Research in Astron. Astrophys. **2012** Vol. **12** No. **6**, 671–677
http://www.raa-journal.org *http://www.iop.org/journals/raa*

***R**esearch in*
***A**stronomy and*
***A**strophysics*

V551 Aur, an oEA binary with g-mode pulsations? *

Nian Liu[1,2], Xiao-Bin Zhang[2], An-Bin Ren[1,2], Li-Cai Deng[2] and Zhi-Quan Luo[1]

[1] Institute of Theoretical Physics, China West Normal University, Nanchong 637002, China; *liunian010101@163.com*

[2] National Astronomical Observatories, Chinese Academy of Sciences, Beijing 100012, China

Received 2011 December 29; accepted 2012 February 28

Abstract We present time-series CCD photometry of V551 Aur, an eclipsing binary located in the open cluster NGC 2126 that shows δ Scuti-like pulsations. Complete covered light curves in the B and V bands were obtained with high-precision over nine nights. Based on them, a revised orbital period and the first photometric solutions were determined. Our eclipsing light-curve synthesis reveals a detached configuration for the binary system with a mass-ratio of about 0.73, and the mean density of the pulsating primary component was deduced to be about $(0.532\pm0.005)\rho_{\odot}$. A frequency analysis of the eclipse-subtracted light curve yields two reliable frequencies at f_1=7.727013(c/d) and f_2=15.45403(c/d), respectively. With the help of the derived mean density, mode identification was performed. The result suggests that the primary component of V551 Aur is very probably g-mode oscillations.

Key words: stars: binaries: eclipsing — stars: oscillations — stars: individual (V551 Aur) — open cluster: individual (NGC 2126)

1 INTRODUCTION

Eclipsing binaries with pulsating components are of particular interest for asteroseismology since the binarity of these objects could provide more independent information about the physical parameters (mass, radius, luminosity) and evolutionary status of member objects, and provide strong constraints on their possible mode identification (Zhang et al. 2009). In addition, asteroseismology can help us to understand more about the interior structure of a pulsating component and hence test the model of binary evolution. In recent years, much attention has been paid to such variables. To date, about 100 such objects have been discovered. The majority are Algol-type binaries consisting of a δ Scuti-type pulsator; they are called oEA (oscillating EA) stars (Mkrtichian et al. 2002), and there are about 44 of them in total (Soydugan et al. 2011).

V551 Aur is a new candidate of a pulsating, eclipsing binary found in the open cluster NGC 2126, though according to its proper motion, it might not be a true member of the cluster. Its complex light variability was discovered by Gáspár et al. (2003) through the first CCD photometric study of the cluster. Based only on V-band measurements, they determined an orbital period of 1.17320(3) days for the eclipsing system. The δ Scuti-like oscillations were found to be dominated by a pulsation period of about 0.13 days with an amplitude of about 0.05 mag. They have also indicated an early F spectral type for the star based on a low resolution spectrum. The eclipsing and δ

* Supported by the National Natural Science Foundation of China.

Scuti-like light variations of this star were later confirmed by Liu et al. (2009). The results suggest that V551 Aur could be a member of the oEA class of stars.

Compared with the oEA stars found by Soydugan et al. (2011) however, V551 Aur shows some different properties. It presents a very high pulsation amplitude compared to its eclipsing amplitude. In addition, it has the second longest pulsation period but a very short orbital period. The ratio of $P_{\rm pul}/P_{\rm orb} = 0.11$ is much larger than the usual value of about 0.02 derived by Soydugan et al. (2006). These facts make V551 Aur a very interesting oEA system.

We therefore choose V551 Aur as the target of our on-going program regarding the study of pulsating eclipsing binaries (Zhang et al. 2009) and performed new CCD photometry of the star during the 2011 observing season; based on which, we hope to make a comprehensive investigation of the evolutionary status of the binary system as well as the pulsating nature of the component following the method used by Zhang et al. (2009).

Details of the observations and data reduction are presented in Section 2. The first photometric solution of the binary system is given in Section 3. In Section 4 the intrinsic oscillations of the star are studied. This is followed by a short discussion and the conclusions.

