RAA 2017 Vol. **17** No. **7**, 69 (10pp) doi: 10.1088/1674–4527/17/7/69

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Research in Astronomy and Astrophysics

V2551 Cyg: a pulsating star with enigmatic peculiarities

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Received 2017 January 16; accepted 2017 March 23

Abstract Intensive photometric and spectral observations of the variable star V2551 Cyg are presented. The light curve shape reveals that the target is a pulsating star, contrary to its previous classification as an eclipsing binary. The period and amplitude of the light curve, the amplitudes of color changes and the radial velocity curve of V2551 Cyg are similar to those of a high-amplitude δ Scuti variable. The target seems to pulsate with the fundamental mode. However, V2551 Cyg exhibits several important peculiarities: (i) the decreasing branch of its light curve is steeper than the increasing one; (ii) the radial velocity curve has a flat section in the phase range 0.7–1.2 and short increase of the negative radial velocity at phase 0.7; (iii) the rotational velocity is quite big for a HADS star; (iv) the Fourier coefficients of V2551 Cyg are quite different from those of HADS stars. The target classification is difficult due to these peculiarities.

Key words: stars: variables: delta Scuti — stars: variables: RR Lyrae — stars: individual (V2551 Cyg)

1 INTRODUCTION

The classification of variable stars is based on the shapes, periods and amplitudes of their light curves. Sometimes it is difficult to classify whether a star is a pulsator or an EW binary (Petersen 1973). Thus, some pulsating stars have been initially classified as EW binaries (like our target) and vice versa (Bramich et al. 2014).

There is a variety of types of pulsating stars differing by periods, amplitudes, global parameters and mechanisms of pulsation. But sometimes, it is difficult to determine the subtype of pulsators. For instance, properties shown by high-amplitude ($\geq$0.1 mag) δ Scuti stars (HADS) partially overlap those of RRc stars (Breger 1979; Meylan & Burki 1986). Most HADS stars show radial single or double pulsation modes (Khokhuntod et al. 2007), while RRc stars pulsate in the first overtone radial mode (Moskalik et al. 2015). HADS stars are rare: only about 0.3% of the total population of Galactic δ Sct stars belong to this subtype (Lee et al. 2008). The mechanism leading to their high-amplitude form of pulsation is unknown (Pietrukowicz et al. 2013).

The main significance of pulsating stars has traditionally been connected with their role as standard candles for distances (based on the period-luminosity relationship) while their main role for modern astrophysicists is that they serve as probes for internal stellar structure. That is why pulsating stars are targets of many large ground-based observing programs such as MACHO, ASAS, OGLE, SWASP, NSVS and CRTS, as well as space missions, including *Kepler* (Uytterhoeven et al. 2011). As a result, there is a large number of photometric studies on pulsating stars. By contrast, detailed spectral investigations of these variables are quite rare, although they may be used as constraints on pulsation theories.

In this paper we present photometric and spectral observations of the variable star V2551 Cyg (AC 1647107, GSC 03950–00275). It has been classified as an EW binary with a period of 0.242324 d and a magnitude range 10.75–11.00 R1 (Otero et al. 2004; Kazarovets et al. 2013).

Our first photometric data of V2551 Cyg are from 2014 when it accidentally fell in the field of view (FoV) of another faint target star GSC 03950-00707. Some images of V2551 Cyg during these observations were saturated but subsequently we noted the strange shape of its light curve with sharper maxima than minima and almost identical halves of the cycle with a period of 0.24 days. We suspected that the target is a pulsating star and undertook intensive spectral and photometric observations.

2 OBSERVATIONS

2.1 Photometry

CCD photometric observations of V2551 Cyg were carried out in Sloan g', i' and Johnson-Cousins *B, V, Ic* bands with the 30-cm Ritchey-Chrétien Astrograph located in the IRIDA South Dome (ISD) at the Rozhen Observatory (Bulgaria) using an ATIK 4000M CCD camera (2048×2048 pixels, 7.4 μm/pixel, FoV $35' \times 35'$) in the seasons 2015 and 2016. Additional observations in *V* and *Ic* bands were obtained in 2016 at the Tigh Speuran Observatory (TSO, USA) using a 0.317-m f/8 Hyperion telescope, equipped with an SBIG STL-6303E CCD camera (3072 × 2048 pixels, 9 μm/pixel).

Information on our photometric observations is presented in Table 1.

The photometric data were reduced by AIP4WIN2.0 (Berry & Burnell 2005). Twilight flat fields were obtained for each filter, and dark and bias frames were also taken throughout the run. The frames were combined respectively into single master bias, dark and flat frames. The standard procedure was used for reduction of the photometric data (de-biasing, dark frame subtraction and flat-fielding).

