CHAPTER 7

The Eclipsing Binary with the Pulsating Component V551 Aur

7.1 Introduction

Eclipsing binaries with pulsating components are crucial objects for asteroseismology, because they provide an independent measurement of physical properties such as mass, radius, temperature of the component stars, and thus provide additional constraints for stellar pulsation models. Moreover, the importance of study of pulsating stars in the binary systems is to understand the effects of tidal forces and mass transfer (Zhang et al., 2014). The advantages of studying binary systems in clusters is that the observed properties of the detached components in the mass-radius-temperature diagrams must match the overall properties of the cluster to which the system belongs. Detached eclipsing binaries with well-determined masses and radii are particularly important. These combinations provide a set of constraints which allow to find more accurate solutions and to study the characteristics of stars and clusters in a consistent way together.

V551 Aur (RA = $06^h02^m38^s$, Dec = $+49^\circ53'2''$) is a detached eclipsing binary with a pulsating component and an orbital period of 1.17320(3) d which was discovered by Gáspár et al. (2003). The system shows steady δ Scuti-like oscillations outside eclipse, with an amplitude of 0.05 mag and pulsation period of 0.12935 days. A low resolution spectrum taken with a 40-cm telescope at the Tel-Aviv University Wise Observatory on 2003 April 10, indicated a spectral type of an early-type F star and were confirmed by Liu et al. (2009). Liu et al. (2012) suggested that the primary component of the system pulsate in g-mode oscillation. We aim to find accurate orbital and pulsation periods of the system and to verify the possible connection between the pulsation and the orbital motion caused by some mechanism of resonance (Willems and Aerts, 2002).

In this chapter, analysis and new results of the eclipsing binary system V551 Aur are discussed. The observations and data reduction are presented in Section 7.2. The eclipsing binary with pulsating component V551 Aur and period analysis are presented in Section 7.3 and Section 7.4, respectively. Section 7.6 is followed by a discussion of results and conclusions.

7.2 Observations and Data Reduction

The CCD images in V band were carried out during 22 nights separated into three observing runs (between 2004 and 2015). The first season was between 24th and 31th March 2004 at the Mount Lemmon Optical Astronomy Observatory Arizona (LOAO), Arizona, using the 1.0-m robotic telescope (Han et al. 2005). The second run was between 12th January and 9th February 2013 using the 2.4-m Thai National Telescope (TNT). In the last period, between 16th and 21st March 2015, we used the 0.5-m Corrected Dall-Kirkham PlaneWave CDK24 remote-controlled telescope located at the Thai National Observatory (TNO). The journal of the observations including the date, start time, length of observations, number of frames and the type of minimum for NGC 2126 are presented in Tables 3.8. Moreover, We obtained three nights additional data in clear filter. The data was observed in 2016 using a 16 inch f/8 Meade telescope equipped with a G2-3200M CCD camera from the company Moravian Instruments (Czech Republic) at Humain Radio-Astronomy Station, Belgium.

The CCD frame processing was performed using the standard routines of CCDPROC in the IRAF package (Stetson, 1987) to measure the differential magnitude of the stars in the FOV. Table 7.1 shows the coordinates in the UCAC4 catalogue (Zacharias et al., 2013) of the variable, reference and check stars.

Table 7.1: Basic information about V551 Aur, reference, and check stars

Name	UCAC4 Catalog	α (J2000)	δ (J2000)
V551 Aur	700-043241	06:02:38.044	+49:53:02.48
Reference star	700-043189	06:02:26.332	+49:50:02.35
Check star 1	700-043225	06:02:34.704	+49:51:57.93
Check star 2	700-043227	06:02:34.941	+49:51:12.88

