive maps in Figure 3 reflect significant spot activity and spot redistribution on a time scale comparable to the rotation period. From the latitudinal cross-correlation maps we measured a weak solar-type surface differential rotation on the G star. The small shear parameter of α=0.01, equivalent with $\Delta\Omega\approx 2^\circ$/d surface shear, suggests that the differential rotation of the G star is probably suppressed (see Figure 4). This is consistent with our previous finding (Kővári et al. 2017) that tidal forces in close binary systems can indeed suppress the differential rotation of a component with convective envelope.

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