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BVR_cI_c light curves, period and spectroscopic study of a low mass-ratio contact binary HV Aqr

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ABSTRACT

New BVR_cI_c light curves of the short period binary system, HV Aqr, are presented. Photometric solutions were derived using the 2015 version of Wilson–Devinney code. The characteristics of complete eclipses showing in the light curves enable us to determine high-precision photometric parameters of the binary system. We have derived $q = 0.159$ from our observations and $q = 0.149$ from the TESS data. The degree of contact is $f = 56.21\%$ and $f = 49.58\%$ from our observations and TESS data, respectively. Based on all available times of light minimum, we analyzed the long-term period changes. A decrease rate of $dP/dt = -1.29\times10^{-7}$ days/yr was determined. The continuous period decrease can be explained by mass transfer from the primary component to the secondary and angular momentum loss via magnetic braking. A conservative mass transfer rate of 2.17×10^{-8} $M_\odot$ yr^{-1} was derived. As the orbital period decreases, its contact of degree will become deeper and it will evolve into a single rapid-rotating star finally.

1. Introduction

W UMa type binaries belong to contact binaries, which are considered to be a universal type of eclipsing binaries. Both components are full of or beyond their respective Roche lobes and share common envelopes (Lucy, 1968). Lucy (1968) and Binnendijk (1970) classified W UMa type binaries into A-subtype and W-subtype. If the component with larger mass is at a higher temperature and bigger, then we refer to it as an A-subtype system. However, the massive component has a larger radius but at a relatively lower temperature as compared to its counter-part in a W-subtype system. EW-type binaries are systems with main characteristics such as fairly equal depth eclipsing light curves, short orbital periods usually less than one day, and frequently mass transfer between the two components which are in contact with each other sharing a common convective envelope. Eclipsing binaries can provide fundamental stellar properties and critical tests on the theories of stellar evolution and structure (Yuan et al., 2019).

The low mass-ratio limit is existed on the contact binaries (Jiang et al., 2010; Yang and Qian, 2015; Wadhwa et al., 2021; Li et al., 2022). The discovery of first low mass-ratio contact binary AW UMa (Paczynski, 1964; Rensing et al., 1985; Ruciński, 1992; Pribulla and Rucinski, 2008) attracts many researcher (e.g., Goderya et al., 1997; Qian et al., 2005b; Liu et al., 2011; Kriwattanawong and Poojon, 2013; Caton et al., 2019; Shokry et al., 2020). These type of binaries are at the late stage of evolution (Zhu et al., 2016; Wadhwa et al., 2021). The study of orbital stability provides a way to identify the potential merger candidates. Literature shows that V1309 Sco was an extreme low mass-ratio contact binary system with decaying orbital period (Nandez et al., 2014; Zhu et al., 2016). The angular momentum is dependent on accurate determination of absolute parameters and contact binary systems provide one of the best avenues for determining the basic absolute parameters such as masses and radii of stars. Arbutina (2007) has shown that orbital instability is likely to occur in systems with extreme low mass ratios in most instances (e.g., Qian and Yang, 2004; Zola et al., 2004; Kriwattanawong and Poojon, 2013).

HV Aqr is considered as an extreme low-mass ratio contact binary system and was first observed by Schirmer and Geyer (1992) with

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Table 1
Atmospheric parameter of HV Aqr.

HJD	Phase	$T_{eff}(K)$	$log(g)$ (cm/s^2)	$[Fe/H](dex)$
2459512.08	0.45	5873.244 ± 33.31	3.527 ± 0.105	0.107 ± 0.052
2459513.125	0.24	5958.406 ± 29.12	3.662 ± 0.094	0.104 ± 0.047