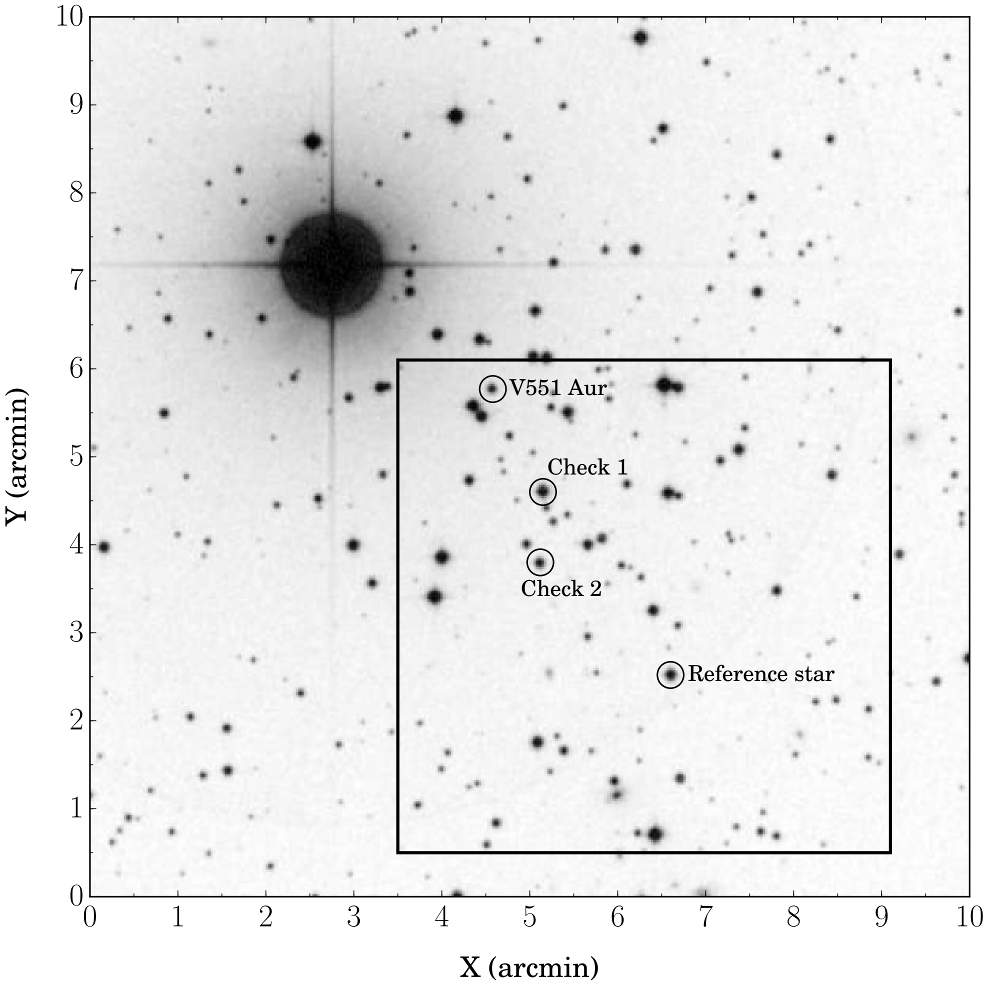

Figure 7.1: The Digitized Sky Survey image of NGC 2126 (FOV = $10' \times 10'$, north is up, east is to the left). The black box shows the FOV covered by our observations in 2013.

7.3 The Binary System

Twenty-three eclipses from Gáspár et al. (2003), Liu et al. (2012) and our data were recorded in Table 7.2. Six times of primary light minima from 2004, 2013, and 2016 along with others compiled from the literature were used to compute an improved ephemeris. By using the least squares fitting method as shown in Figure 7.2, the updated linear ephemeris is

