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Multisite photometry of Algol-type binary system RZ Cas

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1 Introduction

RZ Cas (HD 17138) is an Algol-type system whose primary and secondary components are A3 V and K0 IV respectively. As this binary is bright ($mv = 6.18$ mag at light maxima) with a short orbital period ($P = 1.195$ day), many reports of photometric observations of time of mid-minima have been published. Although the primary minimum of this system is due to a partial eclipse, flat bottoms which resemble a total eclipse have frequently been observed (Arganbright et al. 1988, Hegedüs et al. 1989, Nakamura et al. 1991a and Narusawa et al. 1994 etc.). Several models were proposed, but the cause of the flat bottom was left unknown (Narusawa et al. 1994).

We have performed cooperative photometry of RZ Cas not only during the primary eclipse, but also during the out of eclipse phase from September 1997 to January 1998, and have found a δ Sct type, nonradial pulsation with a frequency of 64.20 cycles day^{-1}(22.4 min), whose maximum amplitude is 0.02 mag (Ohshima et al. 2001; hereafter O01). This has led us to understand that the flat bottom is synthesized with the light variation of the partial eclipse and those of the oscillations as described in section 3.

RZ Cas is also famous for irregular and sudden orbital-period changes(SPCs). Many investigations of period changes of this system have been reported (e.g., Hegedüs et al. 1992, Narusawa et al. 1994, Mkrtichian et al., 2018 and Lehmann et al. 2020). In order to obtain more information, we have continued photometric studies of this system.

2 Observations

The cooperative observations with PMT photometers and CCD cameras were conducted over 70 nights throughout October 1998 to November 2016 at seven sites in Japan. The instruments of each observation are listed in Table 1. The color filters similar to the standard Johnson-Kron-Cousins system were used at all places.

3 Results

We obtained 19 primary and 6 secondary minima during observations over 70 nights. The results of photometric observations at minima are reported here. The key information are summarized in Table 2.

3.1 Shape of light curve at mid-primary minima

We begin by discussing the shape of the light curve at mid-primary minima. O01 categorized the shapes into three types; the "F-type" with a flat bottom; the "V-type" with a V-shaped curve; and the "S-type" with a slant increasing or decreasing smoothly. Furthermore, the subtypes "Sa" and "Sb" were classified which indicate an ascending slant and a descending one respectively. According to the explanation by O01, when the light maximum of the δ Sct pulsation coincides with the center of eclipse, the F-type is observed. When the light minimum of pulsation coincides with the mid-primary eclipse, the V-type light curve is observed. The intermediate case is the S-type. In addition to O01 's classification, we define the "P-type", a partial-eclipsed curve. This type appears when the amplitude of pulsation is small. Shapes at primary minima derived from our observations are listed in the fifth column of Table 2. Apparent F-type and Sb-type curves were observed and they are shown in Figure 1. As shown in the sixth column of Table 2, several of the light curves have asymmetric shapes probably showing the effect of gas stream.

3.2 Orbital period

The estimated moments of minima are listed in the first column of Table 2. The E and $O-C$ values were calculated utilizing the following ephemeris provided by GCVS 5.1 [1].

$$\text{Min I} = \text{HJD } 2456529.766 + 1.19525031\,E. \tag{1}$$

RZ Cas is a well-known system that shows SPCs as described in section 1. The $O-C$ values listed in the fourth column of Table 2 are plotted on the $O-C$ diagram (after HJD 2429875 until the present time) in Figure 2 together with data (based on photoelectric and CCD observations) from *the (B-R)-Generator für die Lichtenknecker-Database of the BAV* [2] and *O-C gateway of Brno Regional Network of Observers (B.R.N.O.)* of the Czech Astronomical Society [3] [4]. Photoelectric data of primary minima that was published in Nakamura et al. (1991b) and photoelectric and CCD data that was published in O01 is also used. However, since this data is

[1] http://www.sai.msu.su/gcvs/gcvs/gcvs5/gcvs5.txt

[2] Obtained from http://www.bav-astro.de/LkDB/index.php?lang=en

[3] Obtained from http://var2.astro.cz/ocgate/index.php?lang=en

[4] Although both minima HJD 2452202.947 and HJD 2452228.048 are stated to be obtained by CCD observations in O-C gateway, they are actually results of visual observations (Nagai 2002). Therefore we do not use these data for this study.

