PHOTOMETRIC INVESTIGATION OF THE TOTALLY ECLIPSING CONTACT BINARY V12 IN THE INTERMEDIATE-AGE OPEN CLUSTER NGC 7789

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ABSTRACT

NGC 7789 is an intermediate-age open cluster with an age similar to the mean age of contact binary stars. V12 is a bright W UMa-type binary star with an orbital period of 0.3917 days. The first complete light curves of V12 in the $V, R,$ and $I$ bands are presented and analyzed with the Wilson– Devinney (W–D) method. The results show that V12 is an intermediate-contact binary with a mass ratio of 3.848, and it is a W-type contact binary where the less massive component is slightly hotter than the more massive one. The asymmetry of the light curves is explained by the presence of a dark spot on the more massive component. The derived orbital inclination ($i = 83^\circ$) indicates that it is a totally eclipsing binary, which suggests that the determined parameters are reliable. The orbital period may show a long-term increase at a rate of $P = 2.48 (0.17) \times 10^{-6}$ days$^{-1}$ that reveals a rapid mass transfer from the less massive component to the more massive one. However, more observations are needed to confirm this conclusion. The presence of an intermediate-contact binary in an intermediate-age open cluster may suggest that some contact binaries have a very short pre-contact timescale. The presence of a third body and/or stellar collision may help to shorten the pre-contact evolution.

Key words: binaries: close – binaries: eclipsing – stars: evolution – stars: individual (V12 in NGC 7789)

1. INTRODUCTION

NGC 7789 is a rich and intermediate-age open cluster. Burbidge & Sandage (1958) determined the colors and magnitudes of nearly 700 stars in the cluster. A proper motion study by McNamara & Solomon (1981) yielded 679 probable member stars in NGC 7789. This cluster has been the target of several searches for variables. Jahn et al. (1995) made the first time-resolved CCD photometry, which resulted in the discovery of 15 variables in the central part, among which most of the variables are of eclipsing type. Later, Kim & Park (1999) detected 16 variables, including 8 suspected variables and 3 old objects previously discovered by Jahn et al. (1995). CCD photometric monitoring on NGC 7789 was carried out by Mochejska & Kaluzny (1999), who observed this cluster in two different fields (the central part and an extended area). A total of 45 variables were found, 31 in the central part and 14 in the extended area. As the second target of the BATC variable searching program in open clusters (Zhang et al. 2003), NGC 7789 was monitored in 2000 and 28 new variable stars were discovered, including 23 eclipsing binaries. Most of the eclipsing variables are of W UMa type with periods shorter than a day.

W UMa-type variable stars are interacting binaries where both components overfill their critical Roche lobe and share a common convective envelope. Photometric investigation of totally eclipsing contact binary stars in stellar clusters is very important to understand their formation and evolution. A few W UMa-type binaries (e.g., V22 and V31) in NGC 7789 have been studied (e.g., Sriram et al. 2010; Kiron et al. 2011). However, those targets are partially eclipsing binaries and the original photometric data showed a large scatter. Therefore, photometric parameters cannot be determined with higher precision. V12 (=2MASSJ23581634 + 5631202) is one of the bright eclipsing binary in NGC 7789 that was discovered by Zhang et al. (2003). It is a typical W UMa binary with an orbital period of 0.3917 days. Recently, several contact binaries in open clusters of different ages have been investigated (e.g., Liu et al. 2007, 2008, 2011; Qian et al. 2006a, 2007; Zhu et al. 2014). The light curve of V12 derived by Zhang et al. (2003) indicates that photometric parameters of the W UMa-type binary can be obtained with high precision because of the brightness and total eclipses. Therefore, it was included in our photometric investigation program of totally eclipsing binaries in stellar clusters.

2. NEW CCD PHOTOMETRIC OBSERVATIONS AND ORBITAL PERIOD CHANGES

Photometric observations of the eclipsing binary system V12 in the intermediate-age open cluster NGC 7789 were obtained on 2013 October 8 and 9 using an EEV CCD 42-40 camera attached to the Newtonian focus of the 1.88 m Kottamia reflector telescope in Egypt (see Azzam et al. 2010). The CCD 42-40 camera has a format of 2048 × 2048 pixels with a scale of 0.′′305 pixel$^{-1}$ that was cooled by liquid nitrogen to −125°C. During the observations, the $V, R,$ and $I$ wide passband filters that are close to the standard Johnson system were used. Because the binary is cool and faint and we need high time-resolution data, the $B$ filter was not used. The package of IRAF, PHOT, was used to reduce the CCD images. Two stars, GSC 1-4009-02036 and TYC 4009-939-1, were chosen as the comparison and the check stars. They are very close to V12 and their positions are shown in Figure 1 where “V12” refers to the

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The Image Reduction and Analysis Facility (IRAF) is a collection of software written at the National Optical Astronomy Observatory (NOAO) geared toward the reduction of astronomical images in pixel array form.
eclipsing binary, “C2” to the comparison star, and “C1” to the check star, respectively. The coordinates, magnitudes, and colors of these stars are listed in Table 1. The brightness and color of the comparison star are very similar to those of V12.

