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S1280 and S1284: Two Oscillating Blue Stragglers in the Open Cluster M67

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Abstract We present results of a time-series CCD photometry of two blue stragglers in the open cluster M67 that are also oscillating variables, S1280 and S1284. The observations obtained on 11 nights confirmed the δ Scuti-like variability of the two stars. Four and five main pulsating frequencies are detected for S1280 and S1284, respectively, through a power spectral analysis. A preliminary mode identification indicates that the two stars are both in radial oscillation. Based on the nature of oscillation, the physical parameters of the two stars are determined, and their evolutionary status discussed.

Key words: blue straggler — open cluster: individual (M67) — stars: oscillation — stars: individual (S1280, S1284)

1 INTRODUCTION

Blue stragglers, i.e., stars brighter and bluer than the turn-off of their stellar population, play an important role in understanding the structure and evolution of stars as well as the dynamic evolution of the host star clusters. In the past two decades, radial velocity and time-series photometric surveys on these objects have begun to provide strong clues to the mechanisms that form blue stragglers. Mass transfer in binaries and dynamical interactions between binaries is now regarded as the two leading mechanisms (Leonard 1996), although the formation of blue stragglers still remains an undecided issue. A final conclusion has to rely on a thorough understanding of the properties and physical nature of the blue stragglers. This calls for a systematic investigation of blue stragglers, especially of variable blue stragglers and related variable stars in star clusters.

M67 is a well-studied open cluster with an age similar to the Sun (Janes & Phelps 1994). It is noted for its richness in W UMa type binaries and other types of variable stars. The H-R diagram of M67 shows the presence of some 30 blue stragglers (Deng et al. 1999; Xin & Deng 2005). Among these, many are found to be photometric variables and/or spectroscopic binaries (Mathieu et al. 1990; Gilliland et al. 1991; van den Berg et al. 2002; Stassun et al. 2002; Sandquist & Shetrone 2003). The large sample of variable blue stragglers extensively observed in M67 provides an opportunity of examining the structure and evolution of blue stragglers.

S1280 (designation from Sanders 1977, = EW Cnc) and S1284 (= EX Cnc) are two blue stragglers in M67. They are both certain members of the cluster consistently identified by the proper-motion studies (Sanders 1977; Girard et al. 1989; Zhao et al. 1993). The δ Scuti-like variability of the two stars was discovered by Gilliland et al. (1991) through a time-series CCD photometric survey. Based on their data set, Gilliland et al. (1991) made a brief power spectral analysis which indicated multi-periodic oscillation behavior in both stars. However, details of the properties and physical nature of these two variable blue stragglers are still unknown. Very recently, Sandquist & Shetrone (2003) stated that they have detected variability in these two blue stragglers as a by-product of their monitor of an eclipsing blue straggler S1082, but they did not provide any more information on S1280 and S1284.

In the 2003/04 observation season, we carried out a long-term time-series CCD photometry on variable stars in the open cluster M67 (Zhang et al. 2005). S1280 and S1284 were two of the monitored objects. During these observations, a large number of measurements for the two variables have been collected. We present here the observations and a complete data analysis of the two variable blue straggler stars.

2 OBSERVATIONS AND DATA REDUCTION

The observations were carried out at the Xinglong Station of NAOC from 2003 December 21 to 2004 January 4. The data were collected using the 85 cm Reflector with an AP7P 512×512 CCD camera. The CCD photometer provides a field of view of about $6' \times 6'$, corresponding to a image scale of about $0.7''$/pixel. A single Johnson V filter was used. The exposure time was 90 seconds for each measurement. Useful data were recorded on 11 nights, amounting to a total of about 80 hours of monitoring. A total number of about 2500 CCD frames were obtained. Details of the observations are given in Table 1.

Table 1 Journal of the Time-series CCD Photometry of S1280 and S1284

Date (UT)	HJD(2,450,000)	Telescope	Filter	$N_{\rm obs}$
2003 Dec. 21	2995.033–2995.422	85 cm	V	184
2003 Dec. 22	2996.181–2996.422	85 cm	V	207
2003 Dec. 23	2997.185–2997.411	85 cm	V	160
2003 Dec. 27	3001.112–3001.425	85 cm	V	260
2003 Dec. 28	3002.175–3002.290	85 cm	V	99
2003 Dec. 30	3004.083–3004.425	85 cm	V	285
2003 Dec. 31	3005.074–3005.421	85 cm	V	293
2004 Jan. 01	3006.076–3006.421	85 cm	V	281
2004 Jan. 02	3007.082–3007.421	85 cm	V	265
2004 Jan. 03	3008.094–3008.422	85 cm	V	250
2004 Jan. 04	3009.169–3009.422	85 cm	V	220

A preliminary processing of the CCD frames was performed with the standard routines in the IRAF/CCDPROC package. Photometry was extracted using the DAOPHOT package (Stetson 1987, 1996).