q = 0.146 and f = 47.5% having the orbital period of 0.374479 days. Further investigations showed that this system has P = 0.37445764 days. Ruciński et al. (2000) derived a mass ratio $q = 0.145 \pm 0.050$ and F5V spectral type from their spectroscopic observations. The published mass ratio and fill-out factor were slightly different from previous observations of Molik and Wolf (2000). They reported q = 0.18 and f = 40%. Later on, Oh et al. (2004) gave out its solutions with a spot's parameters. D'Angelo et al. (2006) found the signature of a tertiary component and identified HV Aqr as a triple system. Gazeas et al. (2007) obtained larger degree of contact (f = 68.3%) and the mass ratio q = 0.151 in a presence of O'Connell effect (O'Connell, 1951). In 2013, Li and Qian (2013) analysis of VRI light curves showed $q = 0.1455$ and $f = 55.9\%$. They derived the period of $P = 0.37445838$ days which is decreasing at the rate of $dP/dt = 8.84 \times 10^{-8} days/yr$. More recently, Gazeas et al. (2021) modeled the light curve of HV Aqr with negligible third light with $q = 0.140$ and $f = 74\%$. It was proposed that this system may further be observed to study the period and light curves.

The eclipsing binaries research has improved rapidly as a result of space satellites. Recently, The Transiting Exoplanet Survey Satellite (TESS) obtained new photometric data of a number of eclipsing binaries (Ricker et al., 2014). HV Aqr is also observed by TESS in sector-5 using 2-minutes cadence from August 05, 2022 to September 01, 2022. The data has also been included in our analysis.

In this paper, we presented the new BVR_cI_c light curves of HV Aqr. Using the 2015 version of Wilson–Devinney code, new photometric solutions of the system were obtained. We analyzed the long-term orbital period variation of HV Aqr based on all available times of light minimum. In addition to that, the spectroscopic observations helped us understand the properties of HV Aqr.

2. Observation of HV Aqr

2.1. Spectroscopic data

The low-resolution spectrum of HV Aqr was obtained using 2.4 m optical telescope at Lijiang observational station of Yunnan Observatories. The Yunnan Faint Object Spectrograph and Camera (YFOSC) is used to obtain low-resolution spectrum. The YFOSC cover a wavelength range of 340 nm–980 nm. More details on the instrument can be obtained from Wang et al. (2019). The CCD for YFOSC is a 2148 × 4612 pixel with the pixel size of $13.5 \mu m \times 13.5$ μm. The data was obtained using a slit size with 168 μm at resolution of $3520 nm/pix$. The target was observed for two consecutive nights on October 24–25, 2021 with an exposure time of 900 s. The obtained spectrum is shown in Fig. 1. The atmospheric parameters and probable errors are shown in Table 1. These parameter were obtained using the Universite de Lyon spectroscopic analysis software (ULySS) (Wu et al., 2011b). This is the same method as used for LAMOST data (Wu et al., 2011a).

2.2. Photometric observations

The photometric data were obtained with the 0.6 m Helen Sawyer Hogg (HSH) telescope located at Complejo Astronomico El Leoncito (CASLEO), San Juan, Argentina. The telescope is equipped with SBIG STL1001E CCD camera with standard Jhonson-Cousins' BVR_cI_c filters. The observing equipment provides a good field of view of 9.3 × 9.3 arc minutes in 1 × 1 binning. The star was observed on August 02, 2019. The standard aperture photometry was processed for all observed images by using the IRAF software packages (Tody, 1986, 1993) to obtain differential magnitude in all BVR_cI_c filters. The exposure time was 10 to 20 s. Table 2 represents GCVS catalog numbers, coordinates and BVR_cI_c magnitudes of HV Aqr, comparison star C1 and check star C2. A sample set of the observed data is shown in Table 3.

Table 2
Coordinates and magnitudes of HV Aqr, its comparison star and check star.

System	α(2000)	δ(2000)	B	V	R	I
HV Aqr (GSC 05198-00659)	21 21 24.81	−03 09 36.84	10.50	9.99	–	9.15
C1 (GSC 05198-01308)	21 21 46.49	−03 11 57.72	9.60	8.40	–	–
C2 (GSC 05198-00636)	21 21 36.30	−03 15 04.93	9.60	8.40	–	–

Table 3
Sample of observed data for HV Aqr.