The light curves in the V, R, and I bands obtained on 2013 October 8 and 9 are displayed in Figures 2 and 3. As shown in the two figures, the light curves are typical EW type, where the brightness varies continuously and the depths of both light minima are nearly the same. The nearly flat eclipse reveals that V12 is a totally eclipsing binary. The amplitudes of the light variation are about ≈0.50 mag in the V, R, and I bands. The light curves show a positive O’Connell effect and the light maxima following the primary minima are higher than the other ones (O’Connell 1951). Three epochs of eclipse times in different bands were determined with the Kwee & van Woerden (1956) method. The mean values are listed in Table 2.

The first linear ephemeris of V12 was determined by Zhang et al. (2003),

\[ \text{Min. } I(HJD) = 2451812.146 + 0.3917 \times E. \]  

The previous eclipse time, HJD 2453765.5186, was determined by Biro et al. (2006). The O–C values with respect to the linear ephemeris derived by Zhang et al. (2003) were computed and are listed in Table 3. The corresponding O–C curve is displayed in Figure 4 along with the epoch number E. As displayed in the upper panel of Figure 4, the general trend of

![Figure 1](image1.png) One of the CCD images of V12 in the intermediate-age open cluster NGC 7789 obtained using the 1.88 m Kottamia reflector telescope in Egypt. C2 and C1 are the comparison and the check stars, respectively. North is up and east is to the left.

![Figure 2](image2.png) CCD photometric light curves of V12 observed on 2013 October 8. Solid squares, circles, and triangles refer to V + 0.1, R, and I-0.1, respectively. Magnitude differences between C2 and C1 are also displayed in the figure as open squares, circles, and triangles for the V, R, and I bands, respectively.

![Figure 3](image3.png) Same as in Figure 2 but observed on 2013 October 9.

### Table 1

| Targets  | Names                  | \( \alpha_{2000} \)   | \( \delta_{2000} \)   | \( B \)     | \( B - V \) |
|----------|------------------------|-----------------------|-----------------------|-----------|-----------|
| V12      | 2MASS J23581634 + 5631202 | 23\(^h\)58\(^m\)16\(^s\)3 | 56\(^\circ\)31\('\)20\("\)3 | 13.873    | 0.636     |
| Comparison (C2) | GSC 1-4009-02036 | 23\(^h\)58\(^m\)12\(^s\)5 | 56\(^\circ\)32\('\)17\("\)8 | 13.874    | 0.596     |
| Check (C1) | TYC 4009-939-1 | 23\(^h\)58\(^m\)20\(^s\)2 | 56\(^\circ\)32\('\)34\("\)9 | 11.818    | 0.280     |

### Table 2

| HJD (days) | Errors (days) | Filters |
|------------|---------------|---------|
| 2456574.4638 | 0.0007        | VRI     |
| 2456575.4450 | 0.0003        | VRI     |
| 2456575.2469 | 0.0006        | VRI     |

### Table 3

| HJD (days) | E   | \( O - C \) (days) | Residuals (days) |
|------------|-----|--------------------|------------------|
| 2451812.146 | 0   | 0.0000             | 0.0000           |
| 2453765.5186 | 4987 | -0.0353            | 0.0000           |
| 2456574.4638 | 12158 | +0.0292            | -0.0005          |
| 2456575.2469 | 12160 | +0.0298            | -0.0009          |
| 2456575.4450 | 12160.5 | +0.0312           | +0.0014          |
the $O-C$ curve shows an upward parabolic change indicating an increase in the orbital period. Using a least-squares method, we yielded

$$\text{Min. } I = 2451812.1460(\pm 0.0004) + 0.3916863(\pm 0.0000001) \times E + 1.33(\pm 0.09) \times 10^{-9} \times E^2.$$  \hspace{1cm} (2)

The quadratic term in Equation (2) reveals a linear increase at a rate of $P = +2.48(\pm 0.17) \times 10^{-6}$ days year$^{-1}$ (or 214 in about 100 years). The solid line in the upper panel of Figure 4 refers to the linear period increase. After the upward parabolic change was removed, the residuals are displayed in the lower panel of Figure 4.