2 OBSERVATIONS AND DATA REDUCTION

We observed V551 Aur during 11 nights between January 1st and January 11th in 2011. The observations were conducted with the 85 cm reflecting telescope located at the Xinglong station of the National Astronomical Observatories, Chinese Academy of Sciences (NAOC). The telescope has a 1024×1024 CCD at the main focus, and the camera covers a field of view of about 16.5 arcmin, corresponding to an image scale of 0.96 arcsec per pixel (Zhou et al. 2009). Standard B (440 nm) and V (550 nm) filters were employed. The exposure time of the B images was set between 60 and 120 s, while that for V images varied from 40 to 90 s, according to the weather conditions during the observation. Useful data were collected over nine nights. In total, we took 2080 frames of V551 Aur in the B band and 2079 frames of V551 Aur in the V band. The record of observations is presented in Table 1.

Table 1 Observations and Data Reduction

Date	V frames	B frames	Start time (UT)	Length (h)	Note
2011 Jan 1	286	286	10:46:33	11.8	Min.I
2011 Jan 3	244	244	11:30:25	10.5	Min.I
2011 Jan 4	288	288	10:36:57	11.0	—
2011 Jan 5	205	205	10:15:34	11.0	Min.II
2011 Jan 6	246	246	10:28:36	11.5	Min.II
2011 Jan 8	173	174	10:10:57	11.6	Min.I
2011 Jan 9	203	203	10:13:21	10.8	Min.I
2011 Jan 10	228	228	10:21:31	11.4	Min.I
2011 Jan 11	206	206	11:07:25	11.1	—

The preliminary CCD frame processing was performed by using the standard routines of CCDPROD in the IRAF package. All frames were bias subtracted and flat-fielded with averaged sky flats. Photometry was extracted using the DAOPHOT II package (Stetson 1987, 1996). Magnitude and color calibration was performed by using secondary standards. To do that, we first detected a number of stars present which were constant to within 0.01 mag in all frames following the method of Zhang & Zhang (2003), from which 14 with good seeing and well-determined standard B and V magnitudes were finally employed as the secondary standard stars. Using these, all the photometric measurements have been transformed into the standard system. We then transformed the observation time from UT into HJD and obtained the real-time B and V light curves of V551 Aur.

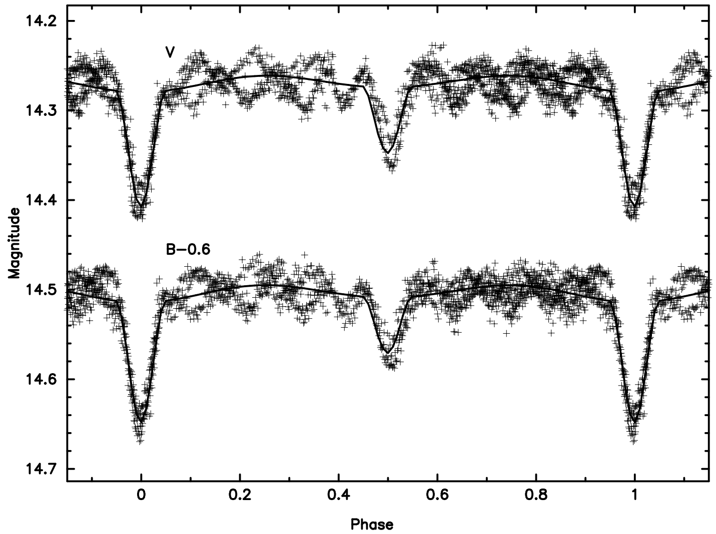

Fig. 1 Phased B- and V-band light curves of V551 Aur along with the theoretical light curves.