For the purpose of differential photometry, we first chose a number of brighter stars which were observed under good seeing in all the CCD frames as reference candidates. From these, five stars were finally chosen to be our comparison stars. The differential magnitudes between two comparisons usually show a typical accuracy (standard deviation) of about 0.005 mag. The basic data for the comparison stars are listed in Table 2. To improve the photometric precision, all

Table 2 Comparison Stars used for the CCD Photometry

Star	α (2000)	δ (2000)	V	$B-V$
S1072	08:51:21.79	+11:52:38.1	11.315	0.61
S1084	08:51:26.21	+11:53:52.1	10.49	1.08
S1040	08:51:23.80	+11:49:49.5	11.520	0.87
S1279	08:51:29.02	+11:50:33.3	10.54	1.11
S1066	08:51:27.05	+11:51:52.8	10.990	0.11

these five stars were used and combined into one subjective comparison. The magnitude differences of the variables were calculated as: $\Delta m = V - C_s$, and $C_s = -2.5\log(\sum_{i=1}^{N} 10^{-0.4C_i}/N)$. Atmospheric extinction was ignored because of the proximity of the program stars. In this way, all the photometric measurements of S1280 and S1284 were extracted. The time of each measurement was converted to Heliocentric Julian time.

3 FREQUENCY ANALYSIS

The light curves of S1280 and S1284 are displayed respectively in Figures 1 and 2. Both curves show obvious oscillations with the peak-to-peak amplitudes varying by more than 0.02 mag. The main pulsating periods for both two variables are within several hours, and multi-period pulsating behavior is clearly shown. Our observations confirmed the δ Scuti-like oscillation of S1280 and S1284 as discovered by Gilliland et al. (1991).

To investigate the nature of oscillation of the two variables, we merged all the data measured for each object, and carried out a frequency analysis using the program Period98 (Breger 1990; Sperl 1998). Following Breger et al. (1994), we selected only those peaks with amplitude signal-to-noise (S/N) larger than 4.0 in the further discussion. The noise levels at each frequency were computed using the residuals between the original data and all the trial frequencies prewhitened. In Figure 3, we present the spectral window as well as the step-by-step amplitude spectra conducted for S1280. Those for S1284 are shown in Figure 4. Table 3 gives the main results of frequency analysis for the two stars. Based on these results, fittings to the observed light curves were made as shown in Figures 1 and 2.

Table 3 Results of the Frequency Analysis for S1280 and S1284

	Frequency (c/d)	Frequency (μHz)	Amplitude (mmag.)	Phase	S/N	mode
S1280						
f_1	18.8362	218.0	2.68	0.819142	7.49	F
f_2	20.1910	233.7	2.23	0.002274	5.76	
f_3	31.4476	364.0	1.70	0.623516	5.60	2H
f_4	28.8326	333.7	1.39	0.059623	4.21	
S1284						
f_1	19.6808	227.8	2.46	0.044656	5.29	$3H^+$
f_2	16.7529	193.9	2.88	0.909596	6.38	2H
f_3	19.6055	226.9	2.72	0.244616	5.62	3H
f_4	16.1954	187.5	1.84	0.463026	4.37	
f_5	21.7324	251.5	2.00	0.206048	4.08	4H

