Research in Astron. Astrophys. **2011** Vol. **11** No. **9**, 1067–1073
http://www.raa-journal.org *http://www.iop.org/journals/raa*

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

Photometric analysis of V30 of open cluster NGC 7789

Yellapragada Ravi Kiron[1], Kandulapati Sriram[2] and Pasagada Vivekananda Rao[1]

[1] Department of Astronomy, Osmania University, Hyderabad 500 007, India;
yravikiron@yahoo.com
[2] Korea Astronomy and Space Science Institute, Hwaam 61-1, Yuseong, Daejeon 305-348, Republic of Korea

Received 2011 April 19; accepted 2011 May 23

Abstract We present the photometric solutions of the variable star V30⋆ that is in the foreground of intermediate open cluster NGC 7789. The observations were done in the V passband using the 2 m telescope at the IUCAA-Girawali Observatory in India. The analysis is done using the Wilson-Devinney Code (2003) and the fitted light curve is presented. The photometric solutions reveal a W-subtype contact configuration. The photometric mass ratio is found to be 0.395 and the absolute masses and radii for the components are deduced as 1.25M_s and 0.97R_s for the primary and 0.49M_s and 0.93R_s for the secondary, respectively. No signature of third light is found in the system.

Key words: stars: binaries: eclipsing — binaries: contact

1 INTRODUCTION

NGC 7789 ($l = 115.49°, b = -5.35°$) is a rich intermediate open cluster. Burbidge & Sandage (1958) determined the colors and magnitudes of nearly 700 stars in this cluster. Friel & Janes (1993) estimated the apparent distance modulus $(m - M)_v = 12$, the reddening $E(B - V) = 0.24$ and the metallicity [Fe/H] $= -0.26 \pm 0.006$. They found the age of the cluster to be about 2 Gyr. Wu et al. (2007) presented new BATC 13 band photometric results and derived a set of best fitting fundamental parameters for this cluster: an age of $t = 1.4 \pm 0.1$ Gyr, a distance modulus $(m - M)_o = 11.27 \pm 0.04$, a reddening $E(B - V) = 0.28 \pm 0.02$ and a metallicity of about $Z = 0.019$. Jahn et al. (1995) discovered 15 variables in NGC 7789, among which most of the variables are of eclipsing type. Mochejska & Kaluzny (1999) monitored this cluster in two different fields (central part and an extended area) of $23 \times 23\,\mathrm{arcmin}^2$. They found that most of the eclipsing variables are of W UMa type with periods shorter than a day. For variable V30, they found the period to be 0.3862d, $V_{\max}$ to be 15.13 and $\langle B - V \rangle = 0.80$. They classified this system as EW type and, using the absolute calibration established by Rucinski & Duerbeck (1997), they obtained M_v and the distance modulus and concluded that the variable V30 is not a member of cluster NGC 7789. Zhang et al. (2003) re-observed the variable V30, but due to incomplete data coverage they could not re-determine the period. They adopted the period from Mochejska & Kaluzny (1999) and determined the epoch to be $T_o = 2451811.088$. They classified V30 to likely be an EA type variable. Considering V30 to be

⋆ We follow the Jahn et al. (1995) nomenclature for variable names.

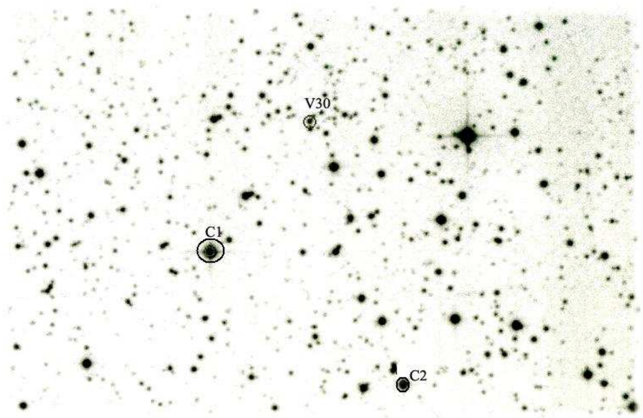

Fig. 1 Variable star V30, comparison star (C1) and check star (C2) are shown in the field.