Table 2 Times of Light Minima of V551 Aur and the Residuals Computed from the Linear Ephemeris

HJD(2 455 560+)	Epoch	$(O-C)$ (d)
2.97033	−7.0	−0.0030
2.97279	−7.0	−0.0005
5.31560	−5.0	−0.0041
5.31542	−5.0	−0.0043
7.08582	−3.5	0.0063
7.08513	−3.5	0.0056
8.25908	−2.5	0.0064
8.25762	−2.5	0.0049
10.00936	−1.0	−0.0031
10.01037	−1.0	−0.0021
11.18334	0.0	−0.0024
11.18352	0.0	−0.0022
12.35932	1.0	0.0004
12.35703	1.0	−0.0019

3 THE ECLIPSING BINARY SYSTEM

A total of seven eclipses were recorded using our observations of V551 Aur. By using the K-W method (Kwee & van Woerden 1956), the epochs of these light minima were determined as given in Table 2. By using the least square fitting method, a linear ephemeris was determined as

$$\mathrm{Min.I(HJD)} = 2455571.1857(10) + 1.173203(3) \times \mathrm{E}. \quad (1)$$

With the derived ephemeris, we computed the phases of all the measurements and formed the phased B- and V-band light curves as shown in Figure 1. The general features of the light curves are typical of EA-type systems. The depths of the primary and secondary eclipses were measured to be 0.153^{m} and 0.076^{m} in B and 0.146^{m} and 0.086^{m} in V, respectively. The δ Scuti-like oscillations,

Table 3 Photometric Solutions for V551 Aur

Parameter	Best-fit value	Formal error
T_1(K)	7000	assumed
T_2(K)	6085	±34
$q = m_2/m_1$	0.725	±0.006
$i\,(°)$	74.30	±0.12
Ω_1	5.293	±0.056
Ω_2	5.256	±0.047
$L_1/(L_1 + L_2)(V)$	0.780	±0.002
$L_1/(L_1 + L_2)(B)$	0.751	±0.002
$r_{1,\mathrm{pole}}$	0.219	±0.003
$r_{1,\mathrm{point}}$	0.224	±0.003
$r_{1,\mathrm{side}}$	0.22099	±0.003
$r_{1,\mathrm{back}}$	0.22339	±0.003
$r_{2,\mathrm{pole}}$	0.17244	±0.002
$r_{2,\mathrm{point}}$	0.17567	±0.002
$r_{2,\mathrm{side}}$	0.17349	±0.002
$r_{2,\mathrm{back}}$	0.17519	±0.002

with amplitudes of about 0.05^{m} outside the eclipses, can be clearly seen. Inspecting the light curves carefully, one can see that the secondary eclipse seems to be saturated by the oscillations more than the primary eclipse, which implies that the oscillations could very probably be from the primary component.

The mean magnitude at maximum light is measured to be about $V = 14.27$ and $B = 15.10$, corresponding to a color index of $B-V = 0.83(\pm 0.04)$. As an early F-type star according to Gáspár et al. (2003), the absolute color index of V551 Aur could be in the range from 0.3 to 0.4, thus the reddening of the star could be deduced to be about 0.48±0.05. This value is larger than the reddening of NGC 2126 ($E(B-V) = 0.2$) determined from isochrone fitting (Gáspár et al. 2003). It indicates that V551 Aur might not be a member of the open cluster, but rather a background field star. This is in accordance with the conclusion of Gáspár et al. (2003) based on proper motion analysis.

The eclipsing light curves were then analyzed by using the 2003 version of the Wilson-Devinney (W-D hereafter) code with the Kurucz atmospheres (Wilson 1979, 1990; Wilson & Devinney 1971; Kallrath et al. 1998). All the measurements were included in the computation of the photometric solution. In computing the photometric solution, the temperature of the primary star was set at 7000 K, as estimated according to its spectral type. The gravity darkening exponents were set to be $g_1 = g_2 = 0.32$ for both components according to Lucy (1967), and the bolometric albedos were taken as $A_1 = A_2 = 0.5$ following Ruciński (1969). The initial bolometric (X_1, X_2, Y_1, Y_2) and monochromatic (x_1, y_1, x_2, y_2) limb-darkening coefficients of the components were taken from van Hamme (1993).