MJD[a]	Δm	Error	Band	MJD[a]	Δm	Error	Band
58697.55670	0.9339	0.0047	B	58697.55708	1.3492	0.0047	V
58697.56117	0.9401	0.0044	B	58697.56154	1.3454	0.0044	V
....	......	......	.	....	......	......	.
58697.58069	0.9479	0.0037	B	58697.58106	1.3475	0.0035	V
58697.59060	0.9680	0.0034	B	58697.59097	1.3656	0.0032	V
....	......	......	.	....	......	......	.
58697.61009	1.0132	0.0031	B	58697.61047	1.4219	0.0028	V
58697.62144	1.0799	0.0030	B	58697.62020	1.4751	0.0027	V
....	......	......	.	....	......	......	.
58697.64098	1.2560	0.0031	B	58697.64135	1.6470	0.0026	V
58697.65086	1.2974	0.0030	B	58697.65124	1.6882	0.0026	V
....	......	......	.	....	......	......	.
58697.67093	1.3068	0.0030	B	58697.67130	1.6899	0.0025	V
58697.68005	1.2923	0.0030	B	58697.68043	1.6853	0.0025	V
....	......	......	.	....	......	......	.
58697.70111	1.0967	0.0027	B	58697.70148	1.5148	0.0023	V
58697.71088	1.0410	0.0026	B	58697.71125	1.4479	0.0022	V
....	......	......	.	....	......	......	.
58697.73033	0.9572	0.0026	B	58697.73071	1.3647	0.0022	V
58697.74014	0.9287	0.0025	B	58697.74052	1.3460	0.0022	V
....	......	......	.	....	......	......	.
58697.55737	1.5926	0.0064	R	58697.55921	1.8219	0.0062	I
58697.56040	1.5883	0.0061	R	58697.56391	1.8124	0.0058	I
....	......	......	.	....	......	......	.
58697.58135	1.5849	0.0046	R	58697.58015	1.8300	0.0047	I
58697.59126	1.6083	0.0041	R	58697.59006	1.8535	0.0042	I
....	......	......	.	....	......	......	.
58697.61075	1.6852	0.0036	R	58697.61118	1.9055	0.0036	I
58697.62048	1.7044	0.0034	R	58697.62091	1.9654	0.0034	I
....	......	......	.	....	......	......	.
58697.64003	1.8604	0.0032	R	58697.64045	2.0948	0.0032	I
58697.65010	1.9113	0.0031	R	58697.65033	2.1440	0.0032	I
....	......	......	.	....	......	......	.
58697.67018	1.9111	0.0030	R	58697.67041	2.1579	0.0030	I
58697.68072	1.9079	0.0029	R	58697.68114	2.1400	0.0029	I
....	......	......	.	....	......	......	.
58697.70015	1.7512	0.0027	R	58697.70057	1.9918	0.0028	I
58697.71011	1.6947	0.0027	R	58697.71034	1.9494	0.0027	I
....	......	......	.	....	......	......	.
58697.73099	1.6049	0.0026	R	58697.73142	1.8534	0.0026	I
58697.74080	1.5832	0.0026	R	58697.74123	1.8416	0.0026	I
....	......	......	.	....	......	......	.
....	......	......	.	....	......	......	.

[a]H.J.D = MJD + 2400000.0000.

3. Orbital period study

We obtain a total of 214 times of primary and secondary minima including our newly determined ones basing on our observations and TESS data. Most of the minima data are available at the O-C gateway (http://var2.astro.cz/ocgate) and Bob Nelson's files (https://www.aavso.org/bob-nelsons-o-c-files). We have also used AAVSO database to collect light minimum of HV Aqr. A sample of available times of minima are listed in Table 4. The electronic version of complete table is available with journal. The ephemeris used to calculate the O-C values

