PHOTOMETRIC STUDY OF THE PULSATING, ECLIPSING BINARY OO DRA

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ABSTRACT

We present a comprehensive photometric study of the pulsating, eclipsing binary OO Dra. Simultaneous B- and V-band photometry of the star was carried out on 14 nights. A revised orbital period and a new ephemeris were derived from the data. The first photometric solution of the binary system and the physical parameters of the component stars are determined. They reveal that OO Dra could be a detached system with a less-massive secondary component nearly filling its Roche lobe. By subtracting the eclipsing light changes from the data, we obtained the intrinsic pulsating light curves of the hotter, massive primary component. A frequency analysis of the residual light yields two confident pulsation modes in both B- and V-band data with the dominant frequency detected at 41.865 c/d. A brief discussion concerning the evolutionary status and the pulsation nature of the binary system is finally given.

Key words: binaries: eclipsing – stars: individual (OO Dra) – stars: oscillations

Online-only material: supplemental data

1. INTRODUCTION

Eclipsing binaries with pulsating components are objects that are important to our understanding of stellar structure and evolution. Investigating the frequencies of oscillations, known as asteroseismology, helps us to identify the physical processes behind the pulsating nature of these components as well as their stellar interiors. Modeling the light and radial velocity curves of an eclipsing binary can precisely determine the physical parameters of the components. This enables one to definitively identify the pulsation modes and compare the results with theoretical models in detail. The study of pulsating stars in eclipsing binaries offers new and strict constraints for stellar theories and helps people to understand the influences of tidal forces and mass transfer among the interacting binaries.

The present study concentrates on the newly discovered pulsating eclipsing binary system OO Dra. The star was first found by Biyalieva & Khruslov (2007) to be an eclipsing binary with an orbital period of 1.23837 days. The pulsating nature of the star was later discovered by Dimitrov et al. (2008) through follow-up observations. With the out-of-eclipse photometric data, they had made a preliminary frequency analysis and detected a main periodicity of about 37 c/d. A linear ephemeris of the binary system was given as HJD(MIN1) = 2451403.832(4)+1.2383832(8)×E. In addition, Dimitrov et al. (2008) had contributed a spectroscopy of the binary system. Twelve radial velocity measurements were given. The spectral type of the primary star in the binary system was identified to be A3 V–IV, with an effective temperature of 8500 K and log g = 4.0.

As a contribution to the ongoing program of searching for and studying pulsating eclipsing binaries (Zhang et al. 2009, 2013; Liu et al. 2012), we have performed a new photometry of OO Dra and collected sufficient photometric data. We present the results of the observations in this paper as well as a comprehensive study of the binary system and its intrinsic pulsation.

2. PHOTOMETRIC OBSERVATIONS

The eclipsing binary OO Dra was observed over 3 weeks in 2014 March–April. Time-series CCD photometry was carried out with the 50 cm binocular telescope (Deng et al. 2013; Zhang et al. 2014) at the Qinghai Station of the Purple Mountain Observatory, Chinese Academy of Sciences. Data were collected with two Andor 2 k × 2 k CCDs, one with a standard Johnson V and the other with a B filter equipped, so that simultaneous two-color photometry is achieved. Each camera provides a field of view of 20′ × 20′, with an image scale of about 0.59 pixel−1. Useful data were obtained over 90 hr during 14 nights from 2014 March 19 to April 12. A total of 1522 frames in B and 3428 in the V filter were collected. The journal of observations is presented in Table 1.

The preliminary processing (bias, dark subtraction, and flat fielding correction) of the CCD frames was performed with the standard routines of CCDPROC in the IRAF package. Photometry was extracted by using the DAOPHOT II package. Following Dimitrov et al. (2008), we used the stars BD+75 415 (=SAO 7402) and BD+75 415 (=GSC4050-1520) as the comparison and check stars. The magnitude difference between the two stars was confirmed to be stable within 0.015 mag during the observation. The differential magnitudes of OO Dra were then extracted. The time of each measurement was converted to Heliocentric Julian date. As an example, we plot in the upper panels of Figure 1 a part of the time-series light curves. The left panel represents the B- and V-band measurements obtained on March 24. Those shown in the right panel were derived on April 6 where the short-term pulsational light variations in addition to the eclipsing light changes can be clearly seen, confirming the discovery of Dimitrov et al. (2008).

