Photometric Analysis of V633 Virginis

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Abstract Photometric analysis of the ASAS-SN V-band photometry of V633 Virginis is presented. The results show an A-type system with an extreme low mass ratio of 0.14 and mid-range contact of 33%. There is good thermal contact between the components. Some astrophysical qualities are examined, and some absolute parameters of the system determined.

1. Introduction

The W Ursae Majoris (EW) group of short period contact eclipsing binary stars is an important test bed for the development of theories of stellar evolution. Numerous new contact systems have been discovered through various automated sky surveys. Most of the new discoveries remain unanalyzed even though the quality of the available photometry is such that reasonable analysis is feasible. The most difficult parameter to determine from light curve analysis is the mass ratio. It has been shown previously that in the presence of total eclipses even noisy data can yield an accurate mass ratio (Terrell and Wilson 2005), and the author has previously successfully analyzed survey acquired photometric data (Wadhwa 2005, 2006). This paper reports the Wilson-Devinney analysis of the V-band photometry from the All Sky Automated Survey for Super Novae of V633 Vir.

2. V633 Virginis

V633 Vir (= TYC 304-73-1, ASASSN-V J130226.05 +071834.2; R.A. $13^h\ 02^m\ 25.96^s$ Dec. +07° 18' 34.38" (J2000)) was first reported as a variable in the Catalina Survey (Drake *et al.* 2014). The ASAS-SN variable star catalog (Jayasinghe *et al.* 2018) lists it as contact binary star with an amplitude of 0.33 magnitude and period of 0.4080688 day. Visual inspection of the ASAS-SN light curve suggests a definite total eclipse and hence the suitability of the system for photometric analysis. Very little other data apart from B–V (0.47) and J–H (0.213) magnitudes are available from the SIMBAD database. Using the color calibration presented by Noll (2014), the star is likely to be of spectral class F with an effective temperature of the primary (T_1) of 6700 K. The V-band photometry for the system is available from the ASAS-SN website (Jayasinghe *et al.* 2018) and was used in the analysis. All data points with reported errors greater than 0.05 magnitude were excluded. This yielded a light curve with over 180 data points with reasonable phase coverage.

3. Photometric analysis

The mass ratio of a contact binary system is usually determined by radial velocity studies. The mass ratio forms a critical part of the formal light curve solution which yields appropriate values for parameters such as the inclination, degree of contact, and temperature variations. However, where radial velocity data are not available, under certain circumstances, such as when the system exhibits at least one total eclipse, a systematic search of the parameter space for various values of the mass ratio can be employed to determine the correct mass ratio for the system. This is sometimes referred to as the grid search method and has previously been employed on many data sources, including data obtained through automated sky patrols (Wadhwa 2005, 2006). One of the most difficult aspects of such an approach is selecting the starting value mass ratio to begin the grid search. Ruciński (1993) through simulation experiments derived a relationship between the amplitude of the light curve and mass ratio for various degrees of fillout. Using this relationship for a mid-range fillout we estimated the likely mass ratio to be near 0.15 and we used this as the starting value for the mass ratio.

The WDWIN 5.6 package (Nelson 2009), which is a graphical front for the LC (light curve) and DC (differential corrections) components of the Wilson-Devinney model, was employed for the complete analysis.

As radial velocity data were not available for any of the systems analyzed in this paper, the grid search method as described in the above-referenced articles was employed. Ruciński (1993) demonstrated that in the case of contact binary systems the light curves are predominately dependent on the three main geometrical parameters, namely, the mass ratio (q), inclination (i), and the degree of contact (f). Other factors such as gravity darkening, reflections effects, effective temperature, albedos, and limb darkening only have a small influence on the shape of the observed light curve. In the analysis of V633 Vir the gravity darkening was set at 0.32, limb darkening coefficients were interpolated from van Hamme (1993), the bolometric albedos were fixed at 0.5, and simple refection treatment was applied. The maximum magnitude of the stars is not well known, therefore, the photometric data were normalized to the mean magnitude between phases 0.24 and 0.26 in each case. This methodology has previously been applied to the analysis of All Sky Automated Survey and ground-based amateur observations (Wadhwa 2005, 2006).

The mass ratio (q) search grid is illustrated in Figure 1. The minimum error is seen at q = 0.14 and this was accepted as the true mass ratio for the system. The WDWIN 5.6 package also computes other parameters such as relative luminosities, relative radii (pole, back, and side), potential (fillout), temperature of the secondary, and inclination. These are summarized in Table 1. The observed and fitted light curves are illustrated in Figure 2 while the three-dimensional representation of the system (Bradstreet 1983) is shown in Figure 3.