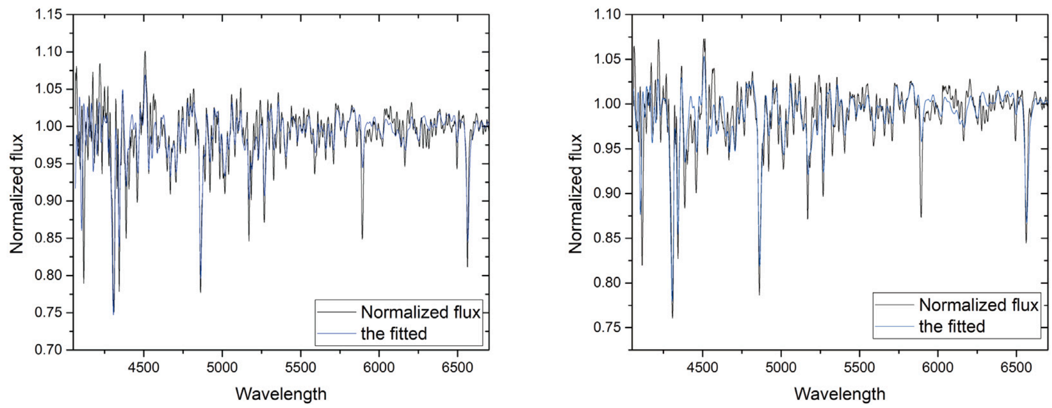

Fig. 1. The black line shows the low-resolution spectrum of HV Aqr observed on October 24–25, 2021 (left to right), and is fitted over the LAMOST spectrum (blue line). The wavelength is in angstrom.

Table 4
Times of Minima for HV Aqr. The H.J.D. are +2400000.0000.

H.J.D.	Error	Minima	Method	E(Cycles)	O-C	Reference
48835.7737	±0.0012	p	RV	−26337.0	0.0330541	Robb (1992)
48840.4544	–	s	V	−26324.5	0.0330243	Schirmer and Geyer (1992)
48842.5161	–	p	V	−26319.0	0.0352032	Schirmer and Geyer (1992)
48843.4507	–	s	V	−26316.5	0.0336573	Schirmer and Geyer (1992)
48850.5641	–	s	V	−26297.5	0.0323481	Schirmer and Geyer (1992)
49217.5230	±0.0012	s	vis	−25317.5	0.0220356	Martignoni (1996)
49219.4120	±0.0012	s	vis	−25312.5	0.0387437	Martignoni (1996)
50017.3790	–	s	vis	−23181.5	0.0349360	Molik and Wolf (2000)
51775.4539	–	s	R	−18486.5	0.0277419	Molik and Wolf (2000)
52491.4263	±0.0001	s	BV	−16574.5	0.0357193	Tanriverdi et al. (2003)
52510.5124	±0.0004	s	R	−16523.5	0.0244419	Sarounova and Wolf (2005)
52535.4188	±0.0003	p	BVRI	−16457.0	0.0293597	Karampotsiou et al. (2016)
52537.2909	±0.0004	p	BVRI	−16452.0	0.0291678	Karampotsiou et al. (2016)
53250.6336	±0.0009	p	ccd	−14547.0	0.0286539	Ogloza et al. (2008)
53562.9286	±0.0002	p	ccd	−13713.0	0.0253649	Krajci (2006)
53576.5953	±0.0005	s	BVRI	−13676.5	0.0243341	Petropoulou et al. (2015)
53579.4047	±0.0002	p	BVRI	−13669.0	0.0252962	Petropoulou et al. (2015)
53631.6426	±0.0001	s	ccd	−13529.5	0.0262522	Dvorak (2006)
53986.6397	±0.0014	s	ccd	−12581.5	0.0368080	Ogloza et al. (2008)
54012.6534	±0.0003	p	ccd	−12512.0	0.0256506	Krajci (2007)
55102.6932	±0.0005	p	V	−9601.0	0.0171064	Diethelm (2010)
55426.0393	–	s	Rc	−8737.5	0.0183952	Kazuo (2010)
55435.0242	–	s	Rc	−8713.5	0.0162941	Kazuo (2010)
55502.0543	±0.0005	s	V	−8534.5	0.0183441	Li and Qian (2013)
55776.5289	±0.0004	s	ccd	−7801.5	0.0149516	Hoňková et al. (2013)
55855.7243	±0.0004	p	ccd	−7590.0	0.0124042	Diethelm (2012)
57669.4080	±0.0040	s	ccd	−2746.5	0.0069407	Paschke (2017)
58059.4060	±0.0050	p	ccd	−1705.0	0.0065379	Paschke (2018)
58357.0962	–	p	V	−910.0	0.0023258	Kazuo (2019)
58697.8510	±0.0002	p	B	0.0	0.0000000	Present Study
58697.8510	±0.0002	p	V	0.0	0.0000000	Present Study
58697.8510	±0.0002	p	R	0.0	0.0000000	Present Study
58697.8510	±0.0002	p	I	0.0	0.0000000	Present Study
58697.6634	±0.0002	s	B	−0.5	−0.0003558	Present Study
58697.6636	±0.0002	s	V	−0.5	−0.0001788	Present Study
58697.6637	±0.0001	s	R	−0.5	−0.0000948	Present Study
58697.6641	±0.0002	s	I	−0.5	0.0003772	Present Study
59437.3858	±0.0010	p	V	1975.0	−0.0205010	Paschke (2021)
59797.2466	±0.0001	p	TESS	2936.0	−0.0142037	–
59800.2418	±0.0001	p	TESS	2944.0	−0.0146707	–
59804.3607	±0.0001	p	TESS	2955.0	−0.0148129	–
59806.2330	±0.0001	p	TESS	2960.0	−0.0148048	–
59811.1004	±0.0001	p	TESS	2973.0	−0.0153637	–
59807.1704	±0.0001	s	TESS	2962.5	−0.0135507	–
59810.9148	±0.0001	s	TESS	2972.5	−0.0136846	–
59816.1573	±0.0001	s	TESS	2986.5	−0.0136219	–
59818.4039	±0.0001	s	TESS	2992.5	−0.0137621	–
59822.8979	±0.0001	s	TESS	3004.5	−0.0133427	–
……	……	…	….	……	………	..