3. THE BINARY SYSTEM

A total of three total eclipses, including two primary ones and one secondary one were recorded in our data. By using a least-squares parabolic fitting method, the epochs of these
light minima were determined as given in Table 2. From the literature (Lampens et al. 2010; Diethelm 2012; Hubscher & Lehmann 2013), we collected four minimum times for the star. Based on these data, the orbital period of the eclipsing binary was analyzed with the classical $O-C$ method. It yields an orbital period of $1.238378$ days for the binary system and the following linear ephemeris is given:

$$\text{HJD}(\text{Min}1) = 2456741.2607(2) + 1.238378(2) \times E. \quad (1)$$

By using the newly derived linear ephemeris, phases of all the measurements were computed. The folded light curves due to eclipsing were formed as shown in Figure 3. The general features of the light curves are typical of Algol-type eclipsing binaries with nearly total eclipses, suggesting a large inclination close to $90^\circ$ for the binary system. The depth of the primary eclipse was measured to be $0.46$ mag in $B$ and $0.44$ mag in $V$. That of the secondary minimum turned out to be $0.11$ mag in $B$ and $0.14$ mag in $V$, respectively.

Figure 1. Upper panels represent a segment of the original real-time $B$- and $V$-band light curves of OO Dra observed on 2014 March 24 and 2014 April 6. The lower panels are those with short-term pulsations subtracted.

(Supplemental data for this figure are available in the online journal.)
We made use of the Wilson–Devinney method (Wilson & Devinney 1971; Wilson 1979) to obtain the first photometric solution for the binary system. The available $B$- and $V$-band light curves were simultaneously synthesized by applying the 2003 version of the WD code with the Kurucz atmospheres (Wilson 1990; Kallrath et al. 1998). A nonlinear limb-darkening law with a logarithmic form was applied in the light-curve synthesis. Considering the short orbital period and evolutionary status of classical Algols such as OO Dra, we assumed a circular orbit $(e = 0)$ and a synchronous rotation $(F_2 = F_2^p = 1.0)$. The temperature of the massive (and usually luminous) primary star was set at 8500 K, adopted from Dimitrov et al. (2008). 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). The gravity darkening exponents were set to be $g_1 = 1.0$ for the primary and $g_2 = 0.32$ for the secondary component from Lucy (1967) according to their temperatures. The bolometric albedos were taken as $A_1 = 1.0$ and $A_2 = 0.5$ following Rucinski (1969).

The adjustable parameters in computing the photometric solutions are the orbital inclination $(i)$, phase shift, mass ratio $(q)$, surface temperature of the secondary $(T_2)$, dimensionless luminosity of the primary $(L_1)$, and the potentials of the two components $(\Omega_1, \Omega_2)$. Since OO Dra is a single-line spectroscopic binary (Dimitrov et al. 2008), there is no mass ratio available from the radial velocity solution. To search for an approximate mass ratio, we made a set of test solutions at the outset. The test solutions were computed at a series of assumed mass ratios with values ranging from 0.02 to 1.0. The mass ratio was photometrically determined to be $0.097 \pm 0.001$. The final best-fitting solution is given in Table 3. The synthesis of the observed $B$- and $V$-band light curves as well as the $(O-C)$ residuals are shown in Figure 2.

The photometric solution reveals a detached configuration with the secondary nearly filling in its Roche lobe. The filling factors, defined as the fraction of the stellar radius to that of the critical Roche lobe, of the two components turned out to be 55.8% and 97.5%. This suggests that the binary could also be semi-detached. To check this possibility, we have modeled the light curves with Mode 5 (a semi-detached model with the second star filling its Roche lobe). This model yields a converged solution at $q = 0.075$, which also gives a satisfactory fitting to the observations, but the sum of the residuals, $\Sigma(O-C)^2$, is about 10% larger than that of the solution with Mode 2 (detached model). We therefore adopted the results with the detached configuration.

Based on the photometric solution, we have carried out a spectroscopic solution for OO Dra with the data published by Dimitrov et al. (2008). As the photometric solution indicated that the less massive secondary star contributes about 10% of the luminosity of the binary system, it is hard to see this in the spectra. Radial velocities for only the primary component could be measured. By using the newly derived ephemeris,
the radial velocity curve of the massive primary component was reformed. Two data points detected at HJD 2454600.4282 and HJD 2454600.4516 were not included in the analysis for the large scatterings. As a result, the radial velocity curve model gives a separation between the two components of $a = 6.27 \pm 0.35 R_\odot$ with a systematic velocity of $-55.92 \text{ km s}^{-1}$ for the binary. With this, the absolute parameters of the components were then calculated as given in Table 3. The synthesis of the radial velocity curve is shown in Figure 3.