Table 1: Observational sites observers, and instruments

Site[a]	Observer	Telescope[b]	Camera/Detector [c]	Filter
Funao	Akazawa (1998-2000)	28 cm SC	PMT R647p PC	B, V
	Akazawa (2015)	8 cm refractor	ST-9XE	Rc
	Akazawa (2016)	20 cm SC	ST-402 ME	V
ARSO	Arai	28 cm SC	PMT R647p VF	V
Bisei	Fujii (except 2011/2012)	7.5 cm refractor	ST-7	Rc, Ic
	Fujii	7.5 cm refractor	ST-10XME	Rc
Sendai	Ito	5.5 cm(Camera lens)	ST-9	Rc
	Ito (last three nights)	6 cm refractor	ST-9	Rc
Yakage	Morikawa	25 cm SC	ST-7	Ic
NHAO	Narusawa, Ioroi, Invernizzi	60 cm Cassegrain	PMT R647p PC	B, V
Senoh	Ohkura	35 cm SC	PMT R647p PC	B, V

a: NHAO: Nishi-Harima Astronomical Observatory, ARSO: Arai River-Side Observatory
b: SC: Schmidt Cassegrain Telescope
c: PC: Photon-counting system, VF: V/F Conversion system

not registered in either *the (B-R)-Generator* nor *the O-C gateway*, we present them here in Table 3 and Table 4.

The Figure 3 shows the $O-C$ values including our data during the period of HJD 2447500 (1988) to HJD 2454500 (2008) and it shows that the orbital period during the period $\sim$ HJD 2448500 (1991) to $\sim$ HJD 2453000 (2003) was constant. This is an exceptionally long steady period for RZ Cas.

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Table 2: Estimated times and shapes of the observed minima

Min (HJD 2450000+)	Type	E[a]	$O-C$[a] (days)	Shape[b]	Asymmetry?	Observer / Site[c]
1090.16541(8)	I	-4551	-0.01643	V		Ohkura
1090.1643(1)	I	-4551	-0.0175	P		NHAO
1131.99788(4)	I	-4516	-0.01772	F: (12 min)		Arai
1137.9744(1)	I	-4511	-0.0175	P		Ohkura
1143.94801(7)	I	-4506	-0.02009	P:		Arai
1143.94933(6)	I	-4506	-0.01877	F (20 min)		Ohkura
1169.0502(1)	I	-4485	-0.0182	P		NHAO
1169.05150(7)	I	-4485	-0.01686	V		Ohkura
1179.2057(1)	II	-4476.5	-0.0222			Fujii
1183.9947(2)	II	-4472.5	-0.0143		Yes (tinny)	Fujii
1186.98036(4)	I	-4470	-0.01676	P:		Akazawa
1195.9479(1)	II	-4462.5	-0.0136			Fujii
1469.06145(7)	I	-4234	-0.01474	Sb:		NHAO
1482.2022(1)	I	-4223	-0.0217	V:		NHAO
1482.20622(6)	I	-4223	-0.01772	V:		Akazawa
1495.9525(2)	II	-4211.5	-0.0168			Fujii
1512.08831(7)	I	-4198	-0.01689	P		NHAO
1794.16848(5)	I	-3962	-0.01579	Sb		NHAO
2137.20653(5)	I	-3675	-0.01458	P		Fujii
2271.07789(3)	I	-3563	-0.01126	P	Yes (tinny)	NHAO
5913.01557(3)	I	-516	-0.00127	P		Fujii
7276.2028(3)	II	+624.5	+0.0030		Yes (tinny)	Akazawa
7279.1960(1)	I	+627	+0.0081			Akazawa
7283.97567(5)	I	+631	+0.00672	P		Akazawa
7387.96376(8)	I	+718	+0.00804	P:		Ito
7396.9245(1)	II	+725.5	+0.0044		Yes	Ito
7425.0159(1)	I	+749	+0.0074	P:	Yes:	Ito
7426.2121(1)	I	+750	+0.0084	P		Ito
7696.33959(7)	I	+976	+0.00929	P		Akazawa

a: The E and $O-C$ values are calculated from the ephemeris (1)
b: P: partial, V: V-shape, F: flat bottom, Sb: smoothly brightening, Null: uncertain
c: NHAO: Nishi-Harima Astronomical Observatory (Main observer was S. Narusawa)

Table 3: Utilized times of minima obtained by Nakamura et al. (1991b)

Min I (HJD) (+2440000)
7507.9864
7809.1875
7856.9968
8174.9307
8201.2257
8211.9832
8219.1546

Table 4: Utilized times of minima obtained by O01

Min I (HJD) (+2450000)	Filter
722.0242	Rc
728.001	Rc
747.1252	V
747.1247	B
747.1258	Rc
754.2947	V
754.2957	B
759.0770	B
759.0765	Rc
759.0764	V
759.0761	B
771.0289	Rc
771.0300	V
771.0284	B
777.0077	V
777.0065	B
777.0070	V
777.0071	B
808.0829	V
808.0828	B
808.0831	V
808.0832	B
808.0825	U
808.0833	I
814.0593	I
826.0125	V
826.0123	B