Table 1 Coordinates of Variable Star V30, Comparison Star (C1) and Check Star (C2)

Star	α (J2000) (h m s)	δ (J2000) (° ′ ″)
V30	23 59 51	56 44 56
Comp. star	00 00 02	56 46 56
Check star	23 59 40	56 49 00

a field star in the direction of NGC 7789 and since no physical parameters were obtained for this system, we selected it for our studies.

2 OBSERVATIONS AND DATA REDUCTION

The observations of V30 of NGC 7789 were carried out from the IUCAA-Girawali Observatory (IGO) using the 2 m telescope. A brief description of the telescope's instruments can be found in Sriram & Vivekananda Rao (2010). The FWHM of the stellar image varied between 3-5 pixels during our observations. The observations in V filter were carried out for three nights during 2009 November 7, 28 and 29 with the field centered at V30.

The exposure time was set to 600 s throughout the observations of V30. The readout time of the detector was 87 s. The object was observed at various air-masses ranging from 1.1–2.0. During the observing runs we took several bias and flat fields to calibrate the images of the stars using standard techniques. The preliminary processing of the raw data was done within IRAF[1]. We selected a comparison star (C1) and a check star (C2) within the field and differential photometry was carried out (Table 1). Since the variable star V30 is close to the comparison star and check star, we ignored the extinction corrections. Figure 1 shows the positions of the variable star V30, the comparison star and the check star.

The Heliocentric Julian Dates were obtained from the time of observations. The phases of the variable V30 were calculated using the period from Mochejska & Kaluzny (1999) and the epoch from Zhang et al. (2003). Figure 2 shows the magnitude difference between comparison and check

[1] IRAF is distributed by the National Optical Astronomy Observatories, which are operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.

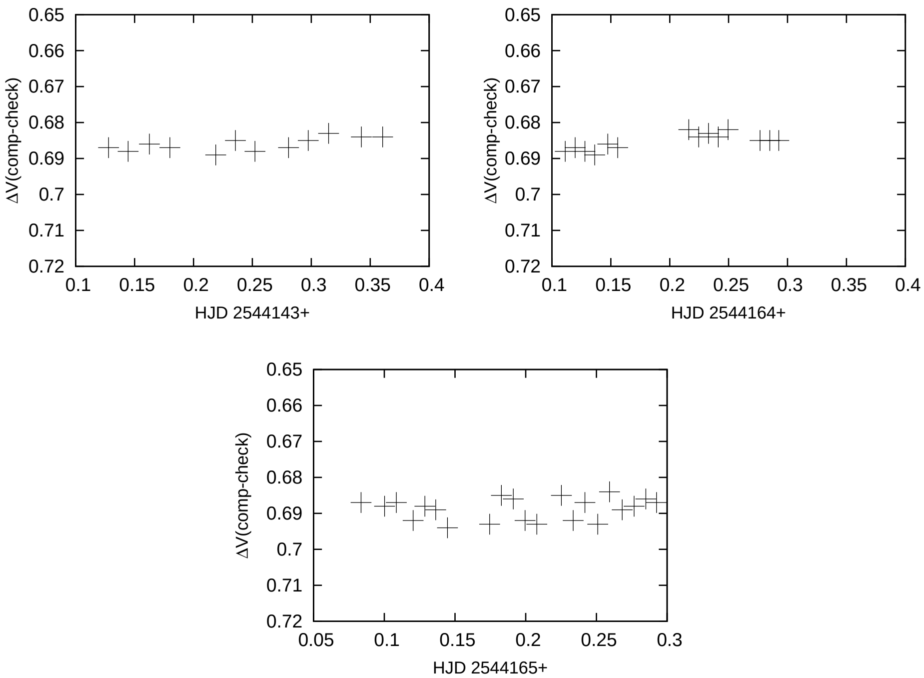

Fig. 2 The three panels show the magnitude differences between the comparison and check stars in V magnitude versus HJD for observations on 2009 November 7, 28 and 29.

stars (C1–C2) versus HJD for the observing dates. The reduced results show that the difference between the magnitudes of the comparison star and check star was constant with a probable error of $\pm 0.009^{\rm m}$.