3. PHOTOMETRIC SOLUTIONS WITH THE WILSON–DEVINNEY (W–D) METHOD

The light curves of V12 displayed in Figures 2 and 3 indicate that it is a totally eclipsing binary. The multi-color light curves of the binary are very useful to determine reliable photometric parameters. Therefore, to derive photometric elements and to understand the evolutionary state of the binary star, those light curves were analyzed simultaneously with the 2010 version of the W-D program (Wilson & Devinney 1971; Wilson 1979, 1990). The phases of those observations are calculated with the following ephemeris,

$$\text{Min. } I (\text{HJD}) = 2456575.24687 + 0^d3916863 \times E,$$  \hspace{1cm} (3)

where the initial epoch is one of our times of minimum light, while the orbital period is from Equation (2). The corresponding phased light curves are shown in Figure 5.

Considering the $B - V = 0.636$, we fixed the temperature for star 1 (star eclipsed at the primary minimum light) as $T_1 = 5862$ K (Cox 2000). Because both components are late-type stars, the gravity-darkening coefficients $g_1 = g_2 = 0.32$ and the bolometric albedo $A_1 = A_2 = 0.5$ were used. The bolometric limb-darkening coefficients $x_{1,\text{bol}}$ and $x_{2,\text{bol}}$ and the passband-specific limb-darkening coefficients were chosen from van Hamme (1993) and are listed in Table 4. For a detailed treatment of limb darkening, we used the square-root functions for both the bolometric and bandpass limb-darkening laws. During the computation, we found that solutions converged at mode 3, and the adjustable parameters are the orbital inclination $i$; the mean temperature of star 2, $T_2$; the monochromatic luminosity of star 1, $L_{1V}$, $L_{1R}$, and $L_{1I}$; and the dimensionless potential ($\Omega_1 = \Omega_2$ for mode 3).

Since no photometric solutions of V12 were obtained earlier, we first used a $q$-search method to determine the mass ratio. We searched for solutions with mass ratios from 0.2 to 4.8, and 75 sets of solutions were derived. The relation between the resulting sum $\Sigma$ of weighted square deviations and $q$ is plotted in Figure 6. Two minimum values are found at $q = 0.28$ and $q = 3.7$. The solution at $q = 0.28$ indicates that V12 is an A-type contact binary, while the other at $q = 3.7$ reveals it is a W-type system. It is interesting that there is a relation between the two values, i.e., $q_A = 0.28$ is close to $1/q_W = 0.27$. However, as shown in Figure 6, the minimum at $q = 3.7$ is much lower than that at $q = 0.28$. Therefore, we chose $q = 3.7$ as the initial value of $q$ and consider it an adjustable parameter. Then, a differential correction were performed and final solutions were obtained. The photometric solutions are listed in Table 4 and the theoretical light curves are displayed in Figure 5. Our solution suggests that V12 is a W-type contact binary.

It was found that the fitted theoretical light curves and the observations are not in good agreement around the two maxima (Figure 5). Since both components are fast-rotating solar-type stars, they should show solar-like activity, including photospheric dark spots. Therefore, the asymmetry of the light curves can be plausibly explained due to the presence of a dark spot. In the W-D program, each dark spot has four parameters: the latitude of the spot center (θ) in degrees, the longitude of the spot center (φ) in degrees, the spot angular radius (r) in radians, and the spot temperature factor $C_\text{fi}$ (c coefficients = 0.3212 $V_{\text{bol}}$). The solid line in the upper panel of Figure 4 reveals a long-term variation of the $O-C$ curve. The upward parabolic variation $C_{\text{fi}}$ curve shows an upward parabolic change indicating a long-term increase in the orbital period. The residuals after the increase was subtracted are shown in the lower panel of Figure 4.

4. DISCUSSIONS AND CONCLUSIONS

Photometric solutions derived in the previous section suggest that V12 is a contact binary system with a degree of contact of $f = 43.0\%$. The mass ratio was determined to be $1/q = 0.26$. The color index of $B - V = 0.636$ suggests that the system is a G2-type main-sequence star. The mass of the more massive component is estimated to be $M_2 = 1.0 M_\odot$ (Cox 2000), so the mass of the less massive one can be estimated as $M_1 = 0.26 M_\odot$, using the value of $q$. The high orbital inclination of 83.3 indicates that the eclipse during the primary minimum is occultation and the derived parameters are reliable. The positive O'Connell effect was explained as the presence of a dark spot on the more massive component. We found that the temperature of the dark spot is about 1170 K lower than the stellar photosphere, while it covers 1.6% of the total photospheric surface.
The general trend of the $O-C$ curve in Figure 4 (solid line) shows an upward parabolic variation, indicating a long-term period increase at rate of $P = +2.48( \pm 0.17) \times 10^{-6}$ days year$^{-1}$. This can be explained by mass transfer from the less massive component to the more massive one. Considering a conservative mass transfer, our calculation, using the