We performed aperture ensemble photometry with the AAVSO's VPHOT software using seven comparison stars in the observed field. The angular separations between the comparison stars and our target are within 10 arcmin and this proximity reduces the effects of differential atmospheric extinction.

Table 2 presents the coordinates of the comparison stars from the UCAC4 catalog (Zacharias et al. 2013) and their magnitudes from the APASS DR9 catalog (Henden 2016) and TASS Mark IV patches photometric catalog, version 2 (Droege et al. 2007). The values in parentheses correspond to the standard deviation of the comparison stars during observational nights.

Ensemble photometry does not allow direct transformation of the instrumental magnitudes to standard ones. This should be made manually using colors of the ensemble comparison star. The IRIDA and TSO transformation coefficients led to corrections of V2551 Cyg instrumental magnitudes of 0.0013 in g', 0.0388 in i', 0.0118 in *B*, 0.006 (-0.0119) in V and 0.0147 (-0.0075) in *Ic* (the values in parentheses are for TSO). In fact, the photometric data in Figures 1 and 2 correspond to instrumental magnitudes but the mentioned corrections were taken into account for determination of target temperature (see Section 3).

The periodogram analysis of the photometric data was made by the software *Period04* (Lenz & Breger 2004). The result is shown in Figure 3. The periods, determined on the basis of data in Johnson-Cousins bands (numerous and spanning a year), are identical (Table 3) and lead to the ephemeris

$$\mathrm{JD} = 2457266.687002 + 0.121158 \times E. \tag{1}$$

The Sloan data were excluded from this calculation because they covered only two consecutive nights.

The new period (0.121158 d) is about one-half of the previous one (0.242324 d). We phased all photometric data with the new period and the corresponding folded curves are shown in Figure 4.

Nonsinusoidal variations of V2551 Cyg implied the presence of second (or higher order) Fourier harmonics. We found contributions of the frequencies f_1, $2f_1$ and $3f_1$ (Table 4) in the V light curve. Their values turned out to be equal for all filters within 0.1%. The Fourier parameters of these three harmonics led to good fit of the observed light curve (Fig. 5). They correspond to amplitude ratios of $R_{21} = A_2/A_1$ = 0.175, $R_{31} = A_3/A_1$ = 0.074 and $R_{32} = A_3/A_2$ = 0.421. To determine the phase differences of V2551 Cyg, we had to make a transformation $\varphi_i = \phi_i - \pi/2$ (ϕ_i are *Period04* values of phases in Table 4) because the standard formula for Fourier decomposition contains the sum of cosines while that of *Period04* is the sum of sines. Thus we calculated $\varphi_{21} = \varphi_2 - 2\varphi_1$ = 2.11 and $\varphi_{31} = \varphi_3 - 3\varphi_1$ = 3.61.

The comparison of Fourier coefficients of V2551 Cyg with those of HADS stars (at P = 0.12 d) from numerous samples (Table 5) revealed considerable differences.

2.2 Spectroscopy

The spectral observations were carried out during two summer nights in 2014 and 2015 (Table 6) with the 2-m RCC telescope of the National Astronomical

Table 1 Log of Photometric Observations

Date	Obs	Filter	Exposure [s]	Number	Error [mag]
2015 Aug 29	ISD	g'	15	256	0.003
2015 Aug 29	ISD	i'	40	255	0.003
2015 Aug 30	ISD	g'	15	205	0.003
2015 Aug 30	ISD	i'	40	200	0.004
2015 Aug 31	ISD	B	40	93	0.003
2015 Aug 31	ISD	V	15	95	0.003
2015 Aug 31	ISD	Ic	40	75	0.004
2015 Sep 1	ISD	B	40	125	0.003
2015 Sep 1	ISD	V	15	86	0.003
2015 Sep 1	ISD	Ic	40	102	0.004
2015 Sep 2	ISD	B	40	126	0.003
2015 Sep 2	ISD	V	15	127	0.003
2015 Sep 2	ISD	Ic	40	120	0.004
2016 Jun 19	TSO	V	45	167	0.003
2016 Jun 20	TSO	V	45	210	0.003
2016 Jun 24	ISD	B	40	47	0.005
2016 Jun 24	ISD	V	15	47	0.005
2016 Jun 24	ISD	Ic	40	41	0.006
2016 Jun 26	TSO	V	30	83	0.003
2016 Jun 26	TSO	Ic	60	84	0.003
2016 Jun 27	TSO	V	20	123	0.003
2016 Jun 27	TSO	Ic	40	120	0.003
2016 Jul 7	TSO	V	20	163	0.003
2016 Jul 7	TSO	Ic	40	162	0.003