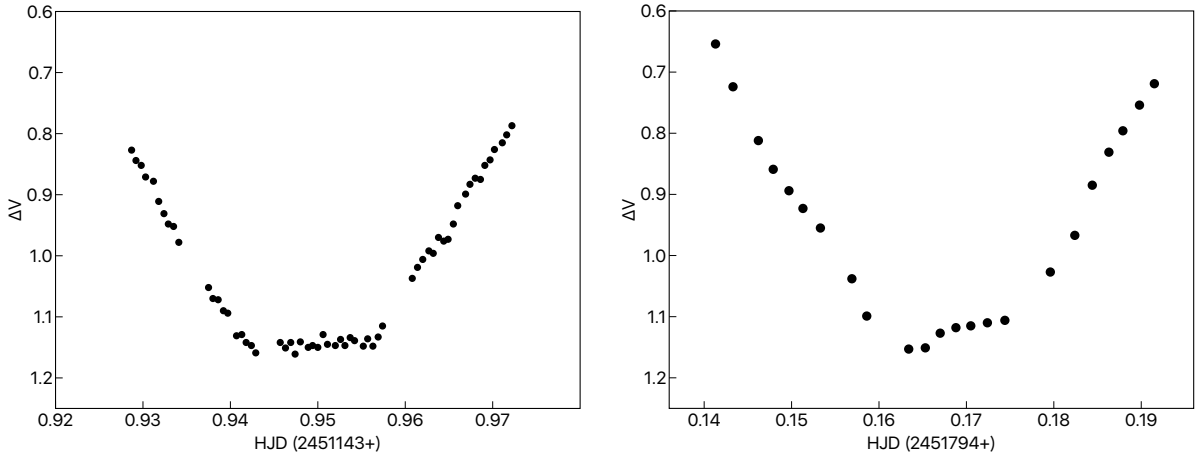

Figure 1: Light curve at a primary minimum in V. Left panel: F-tye (observed by Ohkura). Right panel: Sb-tyep (observed at NHAO).

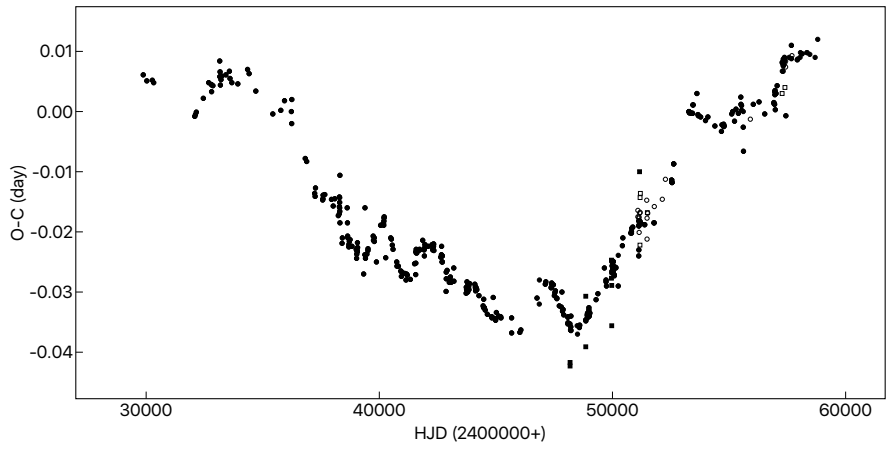

Figure 2: O-C diagram of RZ Cas. The circles and squares display the data determined by the Min I and the Min II respectively. The open symbols are the data from this study, and the filled ones are those from the *the (B-R)-Generator für die Lichtenknecker-Database of the BAV* and *O-C gateway of Brno Regional Network of Observers (B.R.N.O.)* of the Czech Astronomical Society (based on photoelectric and CCD observations). Nakamura et al. (1991b)'s and O01's data is also used.

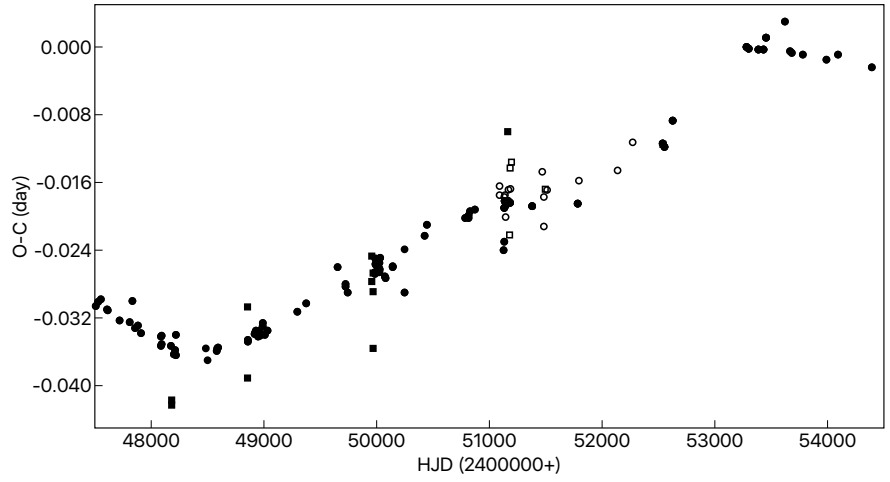

Figure 3: Same as Fig. 2, but the period being from HJD 2447500 (1988) to HJD 2454500 (2008).

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