$$\text{Min I (HJD)} = 2452640.595768 + 1.1731748(8)E. \tag{7.1}$$

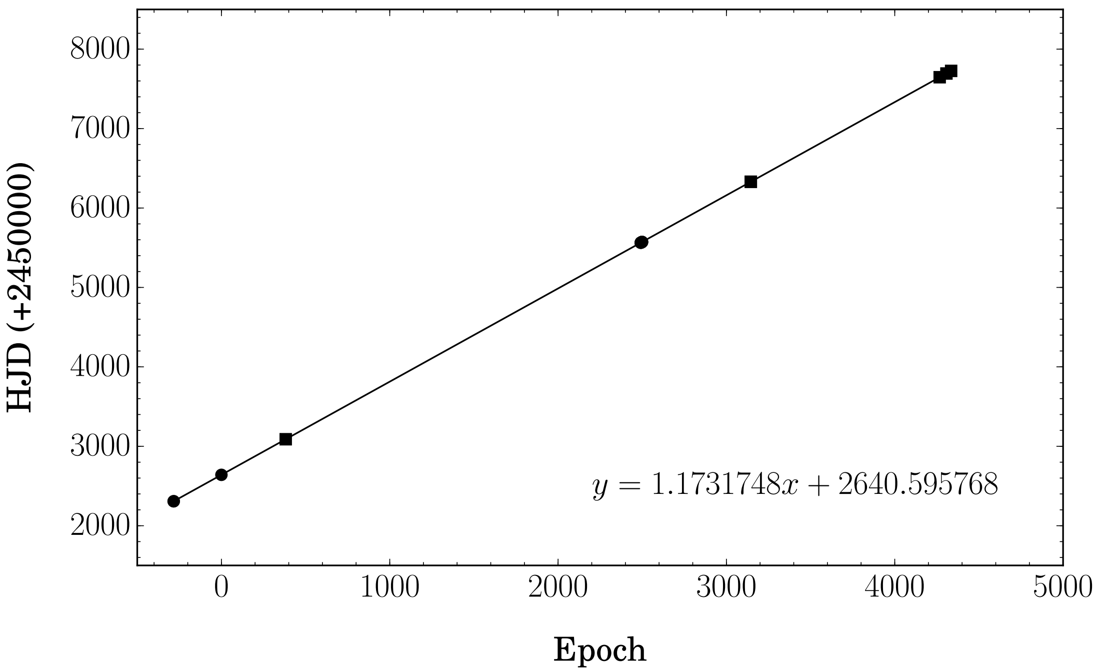

Figure 7.2: The relationship between date (HJD) and epoch of primary light minima for V551 Aur. Filled squares show epochs of primary light minima from our data and filled circles show the data from the literature.

With the updated ephemeris, we obtained the phase diagram shown in Figure 7.3. The offsets between the V band light curves from different years were calculated in order to fit them simultaneously with the program PHOEBE (Wilson and Devinney, 1971). We obtained the best offset values by using a Fortran program (courtesy of L. Vermeylen, ROB) to shift the respective phased light curves. The program computes the offset values from the minimization of the residuals. The resulting offsets are 0.038 (for the year 2013) and 0.017 (for the year 2015) mag compared to the 2004 phase diagram. For one rising branch of the primary minimum, observed in 2015, we had to use a supplementary small offset, however.