Since there is no radial-velocity solution available for V551 Aur, the mass ratio $q = M_2/M_1$ of the system is unknown. To search for an approximate mass ratio, we devised a set of test solutions at the outset. The test solutions were computed at a series of assumed mass ratios ranging from 0.1 to 1.0 with an interval of 0.1. At each assumed mass ratio, the DC program, which is part of the W-D code, started from mode 2 (detached configuration). After several iterations, a converged solution was reached. The results show that the most probable solution would be around $q = 0.73$. We then ran the DC code again at this mass ratio and let the mass ratio be freely adjustable along with the other adjustable parameters. The final best-fitting solution was derived at $q = 0.725$ as given in Table 3. Based on this, the synthesis to the observed B and V light curves is shown in Figure 1, wherein the observations are denoted by the plus signs and the computed light curves are represented by solid lines.

The eclipsing light curve model reveals a detached configuration for the binary system with a mass ratio of about 0.725. The relative radius of the primary component was derived to be $r_1 = R_1/A = 0.202$, where A is the separation between the two components. Following Zhang et al. (2009), the mean density of the pulsating primary star is deduced to be about $\rho_1/\rho_\odot = 0.532(\pm 0.005)$. This value is comparable to that of early F-type main-sequence stars, implying that the star is less evolved.

4 THE INTRINSIC OSCILLATIONS

With the derived photometric solution, the theoretical time-series for eclipsing light curves in both the B and V bands were constructed. Subtracting the computed data from the observations, we found the "pure" light variations due to the oscillations, which are plotted in Figure 2.

Power spectral analysis was then carried out using the algorithm Period04 (Lenz & Breger 2005) so as to investigate the nature of the intrinsic oscillations. In doing that, we selected only those peaks with signal to noise ratio (S/N) larger than 4.0 for further investigation. The noise levels at each frequency were computed using the residuals from the original data when all the trial frequencies were pre-whitened. Considering the long-term noise due to the offsets of our photometry from night to night, peaks appearing in the low frequency region ($< 3\ c/d$) were rejected. We retained the frequencies that appeared in both the B- and V-band data for further discussions.

As a result, we have detected two frequencies with confidences higher than 99.9% at $f_1 = 7.7290(c/d)$ and $f_2 = 15.4555(c/d)$ from both the B- and V-band data. The spectral window and power spectrum of the V-band data are represented in Figure 3. They show that the amplitude spectrum is obviously dominated by f_1, while f_2 can be interpreted as $f_2 = 2f_1$. Thus f_1 and f_2 could both be the real pulsation modes. Table 4 shows the solutions of the final frequency. A synthesized set of pulsations based on the frequency analysis is illustrated in Figure 2.

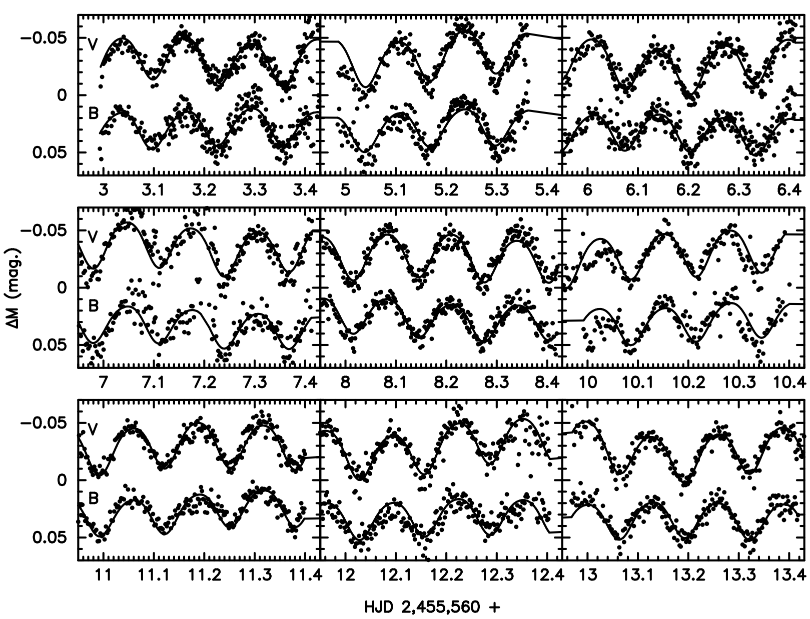

Fig. 2 B- and V-band pulsating light variations of V551 Aur extracted from the photometry along with their theoretical fittings.