3 PHOTOMETRIC SOLUTIONS

The photometric solutions for V30 were obtained by using the Wilson-Devinney Code (van Hamme & Wilson 2003) with an option of non-linear limb darkening via a square root law along with many other features. We defined the more-massive component as star 1 and the less massive component as star 2 in the following analysis. The following assumptions were made in the computation of photometric solutions. The temperature of star 1, T_1, was obtained using the equation $(B-V)_o = 0.062 - 1.31\ \log P$ (Wang 1994), where the orbital period P is in days. The rotation and revolution of the variable was assumed to be synchronized, hence we chose $F_1 = F_2 = 1$. The gravity darkening exponents were taken to be $g_1 = g_2 = 0.32$ (Lucy 1967) and albedos $A_1 = A_2 = 0.5$ were adopted (Ruciński 1969). The limb-darkening coefficients were taken as $x_1 = x_2 = 0.78$ in the V band which is based on the result from Diaz-Cordoves et al. (1995). The adjustable parameters were the orbital inclination i, the mean temperature of the star T_2, the potentials Ω_1 and Ω_2 of the components and the non-dimensional luminosities L_1 and L_2. The wavelength for the V passband was taken as $5497\,$Å.

The photometric solutions were computed at a series of mass ratios $q = m_2/m_1$ with values 0.1, 0.2. 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 1.0. 1.1, 1.2, 1.3, 1.4, 1.5, 2.0, 3.0, 4.0 and 5.0 (Table 2). The differential correction (DC) program started from mode 2 (detached) and rapidly ran to mode 3 (contact). After several runs in iteration, a converged solution was reached for each assumed q.

Table 2 Obtained Values of q and Σ for Variable V30

q	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
Σ for V30	0.0614	0.0249	0.0058	0.0002	0.0066	0.0245	0.0532	0.0926	0.1421	0.2017
q	1.1	1.2	1.3	1.4	1.5	2.0	3.0	4.0	5.0	
Σ for V30	0.2708	0.3495	0.4377	0.5348	0.6408	1.2995	3.2071	5.8142	9.0414	

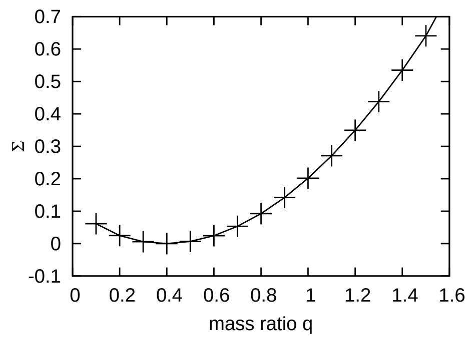

Fig. 3 q verses Σ for variable V30.

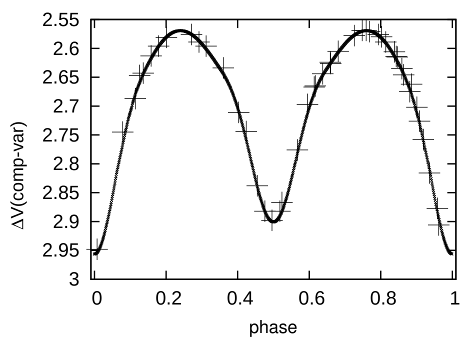

Fig. 4 Best fit in the V band light curve for variable V30 (NGC 7789). The points represent the observed data.

The resulting sum, $\sum(\omega_i(o-c)_i)^2$, of the weighted square deviations of the converged solutions for each value of q are shown in Table 2 and are also plotted in Figure 3. This method was adopted by us in earlier works (Rukmini & Vivekananda Rao 2002; Rukmini et al. 2005; Sriram et al. 2009; Sriram & Vivekananda Rao 2010). The results of the final analysis are shown in Table 3. Using the final parameters given in Table 3, the theoretical light curve is computed using the LC program of Wilson-Devinney and the fit is shown in Figure 4. The quality of the fit was checked by performing a chi square (χ^2) test on the $\sum(\omega_i(o-c)_i)^2$ values obtained and the confidence level was found to be about 95% for the variable.