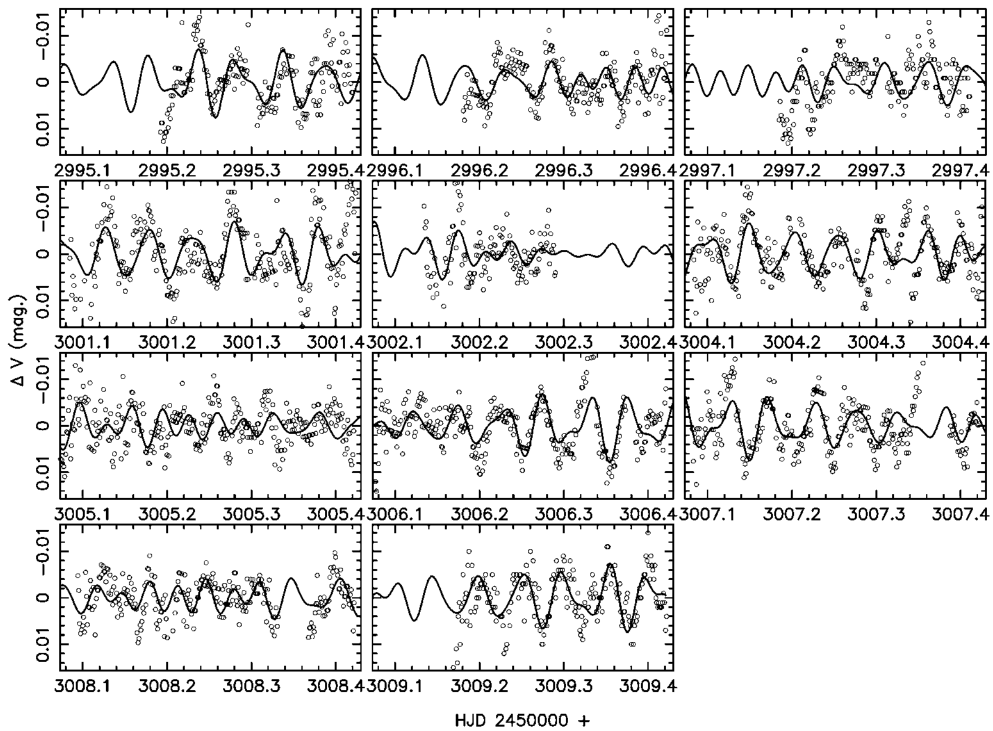

Fig. 1 Observed V-band light curves of S1280 together with the fittings (solid line) with all derived frequencies as given in Table 2.

The Fourier analysis of all the data for S1280 yields four main peaks at 218.0, 233.7, 333.7 and 364.0 μHz, all with S/N larger than 4.0. The results are in broad agreement with the observations previously given by Gilliland et al. (1991). The Fourier spectrum seems to be dominated by two frequencies at 218 and 234 μHz, which have been derived in both of the two observations. In the new data, two frequencies (f_3 and f_4) appear. We did not find the other probable pulsating modes mentioned by Gilliland et al. (1991).

For S1284, we obtained five main pulsating frequencies. The Fourier spectrum is quite different from that of Gilliland et al. (1991). In the new data, all the pulsating peaks are located in the range 187 to 252 μHz, and there are no peaks in a lower frequency range. The dominant pulsating mode appears at 227.8 μHz, which was detected in both of the two observations. Among the five frequencies obtained in the new data, f_1 and f_3, separated by 0.9 μHz, can very well be two components of a triplet, though the third component is absent. If this is the case, it could be interpreted as a split by rotation. For $\delta f = 0.9\,\mu$Hz, a straightforward derivation of the rotation period of the star is given as $P_{\rm orb} = \frac{1}{2\delta f} = 6.4\,$d (Pfeiffer et al. 1996).

4 INTERPRETATIONS

As certain members of the most extensively observed open cluster M67, the basic data of the two stars as well as the host cluster have been well defined. Table 4 lists the main data of the two stars, including the V magnitude, the distance modulus and the broad and narrow band