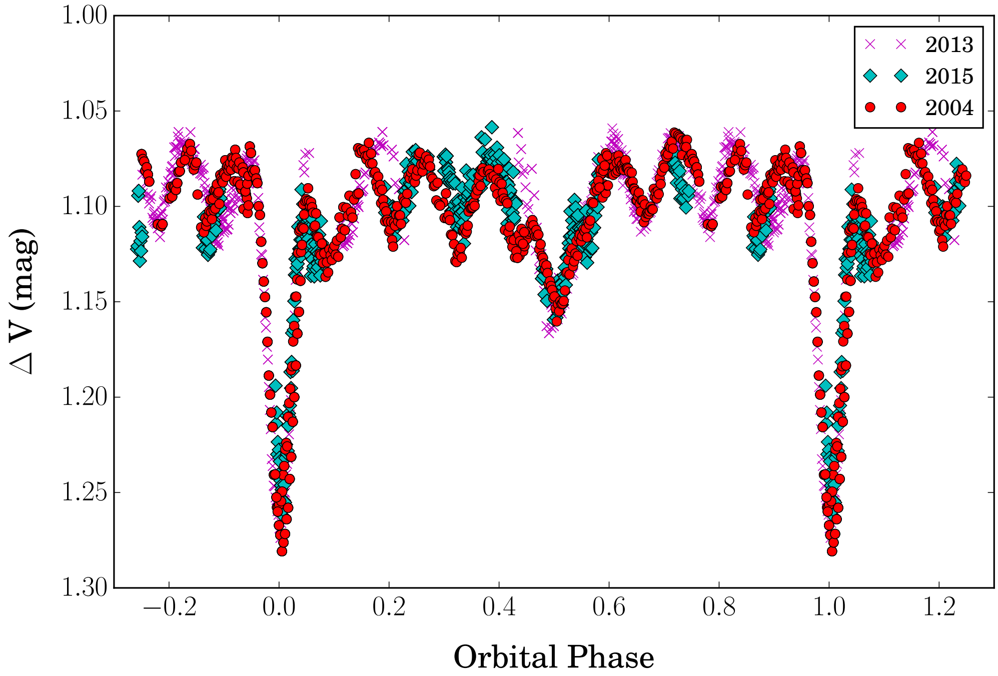

Figure 7.3: Differential V observations of V551 Aur folded in the phase diagram according to the new ephemeris as given in Eq. 7.1.

The light curve was analysed using the Wilson-Devinney code with Kurucz's atmosphere models in program PHOEBE (Wilson and Devinney, 1971). The estimation of interstellar absorption obtained for NGC 2126 $E(B-V)$ = 0.27 $\pm$ 0.01 was used to calculate the temperature of the primary star, T_1, which is in the range of 7000-7250 K. In the search of an eclipsing binary model, T_1 was set to 7000 K and the eccentricity to zero. The bolometric and monochromatic limb darkening coefficients were taken from van Hamme (1993). We used both possibilities of convective and radiative flux transport in the outer stellar atmosphere, the best model was found to have a convective envelope for the primary star. Thus the bolometric albedos of the components were set to $A_1 = A_2$ = 0.6. The gravity darkening exponents were put to $g_1 = g_2$ = 0.32 following (Lucy, 1967). We used the initial mass ratio q = 0.725 proposed by Liu et al. (2012). The best fit model for the light curve of V551 Aur presents a detached configuration for the eclipsing

Table 7.2: Times of light minima of V551 Aur originating from the literature and from this research. The residuals (O-C) were computed with the new ephemeris. Ref: (1) is Gáspár et al. (2003), (2) is Zhang et al. (2012), (3) is this research.

No.	Time of minimum (HJD +2450000)	Epoch	$O-C$	Min	Filter	Ref
1	2307.408	-284.0	-0.0134	I	V	(1)
2	2308.583	-283.0	-0.0121	I	V	(1)
3	2640.605	0.0	0.0	I	V	(1)
4	3088.757	382.0	-0.0026	I	V	(3)
5	5562.970	2491.0	-0.0098	I	V	(2)
6	5562.973	2491.0	-0.0077	I	B	(2)
7	5565.316	2493.0	-0.0108	I	V	(2)
8	5565.315	2493.0	-0.0109	I	B	(2)
9	5567.086	2494.5	-0.0018	II	V	(2)
10	5567.085	2494.5	-0.0024	II	B	(2)
11	5568.259	2495.5	-0.0018	II	V	(2)
12	5568.258	2495.5	-0.0030	II	B	(2)
13	5570.009	2497.0	-0.0099	I	V	(2)
14	5570.010	2497.0	-0.0090	I	B	(2)
15	5571.183	2498.0	-0.0092	I	V	(2)
16	5571.184	2498.0	-0.0090	I	B	(2)
17	5572.359	2499.0	-0.0068	I	V	(2)
18	5572.357	2499.0	-0.0087	I	B	(2)
19	6330.233	3145.0	-0.0068	I	V	(3)
20	6330.233	3145.0	-0.0036	I	B	(3)
21	7646.536	4267.0	-0.0027	I	C	(3)
22	7693.458	4307.0	-0.0065	I	C	(3)
23	7726.312	4335.0	-0.0025	I	C	(3)

binary system with q = 0.769 ± 0.005. The temperature of secondary component, T_2, is about 5900 K. The system parameters and their formal uncertainties are shown in Table 7.3.