Table 4
Photometric Solutions of V12 in NGC 7789

| Parameters | Photometric Elements | Photometric Elements |
|------------|----------------------|----------------------|
| $g_1 = g_2$ | 0.32 | fixed | 0.32 | fixed |
| $A_1 = A_2$ | 0.50 | fixed | 0.50 | fixed |
| $x_{\text{bolo}}^1 = x_{\text{bolo}}^2$ | 0.185 | fixed | 0.185 | fixed |
| $y_{\text{bolo}}^1 = y_{\text{bolo}}^2$ | 0.534 | fixed | 0.534 | fixed |
| $s_1 = s_2$ | 0.229 | fixed | 0.229 | fixed |
| $y_1 = y_2$ | 0.607 | fixed | 0.607 | fixed |
| $s_1R = s_2R$ | 0.104 | fixed | 0.104 | fixed |
| $y_1R = y_2R$ | 0.644 | fixed | 0.644 | fixed |
| $x_{\text{fit}} = x_{\text{fit}}$ | 0.028 | ... | 0.028 | fixed |
| $y_{\text{fit}} = y_{\text{fit}}$ | 0.623 | ... | 0.623 | fixed |
| Phase shift | 0.0026 | $\pm 0.0002$ | 0.0039 | $\pm 0.0002$ |
| $T_1$ | 5862 K | fixed | 5862 K | fixed |
| $T_2$ | 5653 K | $\pm 10$ K | 5686 K | $\pm 7$ K |
| $q$ | 3.766 | $\pm 0.012$ | 3.848 | $\pm 0.009$ |
| $i$ ($^\circ$) | 83.5 | $\pm 0.5$ | 83.6 | $\pm 0.4$ |
| $\Omega_1 = \Omega_2$ | 7.4017 | $\pm 0.0095$ | 7.4417 | $\pm 0.0095$ |
| $\Omega_3$ | 7.6134 | ... | 7.7174 | ... |
| $\Omega_{\text{out}}$ | 6.9723 | ... | 7.0755 | ... |
| $L_1/(L_1 + L_2)(V)$ | 0.2681 | $\pm 0.0014$ | 0.2622 | $\pm 0.0010$ |
| $L_1/(L_1 + L_2)(R)$ | 0.2620 | $\pm 0.0011$ | 0.2572 | $\pm 0.0009$ |
| $L_1/(L_1 + L_2)(I)$ | 0.2576 | $\pm 0.0009$ | 0.2536 | $\pm 0.0007$ |
| $n$ (pole) | 0.2658 | $\pm 0.0013$ | 0.2684 | $\pm 0.0011$ |
| $n$ (side) | 0.2787 | $\pm 0.0016$ | 0.2820 | $\pm 0.0014$ |
| $n$ (back) | 0.3240 | $\pm 0.0033$ | 0.3326 | $\pm 0.0031$ |
| $\eta_1$ (pole) | 0.4778 | $\pm 0.0010$ | 0.4831 | $\pm 0.0009$ |
| $\eta_1$ (side) | 0.5191 | $\pm 0.0014$ | 0.5264 | $\pm 0.0012$ |
| $\eta_1$ (back) | 0.5477 | $\pm 0.0018$ | 0.5563 | $\pm 0.0016$ |
| $f$ | 33.0% | $\pm 2.5\%$ | 43.0% | $\pm 2.2\%$ |
| $\theta$ ($^\circ$) | ... | ... | 85.94 | $\pm 34.13$ |
| $\psi$ ($^\circ$) | ... | ... | 240.64 | $\pm 8.05$ |
| $r$ (rad) | ... | ... | 0.1985 | $\pm 0.1550$ |
| $T_f$ | ... | ... | 0.8000 | $\pm 0.1797$ |
| $\Sigma^2(O-C)^2$ | 0.01518 | ... | 0.01504 | ... |

Figure 5. Theoretical light curves calculated without considering dark spots. Open squares, circles, and triangles refer to the light curve in the $V$, $R$, and $I$ bands, respectively. It is shown that those theoretical light curves cannot fit the observations well around two maximum light values.

Figure 6. Relation between $\Sigma$ and $q$. 