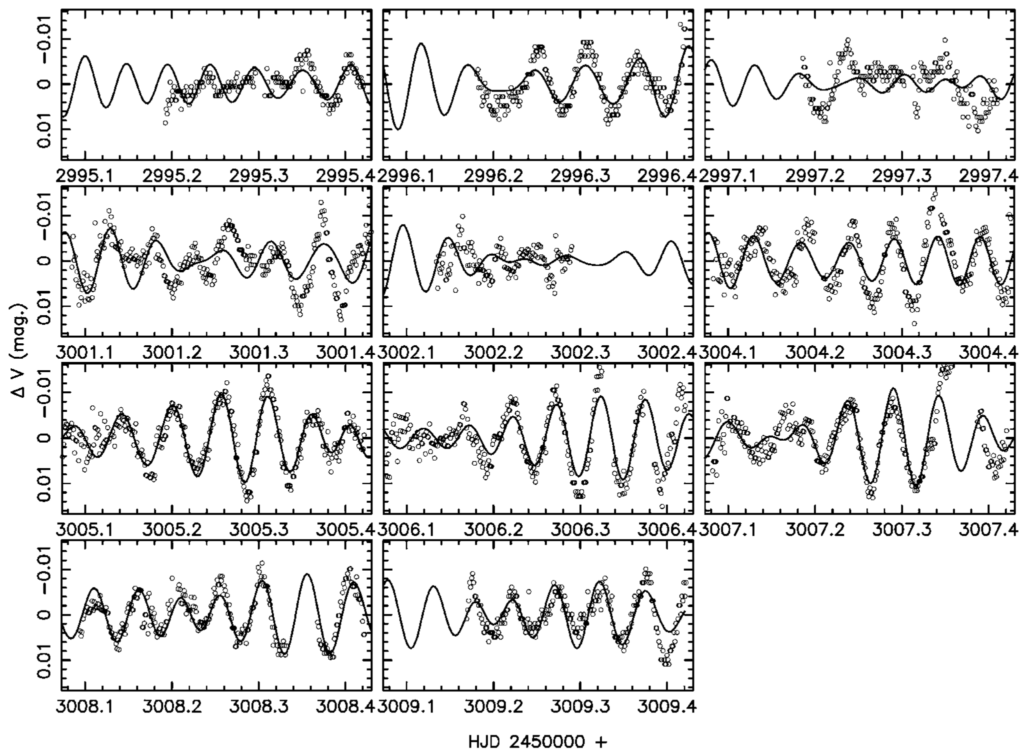

Fig. 2 Same as Figure 1, but for S1284.

color indices, etc. With these values, we can estimate the physical parameters, and hence begin to understand the nature of oscillation of the two blue stragglers.

The color indices of $(B-V)_0$ and $(b-y)_0$ of S1280 both suggest an effective temperature of about 7700±100 K according to the $T_{\rm eff}$ vs. B-V and b-y calibration of Cox (2000). This result also agrees well with the estimation by using the β value through the calibration from Moon & Dworetsky (1985). Adopting a BC=–0.14, the bolometric magnitude, luminosity and radius of the star were further estimated as: $M_{\rm bol} = 2.40 \pm 0.07$, $\log(L/L_\odot) = 0.94 \pm 0.03$ and $R = 1.65 \pm 0.02 R_\odot$. In the same way, the values for S1284 are estimated to be $T_{\rm eff} = 8100 \pm 100$ K, $M_{\rm bol} = 1.10 \pm 0.06$, $\log(L/L_\odot) = 1.46 \pm 0.03$ and $R = 2.66 \pm 0.07\, R_\odot$, respectively, for an assigned BC=–0.12.

Fitch (1981) has published a set of eigenfrequencies calculated for different models relevant to δ Scuti stars. For the adopted values for S1280, Fitch's models predicts an F-mode oscillation period of about 0.05 days, which is very close to the derived frequency of 218 μHz ($P = 0.0531$ days). It suggests that f_1 is very probably a fundamental mode. Under this assumption, we further calculated the eigenfrequencies in different modes and compared with the derived frequencies. Radial oscillation is indicated, and three of the detected frequencies, f_1, f_3, and f_4, can be identified as F, 2H and 1H modes, respectively.

For S1284, the values of $\log T_{\rm eff}$ and $\log(L/L_\odot)$ predict an F-mode frequency always larger than 0.1 days. This means that we have not detected the fundamental frequency of the star. Comparing our Fourier spectrum with the results of Fitch's models in detail, we find that the 194 μHz feature is in excellent agreement with a 2H-mode. However, the 227 μHz and 251 μHz