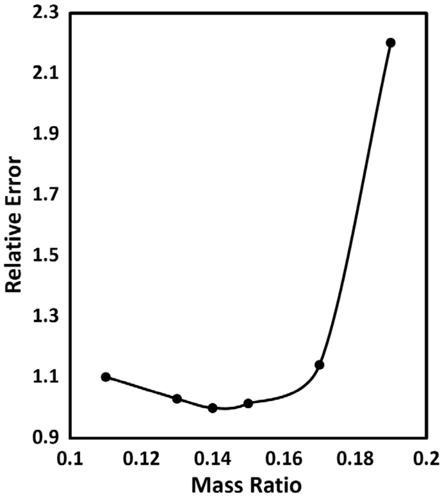

Figure 1. Mass ratio (q) search grid. The relative error has been normalized to the minimum error, which occurs at q = 0.14.

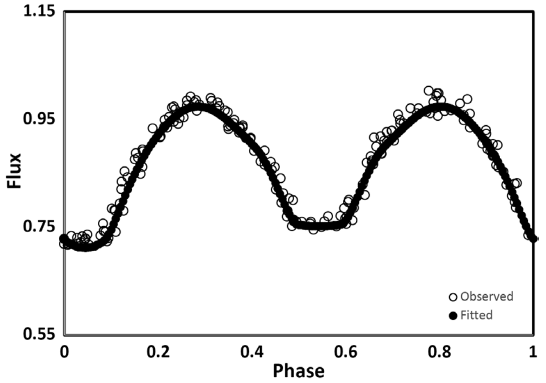

Figure 2. Fitted and observed light curve for V633 Virginis with q = 0.14 and other parameters as noted in Table 1.

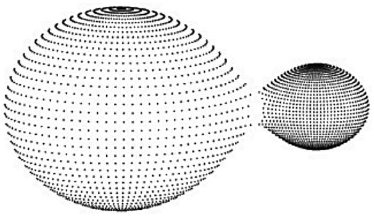

Figure 3. Three-dimensional representation of V633 Vir produced using BINARY MAKER 2.0 (Bradstreet 1983).

Table 1. Light curve solution parameters for V633 Vir.

Parameter	*V633 Vir*
T_1 (Fixed) K	6700
T_2 K	6464 ± 47
Mass Ratio (q)	0.14 ± 0.01
Potential	2.05 ± 0.01
Fillout (%)	33 ± 2.05
Inclination (°)	80.9 ± 1.7
L_1	10.56 ± 0.06
L_2	1.92
r_1 (mean)	0.565
r_2 (mean)	0.24

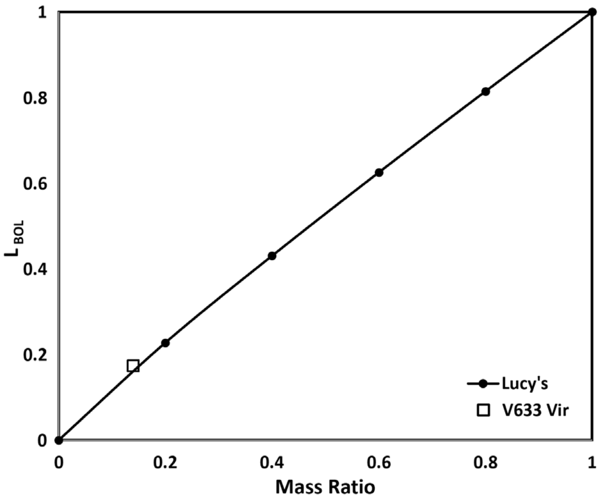

Figure 4. Mass Ratio – Bolometric Luminosity ratio. V633 Vir, being a low mass ratio system, lies close to Lucy's relationship (solid line) as predicted; see text.

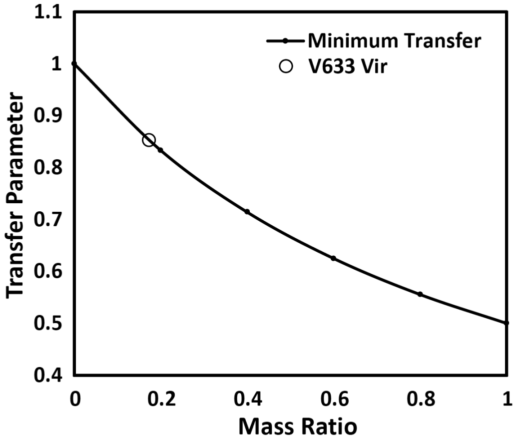

Figure 5. Mass ratio – Transfer parameter. The minimum energy transfer parameter is represented by the solid line. A Type systems of low mass ratio are expected to fall on or near the minimum. V633 Vir conforms with the predicted value; see text.