With the absolute parameters derived for OO Dra, the ratio of orbital angular momentum to rotational angular momentum at equilibrium could be estimated for the binary system following Hut (1981):

$$\alpha = \frac{q}{1 + q \frac{a}{r_g} \left( \frac{a}{R_1} \right)^2},$$

(2)

where $r_g$ is the gyration constant with a typical value of $r_g^2 = 0.1$ for main-sequence stars and varies negligibly during evolution. Inserting the related parameters into Equation (2) gives a result of $\alpha \approx 8.3$. This suggests that the rotational angular momentum is appreciable at equilibrium (Hut 1981). This in turn supports the circular and synchronous assumptions we accepted during the solutions.

4. THE INTRINSIC PULSATIONS

In Figures 1 and 2, the pulsational light variability can be clearly seen in the phases of outside eclipses and the secondary minimum of the light curves. With the derived photometric solution, time-resolved theoretical light curves due to eclipsing were computed. Subtracting the eclipsing light changes from the original observational data, we detected the pure pulsational light variations of the primary star. This enables us to make a detailed analysis of the pulsation nature of OO Dra.

The frequency analysis was carried out with the algorithm Period04 (Lenz & Breger 2005) based on the Fourier transform method. While doing that, we selected only those peaks with a signal-to-noise ratio (S/N) larger than 4.0 that appeared in both the $B$- and $V$-band data for further discussion. The noise levels were computed based on the residuals from the original data when all the trial frequencies were pre-whitened. Figure 4 illustrates the Fourier analysis of both the $B$- and $V$-band data. The spectral window and the step-by-step amplitude spectra were plotted. Each spectrum panel in the figure corresponds to the residuals with all the previous frequencies pre-whitened. The bottom panels show the final residuals of the $B$- and $V$-band data, wherein the dashed lines represent the confidence curves with $4\sigma$. The detected frequencies are listed in Table 4.

The periodograms show a typical feature of $\delta$ Sct stars with multi-periodicity. Two peaks at $f_1 = 41.87 \text{ c/d}$ and $f_2 = 34.75 \text{ c/d}$ are clearly shown in both the $B$- and $V$-band original amplitude spectra. The dominant peak is $41.87 \text{ c/d}$, corresponding to a period of 0.02388 days, and has an amplitude of about 9.8 mmag in $B$ and 8.4 mmag in $V$. The amplitude of the second peak is measured to be 6.8 mmag in $B$ and 5.6 mmag in $V$. When the two frequencies were pre-whitened, a third frequency around...
37 c/d arose. It is likely that one was previously detected by Dimitrov et al. (2008), but it was not above the significance limit due to the high noise. This frequency is therefore not included in Table 4 for further discussion. In addition, no harmonics related to the rotation period are detected, implying that the eclipses and proximity effects have been successfully removed from the data.

To check the result and discuss the pulsation nature further, we have computed the theoretical pulsation light curves using the adopted frequencies given in Table 4. After subtracting the pulsational light variations from the original observations, we detected the “pure” light changes due to eclipsing. A segment of the eclipsing light curves were shown in the lower panels in Figure 1. It can be seen that the short-term light variations have been fairly removed. The totally eclipsing feature is clearly shown. A comparison between the two sets of light curves suggests that the intrinsic pulsations could be very probably from the hotter primary component of the system. This is identical to most eclipsing binaries with δ Sct variables. A discussion on the evolutionary status of the components in the next section also supports this possibility.

Because of the large uncertainty, the absolute parameters derived for the components were not suitable for detailed analysis of the nature of the pulsation. Following the method described by Zhang et al. (2013), we used only the results from the photometric solution to calculate the mean density of the pulsating primary star. The result is $\rho_1/\rho_\odot = 0.232 \pm 0.003$. Inserting this value into the well-known equation, $Q = P_{\text{rad}}(\rho/\rho_\odot)^{1/2}$, pulsation constants of about 0.0116 ± 0.0001 and 0.0139 ± 0.0001 days were calculated for 41.87 c/d and 34.75 c/d oscillations, respectively. By using the FAMIAS (Frequency Analysis and Mode Identification for Asteroseismology) program (Zima 2008), we have tried to make a preliminary mode identification. This suggests an angular quantum number of $l = 0$ or $l = 1$, implying that the star could be pulsating in radial mode or low degree non-radial modes. If this is the case, the detected frequencies could be further identified as the fifth and/or fourth overtone modes (Fitch 1981).

5. SUMMARY AND DISCUSSION

We have presented the simultaneous $B$- and $V$-band photometry of the Algol-type eclipsing binary OO Dra. This photometry confirms the δ Sct-type pulsation nature of the eclipsing binary. The first photometric solution and physical parameters of the binary system were determined. The intrinsic pulsational characteristics of the primary component were analyzed.