4 RESULTS AND DISCUSSION

The periodic variation of the light curve indicates the system to be of W UMa binary type. The period of the system is 0.3862 d and $B-V$=0.603 which corresponds to a G0 spectral type. The result in

Table 3 Photometric Elements Obtained for the Variable V30 by Using the W-D Method

Element		V30
Geometric Parameters		
Period (d)		0.3862
i^o		69.59±0.42
q (m_2/m_1)		0.395±0.018
$\Omega_{1,2}$		2.688±0.037
$\Omega_{\rm in}$		3.536
$\Omega_{\rm out}$		3.057
Fill-out factor		0.163
Fractional radii of star 1		
r_1	pole	0.4300±0.007
	point	0.5565±0.062
	side	0.4582±0.010
	back	0.4841±0.013
Fractional radii of star 2		
r_2	pole	0.2797±0.011
	point	0.3714±0.081
	side	0.2912±0.013
	back	0.3221±0.021
Radiative Parameters		
T_1 (K)		5900
T_2 (K)		5528±74
Spectral type		G0
Luminosity Ratio		
L_1		0.7609
L_2		0.2391
$x_1 = x_2$		0.78
$A_1 = A_2$		0.5
$g_1 = g_2$		0.32
λ		5497
$\Sigma w(o-c)^2$		0.0018

Table 4 Estimated Absolute Elements for Variable V30 of NGC 7789

Parameter	Value
$M_1(M_\odot)$	1.249±0.023
$M_2(M_\odot)$	0.494±0.011
a (au)	2.698±0.046
$H_{\rm orb}$ (CGS Units)	4.64×10^{51}
$R_1(R_\odot)$	0.968±0.024
$R_2(R_\odot)$	0.927±0.023

Notes: 1 – Primary, 2 – Secondary.

the V filter shows a temperature difference of $\sim 375\,$K between the two components. The fill-out factor of 0.16 also shows that the contact is less. The best combined values of q and i came out to be 0.395 and 69.6° respectively. The low mass ratio and the low fill-out factor make this system fall into the category of a W-subtype W UMa system (Gazeas & Stępień 2008). Since the orbital parameters of W UMa-type contact binaries obey the basic relations resulting from the Roche lobe, the formulas given in Gazeas & Stępień (2008) are used to obtain the absolute parameters of masses M_1 and M_2, semi-major axis a, angular momentum H, and stellar radii R_1 and R_2 (Table 4).

Several models have been proposed for the evolution of contact binaries. In his model of a cool contact binary, Lucy (1976) assumed that both components of W type stars are located on the Zero Age Main Sequence (ZAMS) and they evolve via Thermal Relaxation Oscillations (TRO) with a secular mass transfer from the secondary to the primary component until the primary reaches a limiting mass of the CNO cycle which dominates the hydrogen burning process. The primary then evolves off the ZAMS and increases its radius so that both components can fill their critical Roche lobes and be in thermal equilibrium. Gazeas & Niarchos (2006) suggested that the evolutionary process goes from near contact binaries to A-type contact binaries without any need for mass loss from the system. They noted that the mass of the primary components of W UMa-type binaries increases steeply with increasing period, whereas the mass of the secondaries is nearly period independent and varies between 0–1 $M_\odot$. When the total mass is investigated W type systems are generally less massive than A type systems. Gazeas (2009) has demonstrated that knowledge of the orbital period alone suffices to determine the absolute magnitude of the system as well as masses and radii of the components with an accuracy of about 15%. The primary components closely follow the mass-radius relation for main sequence stars.