Table 2 List of the Standard Stars

Label	Star ID	RA	Dec	B	V	Ic	g'	i'
Target	V2551 Cyg	20 35 36.52	+52 45 45.3	10.825(03)	10.442(03)	9.946(04)	10.905(03)	10.273(04)
Chk	UCAC4 714–073376	20 35 42.00	+52 44 17.22	11.895(12)	11.535(21)	11.268(25)	12.191(09)	11.535(10)
C1	UCAC4 715–073609	20 35 26.24	+52 51 47.51	13.546(35)	11.698(38)	9.952(15)	13.115(15)	10.482(09)
C2	UCAC4 714–073315	20 35 29.08	+52 46 40.80	10.568(13)	10.669(18)	9.882(13)	11.458(07)	10.406(09)
C3	UCAC4 715–073721	20 35 52.36	+52 53 58.66	11.941(16)	10.530(22)	9.326(14)	11.593(13)	9.752(07)
C4	UCAC4 715–073617	20 35 27.61	+52 50 19.62	12.936(29)	12.423(20)	11.960(39)	13.497(12)	12.338(14)
C5	UCAC4 714–073237	20 35 06.20	+52 42 21.34	12.535(24)	12.023(28)	11.813(35)	12.413(13)	11.899(12)
C6	UCAC4 714–073426	20 35 53.85	+52 40 04.62	12.196(23)	11.657(24)	11.200(20)	11.957(09)	11.393(11)
C7	UCAC4 714–073323	20 35 30.09	+52 47 17.36	12.256(26)	11.606(21)	11.273(28)	12.372(09)	11.388(11)

Table 3 Time-series Analysis of the Photometric Data

Filter	Period	T_0	Ampl
B	0.121158(4)	2457266.565143	0.348
V	0.121158(2)	2457266.687002	0.271
I	0.121158(3)	2457266.566423	0.172
g'	0.121035(4)	2457264.620234	0.343
i'	0.121035(5)	2457264.509442	0.201

Table 4 Fourier Parameters of the V Light Curve

Frequency f_i	Amplitude A_i	Phase ϕ_i
8.2536314	0.12839	0.1326
16.510546	0.02251	0.8047
24.760848	0.00947	0.8556

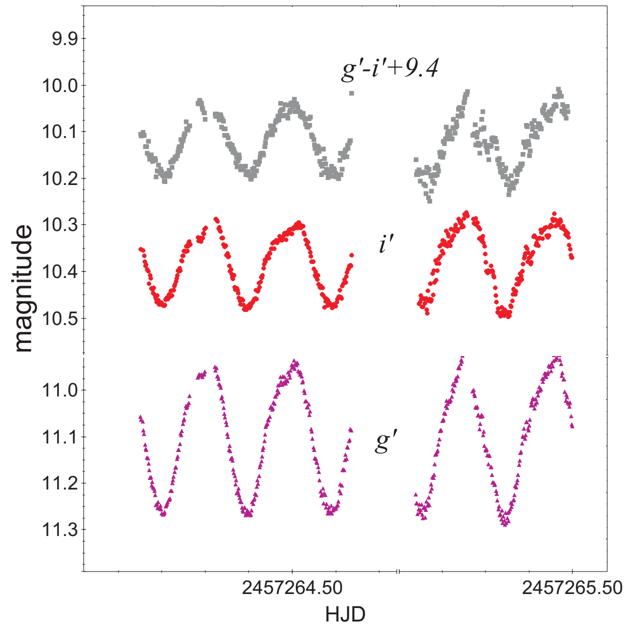

Fig. 1 g', i' and $g' - i'$ light curves of V2551 Cyg from 2015 Aug 29 and 30.