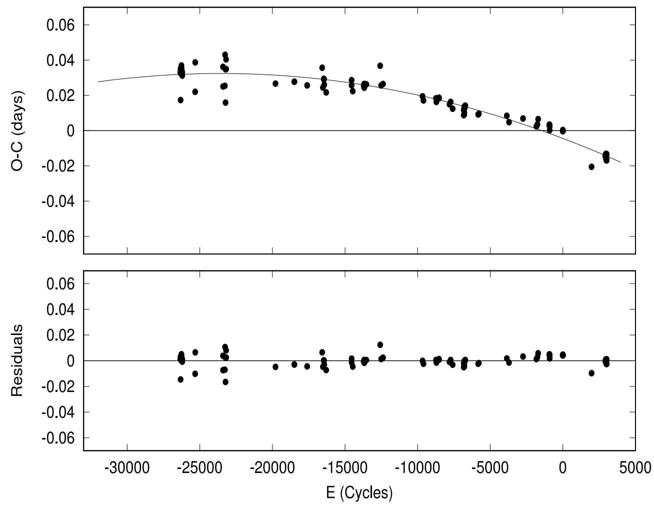

Fig. 2. O-C diagram of HV Aqr. Circles represents all times of primary and secondary minima. Black line shows parabolic fit. Residuals are plotted in the bottom panel.

are shown as follows:

$$MinI = 2458697.8510 + 0.37445838 \times E \quad (1)$$

The O-C diagram indicates parabolic fit as shown in Fig. 2. The least square method reveals that the period of HV Aqr is decreasing. We obtain a new ephemeris as follows,

$$MinI = 2458697.8466(1) + 0.37445525(7) \times E - 6.61(8) \times 10^{-11} E^2 \quad (2)$$

The quadratic term in Eq. (2) leads us to determine a period decrease rate of $dP/dt = -1.29 \times 10^{-7} days/yr$.