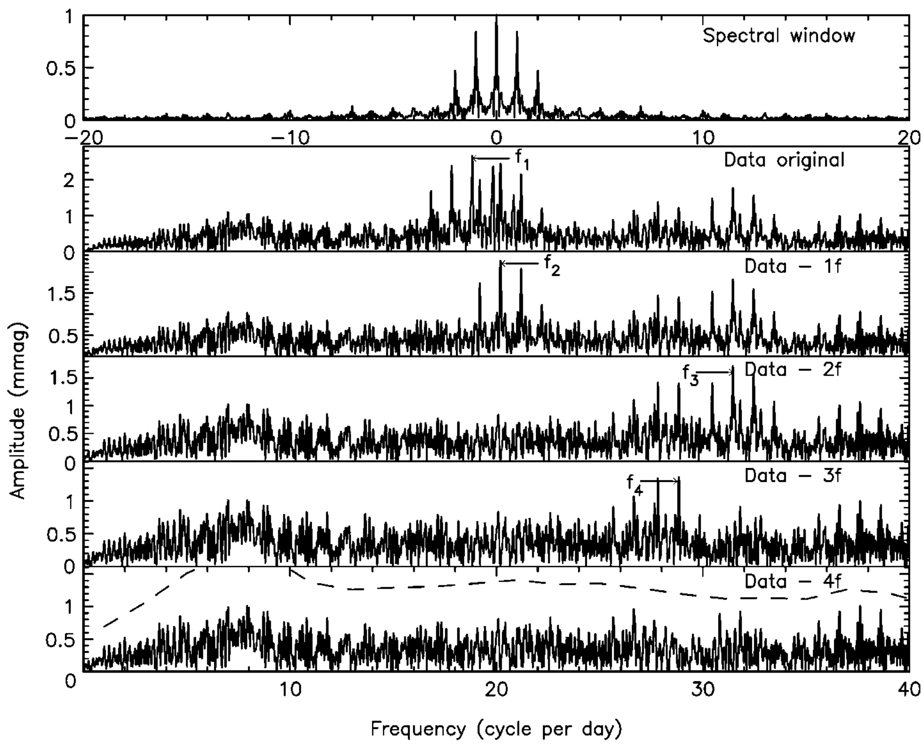

Fig. 3 Spectral window and amplitude spectra of S1280. The dashed line in the last panel represents the significance curve of the residuals with S/N=4.

Table 4 Basic Astrophysical Data for S1280 and S1284

Parameter	S1280	S1284	Reference
m_V	12.257±0.016	10.940±0.008	Montgomery et al. (1993)
$B-V$	0.260±0.024	0.220±0.018	Montgomery et al. (1993)
$E(B-V)$	0.04±0.01	0.04±0.01	Sandquist (2004)
$(m-M)_V$	9.72±0.05	9.72±0.05	Sandquist (2004)
$b-y$	0.162±0.008	0.155±0.007	Nissen et al. (1987)
$E(b-y)$	0.034±0.004	0.041±0.004	Nissen et al. (1987)
m_1	0.190±0.006	0.193±0.007	Nissen et al. (1987)
c_1	0.843±0.011	0.950±0.010	Nissen et al. (1987)
β	2.814±0.010	2.819±0.010	Nissen et al. (1987)

could certainly be identified as a 3H and a 4H-mode, respectively. This star is also in radial oscillation. The fundamental oscillation frequency of this star can be predicted to be nearly 117 μHz. This awaits further examination by future observations.

Based on the results of mode identification, it is possible for us to determine further the masses of the two stars. Applying the formula $Q = P(\rho/\rho_\odot)^{1/2}$, and taking the radii derived above, the mass of S1280 is calculated to be 1.63±0.10 $M_\odot$, that for S1284 is computed to be 2.15±0.15 $M_\odot$.