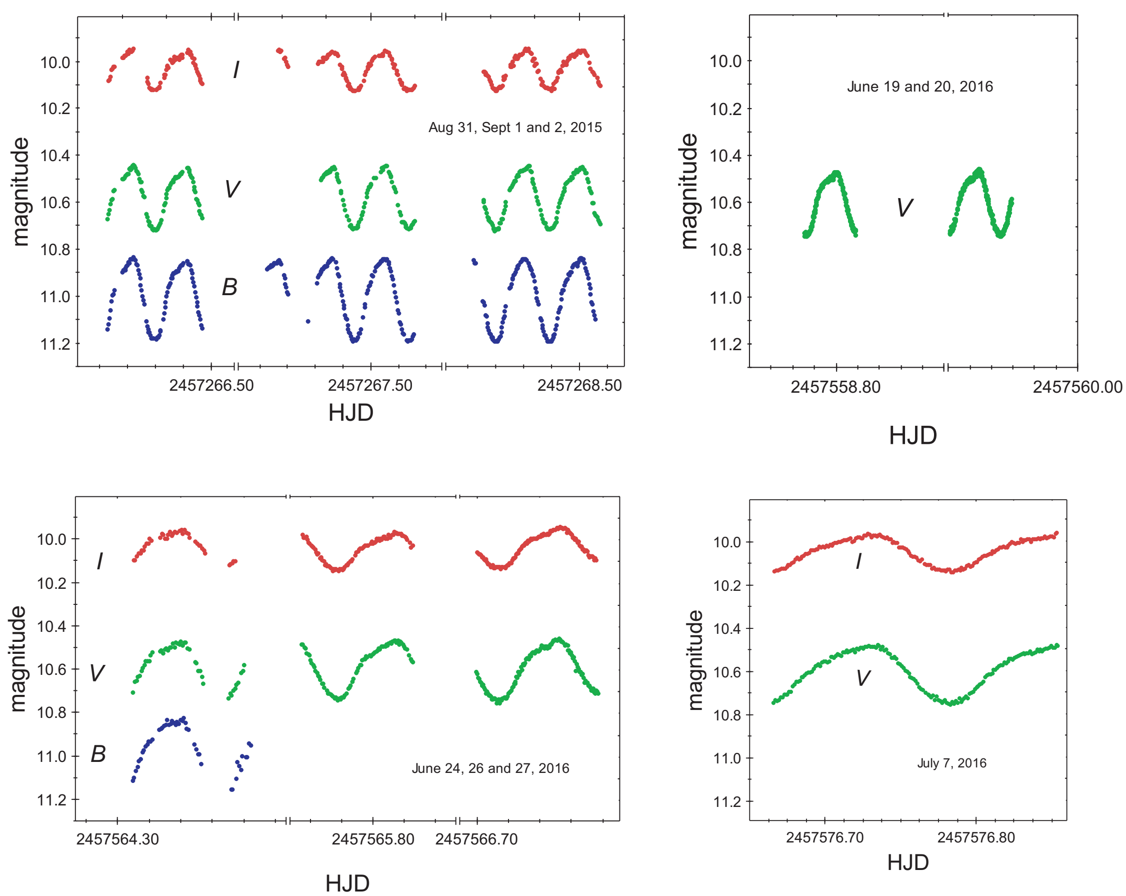

Fig. 2 *BVIc* light curves of V2551 Cyg in 2015 and 2016.

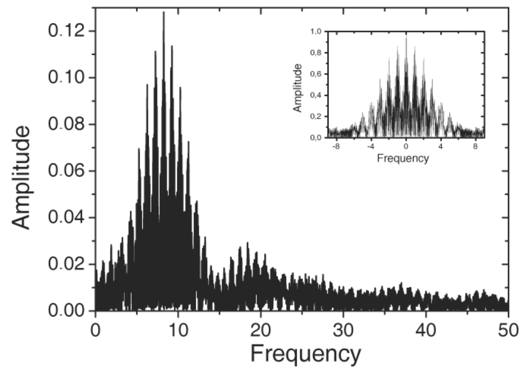

Fig. 3 Periodogram of V2551 Cyg.

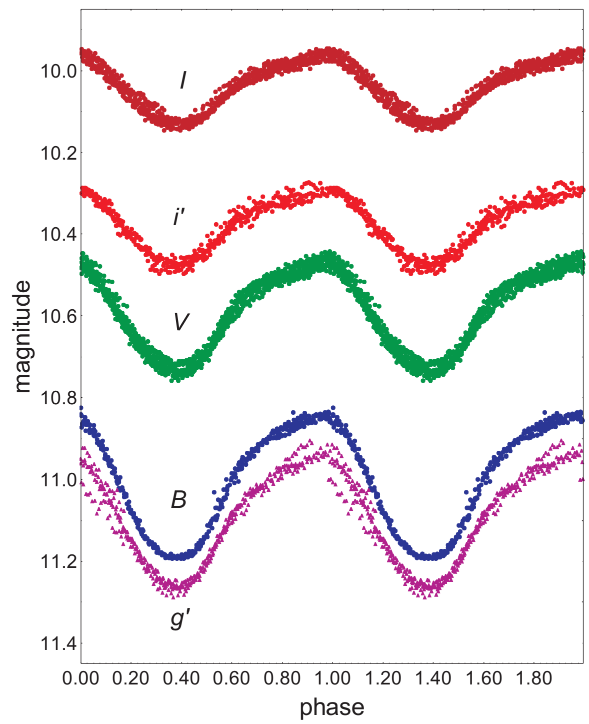

Fig. 4 Folded light curves of V2551 Cyg from 2015–2016.