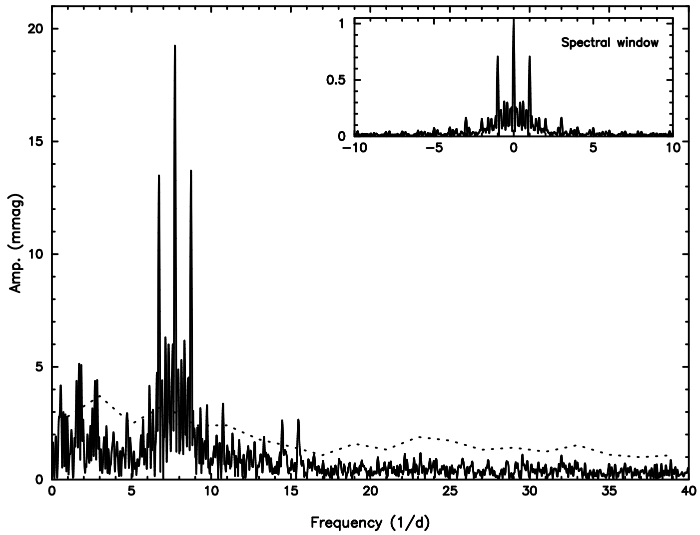

Fig. 3 Spectral window, power spectra and the significance limit (*dashed line*) for V551 Aur.

Table 4 Results of the Fourier Analysis

f_i	Filter	Frequency (c/d)	Amplitude (mmag)	Phase	S/N	Q (d)
f_1	V	7.7290±0.0007	19.15±0.26	0.2899±0.0021	28.95	0.093
	B	7.7289±0.0009	15.67±0.27	0.2912±0.0027	19.22	
f_2	V	15.4555±0.0056	2.42±0.26	0.3772±0.0169	7.07	0.046
	B	15.4573±0.0050	1.98±0.27	0.4637±0.0221	4.10	

By using the well-known equation $Q = P_{\rm pul}(\rho/\rho_\odot)^{1/2}$, and taking the value of $\rho/\rho_\odot = 0.532$ as deduced for the primary star in the previous section, the pulsation constant Q for each pulsation mode was calculated. The values were computed to be about 0.093 days for f_1 and 0.046 days for f_2. This could be a good constraint for us to discuss the pulsational nature of the star.

As a δ Scuti-type star, we first assume that V551 Aur is pulsating in p-modes, like most δ Scuti-type pulsators. In this case, f_2 can be interpreted as two times the harmonic of f_1, and f_1 could be an intrinsic mode. Comparing with the theoretical models contributed by Fitch (1981), however, we find the pulsation constant of f_1 is too long to be treated as a p-mode. This is because the maximum Q value calculated for p-mode pulsations of δ Scuti-type stars is generally less than 0.04 days, which is far shorter than that of f_1. We therefore tend to believe that the star could not be pulsating in p but in g-modes. If this is the case, f_2 could be identified as the g_1-mode with a low angular quantum number ($l = 2$ or 3), and f_1 is then two times the harmonic of g_1.

5 SUMMARY AND DISCUSSION

We have presented a new photometric study of the eclipsing binary V551 Aur. Observations confirmed the oEA-type nature of this binary system. We obtained B- and V-band light curves with complete orbital coverage, and used them to find the first photometric solution for this binary system. Our result indicates that V551 Aur could be a detached binary system with a mass ratio of about 0.725. It also shows that the secondary component could be a late F- or early G-type star. The δ Scuti-like light variations superimposed on the eclipsing light could be from the hotter primary component. Therefore, V551 Aur could be a member of the oEA class of stars.