Stępień (2004) and Stepien (2006a,b) suggested that cool contact binaries are formed from detached close binaries with initial (ZAMS) orbital periods of a couple of days and total masses between about 1.4 and 2.6 $M_\odot$. Components of the binary lose mass and angular momentum (AM) via magnetized stellar wind which results in the tightening of the orbit. The time scale of orbital angular momentum loss (AML) is on the order of several Gyr, i.e. the same as the evolutionary time scale of a more massive (primary) component. Both time scales grow with decreasing stellar mass in a similar way, hence the primary is at or near terminal age main sequence (TAMS) when the shrinking Roche Lobe reaches its surface; Roche Lobe Over Flow (RLOF) results, which is followed by mass exchange between the components through the common envelope phase. The model assumes that mass transfer continues until mass ratio reversal occurs and it stops only when the Roche Lobe of the depleted hydrogen-mass-losing component becomes larger than the stellar size. Depending on the detailed values of the involved parameters, the other component (now more massive) may fill or under-fill its Roche Lobe. A contact binary is formed in the former case and a short period Algol in the later. However, after additional AML, it is also converted into a contact configuration. Both components are in thermal equilibrium. It is assumed that an energy exchange takes place via large scale circulations in the common envelope above the inner critical surface and that it does not influence the stellar radius. As was shown by Kähler (2004), the state of both stars exchanging energy can indeed be in thermal equilibrium. The evolution in the degree of contact is driven by a slow expansion of the present secondary component (which accumulates a helium core) followed by the mass transfer to the present primary component, accompanied by mass and AML due to stellar winds. Depending upon the relative importance of mass transfer and AML, an extreme mass ratio, or a very tight, medium mass ratio binary will be formed. In either case, both the components merge thus forming a single rapidly rotating star.

If we assume the TRO mechanism is the driving process, then the temperature difference (375 K) suggests that the V30 system crossed the marginal contact phase and is evolving towards the shorter period configuration. During the evolution towards the shorter period configuration, the massive component will transfer its mass to a less massive component, however, and the high AML mechanism would accelerate the evolution to reach a shorter period configuration.

In all these evolutionary models, the mass, angular momentum and the mass ratio (q) are the most important parameters. Since the mass ratio obtained from photometric analysis is preliminary, spectroscopic radial velocity measurements are needed to ascertain the value of q.

Acknowledgements We acknowledge the anonymous referee for the useful comments. We thank the Director of IUCAA for allotting observing time for us on the 2.0 m telescope.

References

Burbidge, E. M., & Sandage, A., 1958, ApJ, 128, 174
Diaz-Cordoves, J., Claret, A., & Gimenez, A. 1995, A&AS, 110, 329
Friel, E. D., & Janes, K. A. 1993, A&A, 267, 75
Gazeas, K., & Stępień, K. 2008, MNRAS, 390, 1577
Gazeas, K. D. 2009, Communications in Asteroseismology, 159, 129
Gazeas, K. D., & Niarchos, P. G. 2006, MNRAS, 372, L83
Jahn, K., Kaluzny, J., & Rucinski, S. M. 1995, A&A, 295, 101
Kähler, H. 2004, A&A, 414, 317
Lucy, L. B. 1967, ZAp, 65, 89
Lucy, L. B. 1976, ApJ, 205, 208
Mochejska, B. J., & Kaluzny, J. 1999, Acta Astronomica, 49, 351
Ruciński, S. M. 1969, Acta Astronomica, 19, 245
Rucinski, S. M., & Duerbeck, H. W. 1997, PASP, 109, 1340
Rukmini, J., Rao, P. V., & Sriram, K. 2005, Ap&SS, 299, 109
Rukmini, J., & Vivekananda Rao, P. 2002, Bulletin of the Astronomical Society of India, 30, 665
Sriram, K., Kiron, Y. R., & Vivekananda Rao, P. 2009, RAA (Research in Astronomy and Astrophysics), 9, 1149
Sriram, K., & Vivekananda Rao, P. 2010, RAA (Research in Astronomy and Astrophysics), 10, 159
Stępień, K. 2004, in Stars as Suns: Activity, Evolution and Planets, IAU Symposium, 219, eds. A. K. Dupree & A. O. Benz, 967
Stepien, K. 2006a, Acta Astronomica, 56, 199
Stepien, K. 2006b, Acta Astronomica, 56, 347
van Hamme, W., & Wilson, R. E. 2003, in GAIA Spectroscopy: Science and Technology, Astronomical Society of the Pacific Conference Series, 298, ed. U. Munari, 323
Wang, J.-M. 1994, ApJ, 434, 277
Wu, Z.-Y., Zhou, X., Ma, J., et al. 2007, AJ, 133, 2061
Zhang, X.-B., Deng, L.-C., Xin, Y., & Zhou, X. 2003, ChJAA (Chin. J. Astron. Astrophys.), 3, 151