Table 5 Fourier Coefficients of HADS Stars from Large Datasets

R_{21}	R_{31}	φ_{21}	φ_{31}	Objects	Reference
0.2–0.4	0.2	4	2	Galactic bulge	Alcock et al. (2000)
0.1–0.5		4–4.5	1.5–2.5	OGLE database	Poretti (2001)
0.1–0.5		3.8	1.7	LMC	Garg et al. (2010)
0.145	0.07	2.11	3.61	V2551 Cyg	this paper

Observatory at Rozhen (Bulgaria). We used a Photometrics AT200 CCD camera with an SITe SI003AB 1024×1024 pixel chip mounted on the Coudé spectrograph (grating B&L632/14.7°). All stellar integrations were alternated with Th-Ar comparison source exposures for wavelength calibration. V2551 Cyg was observed in the spectral range of 200 Å around the Hα line. The exposures were 15 min. The resolution of the spectra is 16 400 and most spectra have an S/N ratio in the range 60–90. The spectral observations from the two nights cover whole cycles of V2551 Cyg.

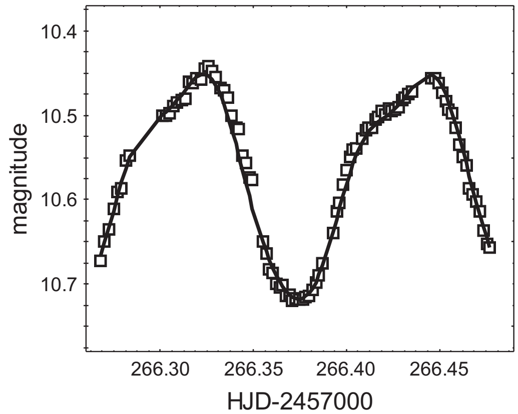

Fig. 5 Fit of V light curve by parameters from Table 4.

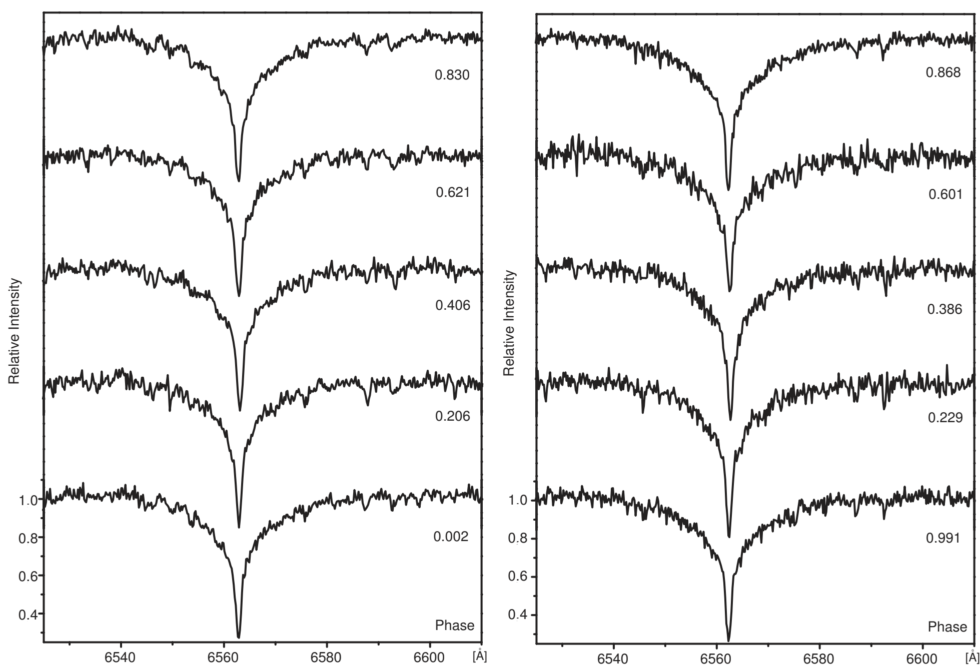

Fig. 6 *Left*: sample of spectra of V2551 Cyg from 2014; *Right*: sample of spectra of V2551 Cyg from 2015.

The reduction of the spectra included bias subtraction, flat fielding, cosmic ray removal and one-dimensional spectrum extraction. The normalized spectra were phased by ephemeris (1). Samples of them separated by around 0.2 in phase are shown in Figure 6. They exhibit a deep absorption Hα line with almost symmetric profiles. There is no splitting of the line during the cycles. This is another argument that V2551 Cyg is not a binary with two equally deep eclipses.