7.4 Period Analysis of Residuals

We used the residuals from which the eclipses were excluded to perform a period analysis by using the program Period04 (Lenz and Breger, 2005) based on the Fourier transform method. Only the peaks with a signal-to-noise ratio (S/N) larger than 4.0 (Breger et al., 1993; Kuschnig et al., 1997) were selected for the next step. Figure 7.4 displays

Table 7.3: System Parameters of V551 Aur

Parameters	Best-fit value
P (d)	1.1731744 $\pm$ 0.0000002
$i(^{\circ})$	73.01 $\pm$ 0.06
e	0
$q = m_1/m_2$	0.769 $\pm$ 0.005
T_1 (K)	7000 (fixed)
T_2 (K)	5938 $\pm$ 23
Ω_1	5.38 $\pm$ 0.03
Ω_2	4.84 $\pm$ 0.02
$L_1/(L_1 + L_2)$	0.680 $\pm$ 0.005
$r_{1,back}(R_{\odot})$	0.220 $\pm$ 0.002
$r_{1,side}(R_{\odot})$	0.218 $\pm$ 0.002
$r_{1,pole}(R_{\odot})$	0.216 $\pm$ 0.002
$r_{1,point}(R_{\odot})$	0.221 $\pm$ 0.002
$r_{2,back}(R_{\odot})$	0.211 $\pm$ 0.002
$r_{2,side}(R_{\odot})$	0.208 $\pm$ 0.002
$r_{2,pole}(R_{\odot})$	0.205 $\pm$ 0.002
$r_{2,point}(R_{\odot})$	0.012 $\pm$ 0.002

Table 7.4: Frequency analysis of the pulsating component in V551 Aur

f_i	Frequency (c/d)	Amplitude (mag)	Phase (rad)	S/N
f_1	7.713147 $\pm$ 0.000002	18.70 $\pm$ 3.4	0.1975 $\pm$ 0.003	18.60
f_2	15.47419 $\pm$ 0.00002	3.01$\pm$ 3.4	0.9921 $\pm$ 0.018	3.80

power spectra of the pulsating component of V551 Aur. As a result, we detected two significant frequencies determined without any ambiguity since the spectral window is well-identified in the consecutive power spectrum. The main frequency is 7.713147$\pm$0.000002 c/d and a semi amplitude of 18.70$\pm$3.4 mmag as shown in Table 7.4. We also detected the first harmonic of the main frequency, $f_2 = 2f_1$ at the limit of the adopted minimum significance level. The resulting phase diagram using the epoch of maximum of HJD 2453092.71 is presented in Figure 7.5. It shows a stable oscillation with a dominant pulsation period of 0.12964877$\pm$0.00000003 d. Therefore, the ratio of orbital to pulsation period is determined to be equal to 9.048870 $\pm$ 0.000008.