4. Light curve analysis

The simultaneous BVR_cI_c solution for HV Aqr is obtained using 2015 version of the Wilson–Devinney program (WD) (Wilson and Devinney, 1971; Wilson and Van Hamme, 2014). The gravity darkening coefficients (g_1, g_2) and albedo (A_1, A_2) were set to 0.32 and 0.5 respectively as these values are reasonable for stars having convective envelopes (Lucy, 1967; Ruciński, 1969). The limb darkening parameters were set to be computed internally by the WD model $(LD1(2) = -2)$. The average value of T_1 obtained through our low resolution spectrum was $5915K$, whereas, B-V index give $6210K$ which was close to Rucinski et al. (2007). During visual fitting in LC module of WD program, we set $T_1 = 5915K$ and kept it fixed during our analysis. While fitting TESS light curve, we also set $T_1 = 5915K$. The spectroscopic mass ratio $(q = 0.145)$ from Rucinski et al. (2007) was used as initial value and kept it adjustable during our analysis. The orbital inclination (i), temperature of star 2 (T_2), the dimensionless gravitational potential (Ω_1) (for contact binaries $\Omega_1 = \Omega_2$), and the luminosity of star 1 (L_1) were also adjustable. All adjustable parameters converged properly. However, significant difference in amplitude was observed in the light curve especially in BVR_c filters. Initially, we added a cool spot which improved the light curve mostly at outside the minima. However, the difference in amplitude of light curve remained. Therefore, we offer a single hot spot which significantly improved the fitting of light curves and the solution converged properly. We found that spot solution showed a smaller value of mean residual. We adopted spot solution and superimposed the modeled light curve over the observed as shown in Fig. 3. We applied the same approach to the TESS light curve. However, no difference in light curve amplitude was observed as shown in Fig. 3. Hence spot solution was not performed on TESS light curve. We have also noted that the temperature of secondary star (T_2) is higher than its counter part by only $54K$ and $33K$ in our solutions, whereas, this difference is $128K$ for TESS observations. The results are tabulated in Table 5.

Table 5
Photometric solution of HV Aqr.

Parameters	H V Aqr		
	No Spot	Spot	TESS
$q(m_2/m_1)$	0.158 ± 0.001	0.159 ± 0.001	0.149 ±0.001
$i(deg)$	79.01 ± 0.29	78.22 ± 0.26	79.18 ± 0.09
$\Omega_1 = \Omega_2$	2.070 ± 0.003	2.072 ± 0.002	2.055 ± 0.001
Ω_{in}	2.116	2.129	2.103
Ω_{out}	2.016	2.026	2.006
f	46.40%	56.21%	49.58%
$T_1(K)$	5915	5915	5915
$T_2(K)$	5969 ± 9	5948 ± 7	6043 ± 4
$r_1(pole)$	0.5179 ± 0.0008	0.5177 ± 0.0006	0.5202 ± 0.0002
$r_1(side)$	0.5737 ± 0.0012	0.5733 ± 0.0009	0.5765 ± 0.0003
$r_1(back)$	0.5993 ± 0.0013	0.5989 ± 0.0010	0.6009 ± 0.0003
$r_2(pole)$	0.2359 ± 0.0033	0.2355 ± 0.0022	0.2282 ± 0.0008
$r_2(side)$	0.2479 ± 0.0041	0.2475 ± 0.0028	0.2393 ± 0.0010
$r_2(back)$	0.3035 ± 0.0117	0.3020 ± 0.0077	0.2890 ± 0.0027
$L_1/(L_1+L_2)_B$	0.820 ± 0.001	0.823 ± 0.001	
$L_1/(L_1+L_2)_V$	0.822 ± 0.001	0.824 ± 0.001	
$L_1/(L_1+L_2)_R$	0.824 ± 0.001	0.825 ± 0.001	
$L_1/(L_1+L_2)_I$	0.825 ± 0.001	0.826 ± 0.001	
$L_1/(L_1+L_2)_{TESS}$			0.883 ± 0.001
Latitude(rad)		2.000	
Longitude (rad)		1.708 ± 0.040	
Angular Radius (rad)		0.400	
Spot Temp. Factor		1.033 ± 0.001	
Mean Residual	3.83×10^{-4}	3.63×10^{-4}	3.74×10^{-8}

Table 6
Table of Max. I–II values for observed HV Aqr light curve.