To measure the Doppler shifts of the Hα line, we fitted its core with a parabola (the fit with a Gaussian corresponded to equal radial velocity within the errors). The radial velocity curve of V2551 Cyg is almost mirror-symmetric with its light curve (Fig. 7).

Table 6 Log of Our Spectral Observations

Date	Number	Phase range
2014 July 9	19	0.91–1.71
2015 Aug 31	17	0.55–1.64

The full width at half maximum (FWHM) of the Hα line (Fig. 8) varies in the range 2.15–3.25 Å without a well-expressed phase trend while the FWHM of the δ Sct

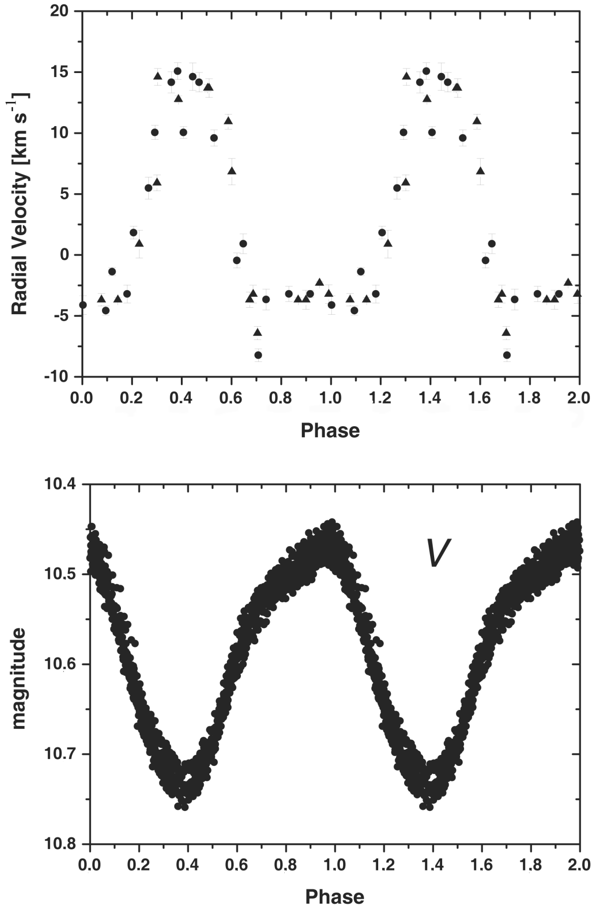

Fig. 7 *Top*: Radial velocity curve: blue circles are for 2014 data and the red triangles are for 2015 data; *Bottom*: phased V light curve.

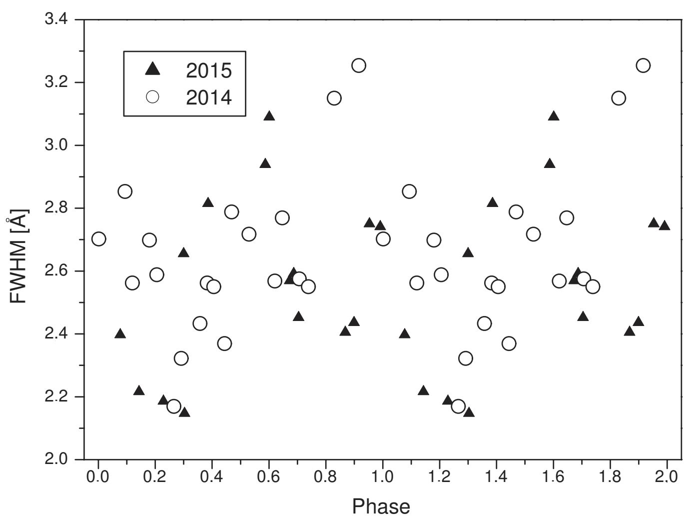

Fig. 8 Phase behavior of the FWHM of the Hα line.

star ρ Pup varies in phase with its radial velocity curve (Mathias et al. 1997).

3 ANALYSIS OF THE DATA

The asymmetric light curves of V2551 Cyg could not be reproduced by our attempted eclipse modeling with PHOEBE. Moreover, the spectral data do not exhibit splitting of spectral lines (indication of binarity).

The amplitude and phase variability of the color index of V2551 Cyg are consistent with those of a pulsating star: it becomes redder at the light minima and bluer at the light maxima (Fig. 1). The target photometric minimum coincides with its radial velocity maximum (Fig. 7), which is also typical for a pulsating star.