4. Astrophysical quantities and absolute parameters

Some astrophysical quantities of the newly analyzed contact system were compared with other systems; the mass ratio-luminosity relationship and energy transfer characteristics were reviewed. In addition, as the distance to the system is known, we derived some absolute parameters for the system.

Lucy (1968) found that observable luminosity ratio is proportional to the mass ratio ($L_2/L_1 = q^{0.92}$); later reviews, however, have found the relationship a little more complex and better reflected as a relationship between bolometric luminosity and mass ratio. Csizmadia and Klagyivik (2004) showed that different sub-types of contact binary systems occupied specific regions of such a diagram. Those with mass ratios below 0.2 still closely follow Lucy's relationship, however, A-type stars with mass ratios > 0.2 tend to occupy the space below the line representing Lucy's relationship.

As the temperatures and relative luminosities of the stars are known from the light curve solutions it is possible to calculate the bolometric luminosities via

$$(L_2/L_1)_{Bol} = (L_2/L_1)V \times 10^{0.4(BC1 - BC2)} \qquad (1)$$

where BC1 and BC2 are bolometric corrections interpolated from Flower (1996). The bolometric luminosity and mass ratio relationship is shown in Figure 4, where the solid line represents Lucy's relationship $L_2/L_1 = q^{92}$. As expected, V633 Vir having a mass ratio below 0.2 is close to Lucy's relationship.

As contact binary stars approach contact and both stars fill their roche lobes there is a transfer of energy usually from the primary to the secondary. Csizmadia and Klagyivik (2004) studied this transfer by defining the transfer parameter $\beta = L_{1\ Observed}/L_{1\ ZAMS}$, which given the existing relationship between mass and luminosity can be expressed as a combination of the mass ratio and the temperatures of the component stars. In addition, they determined that the minimum rate of the transfer parameter could be expressed as $\beta_{Env} = 1/(1+(L_2/L_1)_{Bol})$ and that the transfer parameter corresponds to this minimum rate except in the cases of high mass ratio ($q > 0.72$). We calculated the transfer parameter for each of V633 Vir and the results are illustrated in Figure 5, where the solid line represents the minimum transfer parameter. V633 Vir is on or close to the minimum transfer parameter as predicted by the relationship described by Csizmadia and Klagyivik (2004).

The determination of absolute parameters is critically dependent on knowing the actual stellar masses. In the absence of radial velocity data, total mass cannot be unequivocally calculated; however, if the distance to the system is known, Kepler's relationships along with mass-luminosity relationship can be employed to estimate the total mass and other physical parameters. In our case the estimated distance for V633 Vir is available (511 Pc) from the SIMBAD data service.

As the primary eclipse is total, the measured magnitude at mid-eclipse represents the light from the primary star only, as the secondary is totally eclipsed. Given the distance we can estimate the absolute magnitude of the primary star. Knowing the absolute magnitude an estimation of the luminosity relative to the Sun is given by $L_1/L_\odot = 10^{-0.4(M-M\odot)}$ (M = absolute magnitude). Knowing the luminosity one can use the mass luminosity relationship to derive the mass of the primary. Individual stellar masses and the mass of the system as a whole can be derived using the mass ratio from the light curve solution. Using Kepler's third law and the derived total mass one can estimate the semi-major axis of the system.

As noted above the WD light curve solution provides an estimation of the relative radii for each star in three formats. The average of each of the reported values for r_1 and r_2 were used in conjunction with the calculated semi-major axis to estimate the true radius of each star. Knowing the actual radius and temperature then allows an estimation of the bolometric magnitude of each star. All results of the actual parameters of each system as summarized in Table 2.

Table 2. Absolute parameters for V633 Vir derived from parallax distance of 511 Pc (SIMBAD). Bolometric magnitude assumes solar temperature of 5772 K and relative radius assumes $R_\odot = 997{,}500$ KM.

Absolute Parameter	*V633 Vir*
Distance (Pc)	511
Total Mass ($M_\odot$)	1.596
Mass Primary ($M_\odot$)	1.40
Mass Secondary ($M_\odot$)	0.196
Semi-Major Axis ($R_\odot$)	1.89
Primary Radius/$R_\odot$	1.07
Secondary Radius/$R_\odot$	0.45
Primary M_{Bol}	3.96
Secondary M_{Bol}	0.45

5. Conclusion

A photometric solution of V633 Vir is presented which indicates an A-type system with the secondary star cooler than the primary and extreme low mass ratio of 0.14. There is relatively shallow contact at less than 35%, however thermal contact is quite good with temperature difference between the stars of less than 250 K. The system behaves similarly to others of its type with respect to some astrophysical quantities.

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