Following the method of Zhang et al. (2009), we have extracted the "pure" oscillation light curves of the primary star from the observations so as to investigate the pulsational nature of the primary component in detail. The Fourier analysis yields two reliable frequencies at $f_1 = 7.7290(c/d)$ and $f_2 = 15.4555(c/d)$. With the help of the mean density of the primary star deduced from the photometric solution, the pulsation constants were calculated to be about 0.093 days for f_1 and 0.046 days for f_2. A mode identification comparison with Fitch's model suggests that the star is very probably pulsating in g-modes with a low order ($l = 2$ or 3). This makes V551 Aur a very interesting object for asteroseismology.

Theoretically, δ Scuti stars are predicted to pulsate in low-order g- and p-modes driven by the κ mechanism. However, very few such objects were identified to be oscillating in g-modes. Recently, a small group of stars were discovered to be pulsating in both p- and g-modes by the MOST and Kepler space missions (Monnier et al. 2010; Grigahcène et al. 2010). They are called hybrid γ Dor-δ Scuti pulsators and have attracted great attention, since they provide an opportunity for us to probe both the stellar envelope and the stellar core.

As an eclipsing system with probable g-mode oscillations, V551 Aur is shown to be a very interesting object in many aspects of research. We appeal for great attention to be given to this star. Is V551 Aur also a hybrid star? To answer this question, further observations, including high duty-cycle photometry and radial-velocity spectroscopy, are urgently needed.

Acknowledgements This paper is based on observations obtained by using the 85 cm reflecting telescope at the Xinglong Station of the National Astronomical Observatories, Chinese Academy of Sciences. This research is supported by the National Natural Science Foundation of China (Grant Nos. 10773015 and 10778719).

References

Fitch, W. S. 1981, ApJ, 249, 218
Gáspár, A., Kiss, L. L., Bedding, T. R., et al. 2003, A&A, 410, 879
Grigahcène, A., Antoci, V., Balona, L., et al. 2010, ApJ, 713, L192
Kallrath, J., Milone, E. F., Terrell, D., & Young, A. T. 1998, ApJ, 508, 308
Kwee, K. K., & van Woerden, H. 1956, Bull. Astron. Inst. Netherlands, 12, 327
Lenz, P., & Breger, M. 2005, Communications in Asteroseismology, 146, 53
Liu, S.-F., Wu, Z.-Y., Zhang, X.-B., et al. 2009, RAA (Research in Astronomy and Astrophysics), 9, 791
Lucy, L. B. 1967, ZAp, 65, 89
Mkrtichian, D. E., Kusakin, A. V., Gamarova, A. Y., et al. 2002, in Observational Aspects of Pulsating B- and A Stars, Astronomical Society of the Pacific Conference Series 256, eds. C. Sterken, & D. W. Kurtz, 259
Monnier, J. D., Townsend, R. H. D., Che, X., et al. 2010, ApJ, 725, 1192
Ruciński, S. M. 1969, Acta Astronomica, 19, 245
Soydugan, E., İbanoğlu, C., Soydugan, F., Akan, M. C., & Demircan, O. 2006, MNRAS, 366, 1289
Soydugan, E., Soydugan, F., Şenyüz, T., Püsküllü, Ç., & Demircan, O. 2011, New Astron., 16, 72
Stetson, P. B. 1987, PASP, 99, 191
Stetson, P. B. 1996, PASP, 108, 851
van Hamme, W. 1993, AJ, 106, 2096
Wilson, R. E. 1979, ApJ, 234, 1054
Wilson, R. E. 1990, ApJ, 356, 613
Wilson, R. E., & Devinney, E. J. 1971, ApJ, 166, 605
Zhang, X.-B., & Zhang, R.-X. 2003, ChJAA (Chin. J. Astron. Astrophys.), 3, 311
Zhang, X.-B., Zhang, R.-X., & Li, Q.-S. 2009, RAA (Research in Astronomy and Astrophysics), 9, 422
Zhou, A.-Y., Jiang, X.-J., Zhang, Y.-P., & Wei, J.-Y. 2009, RAA (Research in Astronomy and Astrophysics), 9, 349