The period (0.12 d) and amplitudes of the light curves ($\Delta B = 0.36$ mag, $\Delta g' = 0.35$ mag, $\Delta V = 0.25$ mag, $\Delta I = 0.19$ mag, $\Delta i' = 0.18$ mag) of V2551 Cyg are consistent with those of a pulsating star of HADS type (Breger 1979). Its temperature of 7560 K (determined by the de-reddened color indices $B - V = 0.18$ mag, according to Flower 1996) is also suitable for a δ Scuti star. The parameters of both light and radial velocity variability of V2551 Cyg are very close to those of the single-period HADS star AD CMi (Abhyankar 1959, Rodríguez et al. 1988, Kilambi & Rahman 1993, Khokhuntod et al. 2007) with period 0.123 d, amplitudes $\Delta V = 0.27$ mag and $\Delta B = 0.37$ mag, and radial velocity amplitude 39 km s^{-1}.

Most characteristics of V2551 Cyg are similar to those of HADS stars. However, there are several important peculiarities associated with this target.

(1) In contrast to almost all pulsators of different subtypes whose light curves have a steeper increasing branch, that of V2551 Cyg shows opposite asymmetry. Only three HADS stars (AN Lyn, V1719 Cyg and V798 Cyg) exhibit light curves with a steeper decreasing branch (Poretti 2002). Another example is RRc variable KIC 8832417 (Moskalik et al. 2015). Hence, V2551 Cyg is a fifth exception but with a shorter period than the previous ones.

(2) There is a change of slope before the brightness maximum of V2551 Cyg (around phase 0.7, Fig. 4). Such a behavior is rather inherent to some RRc variables (Lub 1977, Stellingwerf et al. 1987, Olech et al. 2001). However, it was found also for V798 Cyg, which is of HADS type (fig. 6, Poretti 2002).

(3) The radial velocity curve of V2551 Cyg seems peculiar with its flat section in phase range 0.7–1.2. It coincides with the light maximum and radial velocity minimum. We exclude instrumental effects or data reduction artifacts as the cause for this behavior because it repeats during the two years (Fig. 7). We found a faint hint of such a behavior for some RRc stars from the sample of Govea et al. (2014), but their flat sections have considerably smaller phase duration.

(4) We also consider the feature around phase 0.7 of the radial velocity curve (short increase of the negative radial velocity) to be a real effect because it repeats during the two years (Fig. 7). Its phase coincides with the beginning of the slope change before the brightness maximum of V2551 Cyg. The pulsation cycle of the target probably passes thorough some fast radical episode around phase 0.7. The radial-velocity curve of the δ Scuti variable ρ Pup also reveals additional extrema (Dravins et al. 1977).

(5) According to McNamara (1997) and Breger (2000), low-amplitude δ Scuti stars exhibit high $V \sin i$, while HADS are slowly rotating objects ($V \sin i \leq 30$ km s^{-1}). The FWHM of the V2551 Cyg Hα line corresponds to a velocity above 90 km s^{-1}, i.e. larger value than the expected rotation velocity of a HADS star (as well as of an RR Lyr without detectable rotation, Peterson et al. 1996). However, Ripepi et al. (2014) also measured a high projected velocity of 85 km s^{-1} for the pre-main sequence δ Sct star H254.

4 GLOBAL PARAMETERS AND PULSATION MODE OF THE TARGET

The Baade-Wesselink method for determination of radii and distances of pulsating stars can be applied to Cepheid stars (Molinaro et al. 2012) whose light curves show large amplitudes (around 1 mag). Recently, it was also used for low-amplitude star H254 (Ripepi et al. 2014), which has smooth light and radial velocity curves. However, the radial velocity curve of V2551 Cyg is quite peculiar and we assume the Baade-Wesselink method is inappropriate for its analysis.

In order to approximately estimate the global parameters of V2551 Cyg and its pulsation mode, we use empirical relationships for pulsating stars.

(a) The absolute magnitude $M_{\rm V}$ was determined from an empirical period-luminosity relationship (McNamara et al. 2007) for solar type composition

$$M_{\rm V} = -1.27 - 2.9 \log P\,, \qquad (2)$$

where P is in days. For V2551 Cyg it gives $M_{\rm V} = 1.388$.

For a bolometric correction $BC = 0.032$ (according to Table 3 of Flower 1996 for $T = 7560\,\mathrm{K}$) we obtained absolute magnitude $M_{\mathrm{bol}} = 1.42\,\mathrm{mag}$. It corresponds to a luminosity of $L = 22.28\,L_{\odot}$ and radius of $R = 2.76\,R_{\odot}$.

(b) The mass M (in solar masses $M_{\odot}$) can be calculated from the relationship (Cox 2000)

$$\log M = 0.46 - 0.10 M_{\mathrm{bol}}. \quad (3)$$

We obtained a V2551 Cyg mass of 2.08 $M_{\odot}$ and corresponding mean density $\rho/\rho_{\odot}$ = 0.099.