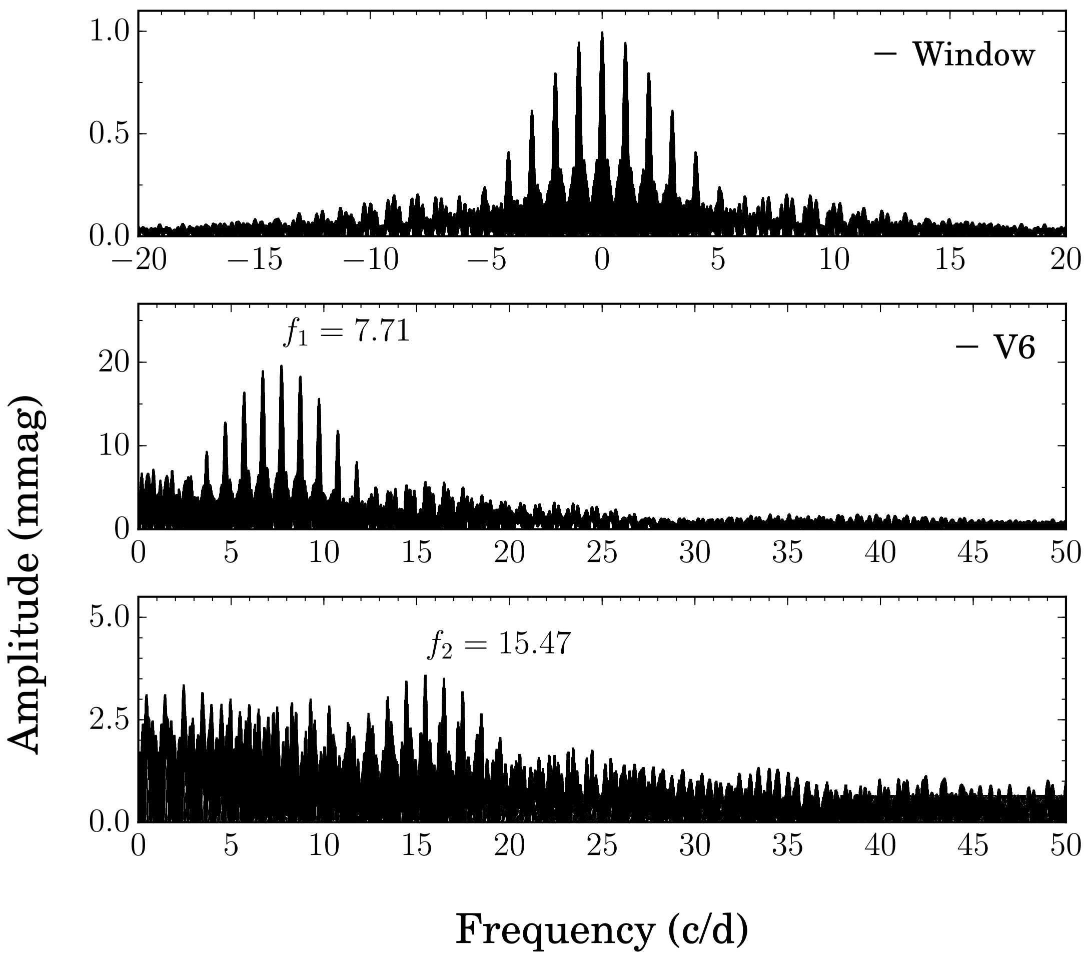

Figure 7.4: Power spectra of the eclipsing binary with pulsating component V551 Aur. Window spectra are shown at top.