Filter	Max. I–Max. II	Reference
B	0.035	Present study
V	0.024	Present study
	−0.019	Robb (1992)
	0.013	Gazeas et al. (2007)
	−0.003	Li and Qian (2013)
R	0.019	Present study
	−0.015	Robb (1992)
	0.012	Gazeas et al. (2007)
	−0.004	Li and Qian (2013)
I	0.007	Present study

5. Results and discussion

5.1. Spot activity

The asymmetries in light curve were first reported by Schirmer and Geyer (1992) and Robb (1992). However, Molik and Wolf (2000) and Li and Qian (2013) presented symmetric light curves. Rucinski et al. (2007) found a tertiary component with HV Aqr. Gazeas et al. (2007, 2021) suggested the presence of O'Connell effect (Max. II fainter than Max. I) and introduced a cool spot on of the component stars. They also presented the third light solution of the system. However, we did not find any third light in our solution. In our new determined BVR_cI_c light curves, we observed that Max. I is fainter than Max. II. This can easily be noticed particularly in B band light curve. We calculated the Max. I - Max. II values of the light curves and list in Table 6. This indicates that HV Aqr is under going a cycle of magnetic activity and there may be a hot spot on one of the component stars. The Max. I - Max. II values of TESS data are negligible. The variation in Max. I - Max. II values and the spot parameters shows that the O'Connell effect is variable. This also shows two types of activity scenarios. We call it the active scenario when Max. I ≠ Max. II and inactive scenario when Max. I = Max. II (Qian et al., 2014). The movement of spots on the component stars along with the rotation of stars make the study of spot

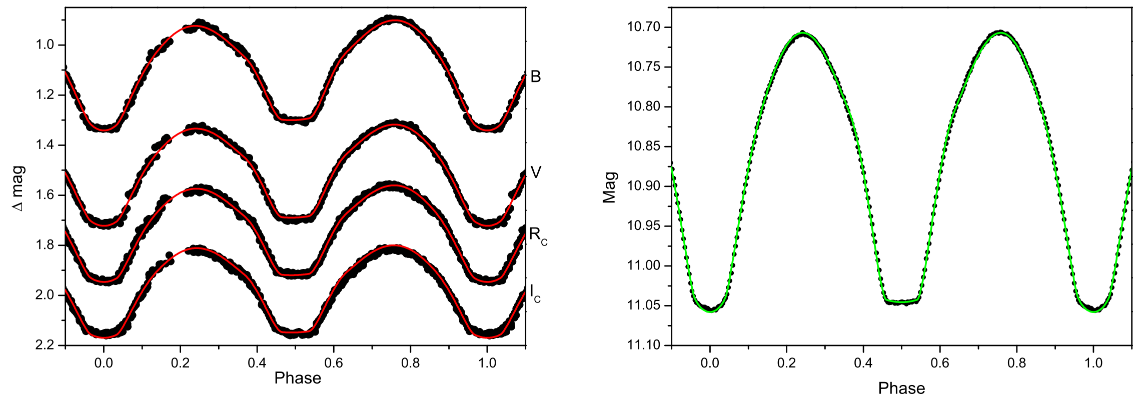

Fig. 3. Combined light curves of HV Aqr. The right panel shows our observations in BVR_cI_c filters where solution (solid lines) is superimposed over observed light curve. The right panel shows TESS light curve where solid line represents the photometric solution.

Table 7
Star spot parameters for HV Aqr.

Parameters	Oh et al. (2004)	Gazeas et al. (2007)	Gazeas et al. (2021)	Present study
Latitude(deg)	70.00	65.6	151	114.65
Longitude (deg)	90.50	32.1	33	97.91
Angular Radius (deg)	20.00	17.3	30.7	22.93
Spot Temp. Factor	0.908	0.945	0.89	1.033

Table 8
Absolute parameters for $HV\,Aqr$.

Parameters	Value
a	$2.33R_\odot \pm 0.05$
M_1	$1.05M_\odot \pm 0.07$
M_2	$0.16M_\odot \pm 0.01$
R_1	$1.32R_\odot \pm 0.03$
R_2	$0.58R_\odot \pm 0.01$
L_1	$1.91L_\odot \pm 0.10$
L_2	$0.41L_\odot \pm 0.02$

Table 9
Some extreme low mass-ratio contact binary systems with decaying period.