The light curves of OO Dra show total eclipses. This enables us to obtain a reliable photometric solution for the binary system through light modeling by using the Wilson–Devinney method to determine the geometric parameters. The photometric solution reveals a very small mass ratio of 0.097. This could be the lowest mass ratio after KIC10661783 (Southworth et al. 2011) among the known eclipsing binaries containing δ Sct-type pulsating components. The light-curve synthesis indicates a detached configuration for the binary system although the secondary component is very nearly filling its Roche lobe. This means that OO Dra could not be a member of the oEA (Mkrtichian et al. 2004) class. Since the number of δ Sct stars in confirmed detached Algos is very small (Liakos et al. 2012), this star could be an important object in the study of pulsating eclipsing binaries.

With results from the photometric solution, a radial velocity synthesis was further performed with the measurements published by Dimitrov et al. (2008), and the absolute parameters of the components of the binary were calculated. The results show that the primary component is almost an un-evolved main-sequence star, while the secondary is quite evolved, over-luminous, and over-sized. Through comparison with the mass-luminosity relations of Algos (İbanoğlu et al. 2006), we find that the mass and radius detected for the primary component of
OO Dra match well with those of detached Algols \((L_1 \propto M_1^{3.92\pm0.05})\) rather than semi-detached ones \((L_1 \propto M_1^{2.10\pm0.25})\). This in turn supports the detached configuration as indicated by the photometric solution.

Based on the photometric solution, we have calculated the theoretical light curves due to eclipsing. Subtracting the theoretical eclipsing light changes from the observations, the intrinsic pulsational light variations from the hotter primary component were picked up. A frequency analysis of the remaining residuals showed multiple periodicities of the pulsating star. Two confident frequencies at 41.87 and 34.75 c/d were detected in both filters. The dominant pulsation period was determined to be 0.02388 days. The ratio of the pulsational to orbital period of the star turned out to be \(P_{\text{pul}}/P_{\text{orb}} = 0.0193\). It agrees well with the correlation between the orbital and pulsational periods proposed by Zhang et al. (2013) for eclipsing binaries containing \(\delta\) Sct-type components.

With the mean density of the primary component deduced from the photometric solution, the pulsation constants of the detected frequencies were computed and a preliminary mode identification was made. The pulsation constant of the dominant frequency was computed to be about 0.012 days, which is very close to the mean value of \(\delta\) Sct stars in eclipsing binaries (Zhang et al. 2013). It also suggests that the primary component of OO Dra could pulsate in the fifth or fourth overtone assuming that it is in radial or low degree non-radial modes like most \(\delta\) Sct stars.

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REFERENCES

Biyalieva, N. A., & Khurslov, A. V. 2007, PZP, 7, 17
Deng, L. C., Xin, Y., Zhang, X. B., et al. 2013, in IAU Symp. 288, Astrophysics from Antarctica, ed. T. Montmerle et al. (Cambridge: Cambridge Univ. Press), 318
Diethelm, R. 2012, IBVS, 6029, 1
Dimitrov, D., Kraicheva, Z., & Popov, V. 2008, IBVS, 5842, 1
Fitch, W. S. 1981, ApJ, 249, 218
Hübischer, J., & Lehmann, P. B. 2013, IBVS, 6070, 1
Hut, P. 1981, A&A, 99, 126
Ibanoğlu, C., Soydugan, F., Soydugan, E., & Dervişoğlu, A. 2006, MNRAS, 373, 435
Kallrath, J., Milone, E. F., Terrell, D., & Young, A. T. 1998, ApJ, 508, 308
Lampens, P., Kleidis, S., van Cauteren, P., et al. 2010, IBVS, 5933, 1
Lenz, P., & Breger, M. 2005, CoAst, 146, 53
Liakos, A., Niarchos, P., Soydugan, E., & Zasche, P. 2012, MNRAS, 422, 1250
Liu, N., Zhang, X. B., Ren, A. B., Deng, L. C., & Luo, Z. Q. 2012, RAA, 12, 671
Lucy, L. B. 1967, ZA, 65, 89
Mkrtichian, D. E., Kusakin, A. V., Rodríguez, E., et al. 2004, A&A, 419, 1015
Rucinski, S. M. 1969, AcA, 19, 245
Southworth, J., Zima, W., Aerts, C., et al. 2011, MNRAS, 414, 2413
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., Deng, L. C., Wang, K., et al. 2014, AJ, 148, 40
Zhang, X. B., Luo, C. Q., & Fu, J. N. 2013, ApJ, 777, 77
Zhang, X. B., Zhang, R. X., & Li, Q. S. 2009, RAA, 9, 422
Zima, W. 2008, CoAst, 155, 17