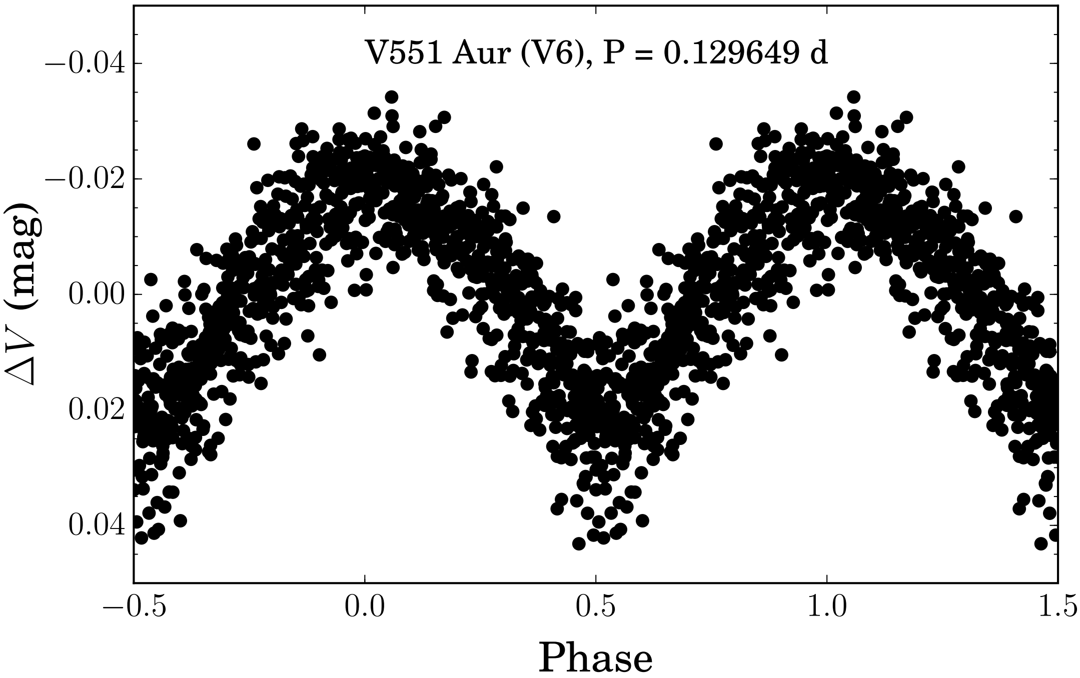

Figure 7.5: The phase diagram for V551 Aur plotted against the dominant pulsation period.

7.5 Possible Mode Identification

Ledoux and Walraven (1958) introduced the pulsation relation in the star, a theoretical period-luminosity relation maybe derived from following equation:

$$Q = P\sqrt{\frac{\rho}{\rho_{\odot}}}, \tag{7.2}$$

where Q is the pulsation constant, ρ is the mean density, and P is the period of pulsation. The pulsation constant value is different for different pulsation modes. If ρ is replaced by the radius and mass, we derive:

$$\log Q = \log P + \frac{1}{2}\log\left(\frac{M}{M_{\odot}}\right) - \frac{3}{2}\log\left(\frac{R}{R_{\odot}}\right). \tag{7.3}$$

We derived the Q-value of 0.095 ± 0.017 days for f_1 using expression by Breger (1990):

$$\log Q = -\log f + 3.33\log g + 0.1logM_{bol} + 10\log T_{eff} - 6.456. \tag{7.4}$$

The pulsation constant Q is at most equal to 0.033 d for the fundamental/overtone radial and non-radial (p-) modes of models of δ Scuti variables from 1.5 to 2.5 solar masses (Fitch, 1981). Since Q is much larger, we conclude that the detected mode is not of the acoustic type. We found the ratio of orbital to pulsation period, which is close to 9 (to within 5%). However, the degree l and the azimuthal number m of the pulsation mode is still unknown, so the pulsation period in the co-rotating frame of the pulsating component cannot be determined. Thus, we believe the orbital period. V551 Aur has a proper motion $\mu_{\alpha}\cos\delta$ = -0.7 mas/yr and μ_{δ} = 5.1 mas/yr as extracted from UCAC4 catalogue.

7.6 Discussion and Conclusions

The CCD times of the light mininma of V551 Aur in the V-band were obtained in the years 2004, 2013 and 2015 by using the 1-m telescope at the LOAO, Arizona and the 0.5

and 2.4-m telescopes at TNO, Thailand. From this study, we obtained a new value of the orbital period of V551 Aur (1.1731748 $\pm$ 0.0000008 days). The light curve was analyzed using the Wilson-Devinney technique to calculate new system's parameters. According to our analysis, the solution shows that V551 Aur is a detached binary system with q = 0.769 and i = 73.01 degrees. From the period analysis of the residuals, we confirm the presence of pulsations with a main frequency of 7.71315 c/d. The results show that f_2 is the first harmonic of f_1. The ratio between the orbital and pulsation periods is equal to 9.048870$\pm$0.000008, that suggests the high order resonance between the orbital and the pulsation periods. However, this ratio is not the exact integer value within the accuracy of our periods determinations. This is similar to the case of 12.0008 period commensurability of pulsations in a 1.2198675 d exoplanet host system WASP-33 having close planet on the circular orbit. These resonances are likely a common case in the binary/planetary systems and have to be studied on a larger sample of systems.