The surface gravity of V2551 Cyg is $g/g_{\odot} = 0.273$. That yields $\log g = 3.88$.

(c) Interstellar absorption in the V2551 Cyg direction is $A_V = 3.15E(B-V) = 0.63\,\mathrm{mag}$ (*http://argonaut.skymaps.info/query*), which means the true target magnitude is $V_0 = 9.97$. Then we calculated the distance by the expression $V_0 - M_V = -5 + 5\log d$ and obtained $d = 504\,\mathrm{pc}$. The Gaia mission determined $\pi = 1.29 \pm 0.24\,\mathrm{mas}$, i.e. $d = 775 \pm 146\,\mathrm{pc}$ to V2551 Cyg. Hence, our estimate is smaller than the Gaia measurement. This difference may be due to the metal poor composition of the target.

(d) The Q value of the target

$$\begin{aligned} Q &= P\sqrt{(\rho/\rho_{\odot})} = 0.1211 \times \sqrt{0.099} \\ &= 0.0381\,\mathrm{d} \end{aligned} \quad (4)$$

is nearest to the best-known value 0.033 d (Breger 1990) for the radial fundamental mode (that of the first overtone is 0.026 d). Moreover, the parameters of V2551 Cyg are near (within 10%) those of Model 0.4 (Stellingwerf 1979) of a δ Sct star (mass 2.0 $M_{\odot}$, temperature 7400 K, $M_{\mathrm{bol}} = 1.41$, $\log g = 3.83$, composition $X = 0.7$ and $Z = 0.005$) pulsating in the fundamental mode with a period of 0.1116 d. So, our target seems to pulsate in the fundamental mode. All obtained values of physical parameters should be considered as very approximate.

5 CONCLUSIONS

We conducted an intensive study of V2551 Cyg on the basis of our photometric and spectral observations. It indicates that this target is not an eclipsing binary system, but rather a pulsating star with a newly calculated period of about one-half of the previously reported period.

The pulsation period, amplitudes of variabilities in different bands, amplitude of color change and amplitude of radial velocity variability of V2551 Cyg are appropriate for a HADS star. The target seems to pulsate with the fundamental mode.

However, V2551 Cyg exhibits several enigmatic deviations (peculiarities) from the standard behavior of HADS stars: (i) the decreasing branch of its light curve is steeper than the increasing one; (ii) the shape of the radial velocity curve exhibits a flat section in the phase range 0.7–1.2; (iii) some fast radical episode occurs at phase 0.7 of the pulsation cycle, appearing as a short increase of the negative radial velocity and slope change before the brightness maximum; (iv) its rotational velocity is quite big both for a HADS star and an RRc star; (v) the Fourier coefficients of V2551 Cyg are quite different from those of a HADS star at $P = 0.12\,\mathrm{d}$. That is why more observations are needed for the correct classification of this pulsating star.

Hence, V2551 Cyg exhibits lack of rigorous boundaries between the different types of pulsation stars (particularly between HADS and RRc types), i.e. the nature is richer than our coarse classification schemes. Moreover, our study illustrates that detailed spectral observations may lead to finding phases of the pulsation cycle with strange behavior shown by pulsating stars, requiring physical explanation.

Acknowledgements The paper is based on observations obtained at the Rozhen Observatory (Bulgaria) and the Tigh Speuran Observatory (USA). The research was supported partly by project DN 08/20 of the Fund for Scientific Research of the Bulgarian Ministry of Education and Science and project RD 08-102 of Shumen University. This publication makes use of data products from the Two Micron All Sky Survey, which is a joint project of the University of Massachusetts and the Infrared Processing and Analysis Center/California Institute of Technology, funded by the National Aeronautics and Space Administration and the National Science Foundation. This research has also made use of the SIMBAD database, operated at CDS, Strasbourg, France, NASA's Astrophysics Data System Abstract Service, the USNOFS Image and Catalogue Archive operated by the United States Naval Observatory, Flagstaff Station (*http://www.nofs.navy.mil/data/fchpix/*) and the VPHOT photometric software provided by the AAVSO, Cambridge, Massachusetts. This research has made use of the International Variable Star Index (VSX) database, operated by AAVSO, Cambridge, Massachusetts, USA. This work has made use of data from the European Space Agency (ESA) mission Gaia (*http://www.cosmos.esa.int/gaia*), processed by the Gaia Data Processing and Analysis Consortium (DPAC, *http://www.cosmos.esa.int/web/gaia/dpac/consortium*). Funding for the DPAC has been provided by national institutions, in particular the institutions participating in the Gaia Multilateral Agreement. The authors are very grateful to the anonymous referee for valuable recommendations and notes.

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