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\[ \frac{\dot{P}}{P} = -3 \dot{m} \left( \frac{1}{M_1} - \frac{1}{M_2} \right), \tag{4} \]

yields a mass transfer rate of \( \dot{m}/dt = 2.9 \times 10^{-7} M_\odot \text{ year}^{-1} \).

A similar period increase was observed in some contact binaries, e.g., EM Psc with a rate of period increase of \( \dot{P} = + 3.97 \times 10^{-6} \text{ days year}^{-1} \) (Qian et al. 2008). V12 is a low mass ratio contact system with a mass ratio of \( 1/q = 0.26 \); the rapid mass transfer from the less massive to the more massive component will cause it to evolve toward an extreme mass ratio. It will finally coalesce to form a single rapidly rotating star when it meets the more familiar criterion that the orbital angular momentum is less than three times the total spin angular momentum, i.e., \( J_{\text{orb}} < 3J_{\text{tot}} \) (Hut 1980). However, as shown in the upper panel of Figure 4, the period increase is only supported by several eclipse times. Moreover, since the rate of the long-term period change is very large, the upward parabolic change may be only a part of a long-period cyclic oscillation that may be caused by the presence of a third body. To confirm this conclusion, more times of minimum light are required in the future.

The origin and evolution of W UMa-type contact binaries were discussed in several studies (e.g., Huang 1966; van’t Veer 1979; Vilhu 1982; Guinan et al. 1988; Eggen & Iben 1989 and Bradstreet & Guinan 1994). These authors considered that this type of binary evolves into contact configuration from initially detached binaries through angular momentum loss (AML) via magnetic torques from stellar winds. The evolutionary expansion of the more massive component together with the orbital shrinkage due to AML should result in mass transfer from the more massive component to the less massive one, and finally a contact system is formed. Using the magnitude \( V = 13.42 - 13.95 \) determined by Zhang et al. (2003) and the color index \( (B - V) = 0.636 \) obtained by Zacharias et al. (2013), we plotted the position of V12 in the color–magnitude diagram (CMD) of NGC 7789 in Figure 9, with CMD data from Gim et al. (1998). It is shown that the system is just above the main-sequence turnoff point. This indicates that V12 has undergone a mass transfer from the more massive star to the less massive one. It seems like a blue straggler of this cluster and it may be a member star in NGC 7789. However, since the distance of V12 was not determined independently, the question whether or not it is a member of NGC 7789 is still open.
Gyr. The mean age of contact binaries is about \( t = 1.4(\pm 0.1) \) Gyr. Figure 9. Position of V12 in the color–magnitude diagram of NGC 7789.

Friel & Janes (1993) found the age of NGC 7789 to be about 2 Gyr, while the age determined by Gim et al. (1998) is about 1.6 Gyr. Recently, Wu et al. (2007) presented new BATC 13 band photometric results and derived a set of best fitting fundamental parameters for this cluster, including an age of \( t = 1.4(\pm 0.1) \) Gyr. The mean age of contact binaries is about 1.61 Gyr (e.g., Bilir et al. 2005), which suggests that the age of NGC 7789 is close to the mean lifetime of contact binary stars. On the other hand, the aforementioned evolutionary scheme predicted that the pre-contact timescale would be long and intermediate, or deep contact binary stars would appear in old open clusters such as AH Cnc in the old open cluster M67 (e.g., Qian et al. 2006b). It is somewhat surprising that the contact system V12 (\( f = 43.0\% \) and \( 1/q = 0.26 \)) exists in the intermediate-age open cluster NGC 7789 (with an age of \( \sim 1.6 \) Gyr). The other two interesting cases are QX And (\( f = 55.9\% \)) in the intermediate-age open cluster NGC 752 (with an age of \( \sim 2.0 \) Gyr) and TX Cnc (\( f = 24.8\% \)) in the young open cluster NGC 2632 (e.g., Qian et al. 2007; Liu et al. 2007). However, only a few contact binaries in open clusters were investigated in detail and no relation between the evolution of a contact binary and the respective open cluster’s age is obtained.

The probable detection of an intermediate-contact binary (\( f = 43.0\% \)) in the intermediate-age open cluster NGC 7789 reveals that it has a very short pre-contact timescale. One explanation is that it has undergone a collision path to faster evolution and thus has a very short initial orbital period. On the other hand, if there is a third body in the system, it should play an important role by removing angular momentum from the central binary (e.g., Qian et al. 2013a, 2013b, 2013c). An independent determination of the cluster membership of V12 is important in establishing the conclusion suggested in this paper.

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