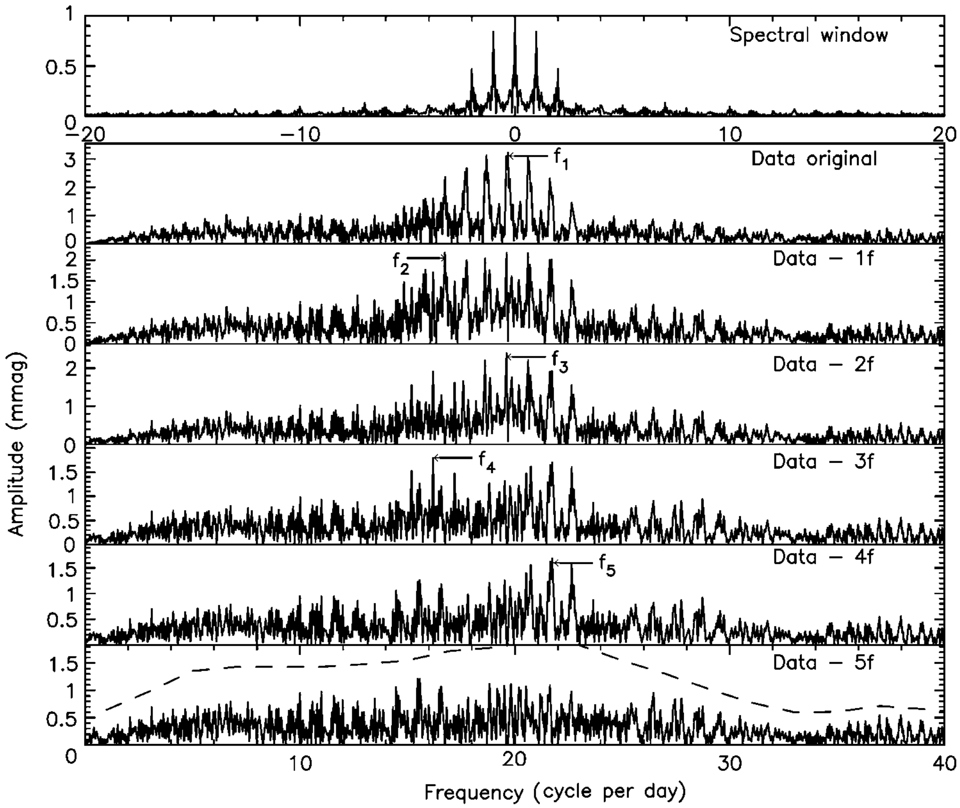

Fig. 4 Same as Figure 3, but for S1284.

5 DISCUSSION AND CONCLUSIONS

We have presented some high precision CCD photometry of two variable blue stragglers, S1280 and S1284, in the open cluster M67. The new observations confirmed the δ Scuti-like variability in the two stars. A Fourier analysis was applied for multi-periodicity. As a result four main frequencies with amplitude S/N higher than 4.0 were detected for S1280, and five for S1284. A preliminary mode identification reveals that the two stars seem to be both in radial oscillation. Two detected frequencies in S1280, $f_1 = 218.0\,\mu$Hz and $f_3 = 364.0\,\mu$Hz , could be fairly identified as the fundamental and the 2H modes. For S1284, we did not detect any F-mode frequency from the data. However, three of the determined frequencies at $f_2 = 193.9\,\mu$Hz, $f_3 = 226.9\,\mu$Hz and $f_5 = 251.5\,\mu$Hz can be excellently interpreted as those of the 2H, 3H and 4H modes, respectively.

Based on the results of frequency analysis, and adopting the basic data determined by other authors, we have further deduced the physical parameters of the two stars. The values of effective temperature, mass, radius and luminosity computed for S1280 agree well with those of an un-evolved late A type star. It suggests that S1280 could be identified as a typical δ Scuti variable. Meanwhile, The mass derived for S1280 is about $0.4\,M_{\odot}$ larger than that of a turn-off star (at about $1.25\,M_{\odot}$). This result in turn matches well the position of this blue straggler in the color-magnitude diagram (CMD).

For S1284, the situation seems to be somewhat complicated. S1284 (also known as F190, designation from Fagerholm 1906) has been proved to be a spectroscopic binary (Milone & Latham 1992). With a period of 4.18284 days, it is one of the closest binaries among the blue stragglers in M67. However, it possess a significant eccentric orbit with e=0.205, which is hard to understand. This blue straggler is suggested to be formed through stable mass transfer from an initially more massive companion but which is now a white dwarf remnant (Rappaport et al. 1995). Based on high precision radial velocity measurements, Milone & Latham (1992) obtained a spectroscopic orbital solution for the system. They estimated further a mass of 2.0 to 2.2 $M_\odot$ for the dominant component. This value is quite close to that derived in the present work. In our results, the values of mass and temperature derived for S1284 match well with those of an A5 star, but the radius and luminosity are obviously larger than those of a normal star of the spectral type. It suggests that this star could be relatively evolved. The high estimates of the luminosity (and hence of the radius) can also partly caused by contribution in brightness by the secondary component, for what it is worth.

In addition, we have detected a probable frequency split from the power spectral analysis, which yields a rotation period of about 6.4 days for the star. This value is comparable to, though significantly larger than, the orbital period. This is understandable considering the high eccentricity of the orbital. However, being limited by the time span of the data, the derived rotation period can be very uncertain.

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