System	q	$P(days)$	dP/dt (d/yr)	Reference
GR Vir	0.122	0.3469	-4.32×10^{-7}	Qian and Yang (2004)
SX Crv	0.071	0.3166	-2.88×10^{-9}	Zola et al. (2004)
CU Tau	0.177	0.4125	-1.81×10^{-6}	Qian et al. (2005a)
TV Mus	0.166	0.4456	-2.16×10^{-7}	Qian et al. (2005a)
GV Leo	0.188	0.2667	-4.95×10^{-7}	Kriwattanawong and Poojon (2013)
V1187 Her	0.04	0.3107	-1.50×10^{-7}	Caton et al. (2019)
J082700	0.055	0.2771	-9.52×10^{-7}	Li et al. (2021b)

activity on eclipsing binaries more complicated (Sarotsakulchai et al., 2019).

According to the photometric solution of Gazeas et al. (2007), HV Aqr showed the O'Connell effect in the light curves which he explained with a small cool spot with radius of 17.3 degree. Later on, Gazeas et al. (2021) introduced a larger cool spot with its radius of 30.7 degrees. The latitude of both spots were different, however, they were almost at the same longitudinal position and the later was relatively at lower temperature. The same spot may have grown larger in size and cover up more stellar surface along latitude. This can make a spot cycle of more than 14-years. The present study indicates that HV Aqr has a hot spot of 22.93 degrees in radius. The latitude and longitudinal positions are also different compared to previously reported spots which means that a new spot has been formed on the primary surface. We have also checked the TESS light curve but no O'Connel was observed in the light curve. In order to understand spot activity, the continuous monitoring of HV Aqr is recommended. Table 7 list the values of spot parameters. A simple unit conversion make the values consistent.

5.2. Absolute parameters and evolutionary states

A small mass ratio along with high value of orbital inclination produces a total eclipse in eclipsing binaries. Such situation allows to determine accurate parameters of the system (Li et al., 2019, 2021a). Using radial velocity data of Ruciński et al. (2000) and our present photometric solution, we have derived the absolute parameters for HV Aqr. These are listed in Table 8.

The period study shows that the period of HV Aqr is decreasing at a rate of $1.29\times10^{-7}days/yr$. This can be explained through evolutionary scenario of thermal relaxation oscillation with angular momentum loss (AML) via change in degree of contact (Lucy, 1976; Flannery, 1976; Robertson and Eggleton, 1977; Qian, 2003). This suggests that evolution of HV Aqr is controlled by AML. Some extreme low mass-ratio binaries with decay in period are listed in Table 9.

The continuous decrease in period also suggests that HV Aqr is undergoing a process of mass transfer from primary to secondary component. We can use the well-known equation (Singh and Chaubey, 1986)

$$\frac{dM_2}{dt} = -\frac{M_1M_2}{3P(M_1-M_2)} \times dP/dt, \tag{3}$$

and determined the mass transfer rate to be $2.17\times10^{-8}M_\odot yr^{-1}$. The continuous decrease in period is not only caused by mass transfer from primary to secondary component but also from AML. The cyclic variation in period cannot be determined since there is no sufficient data on light minima. If we look into the Mass–Luminosity diagram (Yang et al., 2022; Yang and Wang, 2023), the primary component of HV Aqr can easily be placed at Zero Age Main-Sequence (ZAMS) and the secondary component at Terminal Age Main-Sequence (TAMS). This means that both components of HV Aqr are evolved stars. Compare the rate of decrease in period from Li and Qian (2013) to current value, it is noted that rate of decrease in orbital period has slowed down from 8.84×10^{-8} to 1.29×10^{-7} in 12 years' time (from 2010 to 2022), which in turn also lowers the degree of contact from 56.21% to 49.58%. With the decrease in orbital period, the inner and outer Roche Lobes will shrink which causes the common convective envelope to become deeper. The process will continue until the formation of a single rapidly rotating star.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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