THE FIRST PHOTOMETRIC ANALYSIS OF THE NEAR CONTACT BINARY IR Cas

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ABSTRACT

The first photometric analysis of IR Cas was carried out based on the new observed BVRI light curves. The symmetric light curves and nearly flat secondary minimum indicate that very precise photometric results can be determined. We found that IR Cas is a near contact binary with the primary component filling its Roche lobe. An analysis of the O–C diagram based on all available times of minimum light reveals evidence for a periodic change with a semi-amplitude of 0.0153 days and a period of 39.7 yr superimposed on a secular decrease at a rate of \( dp/dt = -1.28(\pm 0.09) \times 10^{-7} \) days yr\(^{-1}\). The most reasonable explanation for the periodic change is the light time-travel effect due to a third body. The period decrease may be caused by mass transfer from the primary component to the secondary. With the decreasing period, IR Cas would eventually evolve into a contact system.

Key words: binaries: close – binaries: eclipsing – stars: individual (IR Cas)

Online-only material: machine-readable and VO tables

1. INTRODUCTION

A binary star is called a near contact binary if the components are very close to filling their Roche lobes. The typical light curve of a near contact binary is an EB-type light variation. The spectral types of their primary and secondary components are A or F and G or K, respectively. Theoretical studies suggest that near contact binaries could be in the intermediate stage between a detached or semi-detached state and a contact state (e.g., Hilditch 2001 and Shaw 1990). Once a component fills its critical Roche lobe, mass transfer will occur. Therefore, these binaries are important observational targets to study mass transfer in close binaries and understand the evolutionary stages of interacting binaries.

In this context, we chose IR Cas (GSC 03998-02007, \( V = 11.14 \) mag) as the target to study. The light curve of IR Cas shows typical EB-type light variation. VanLeeuwen & Milone (1987) observed the \( VBI \) light curves of IR Cas using the Rapid Alternate Detection System, and published differential \( I \) light curves. IR Cas displayed an apparent variable O’Connell effect during their observation. The orbital period of IR Cas was first analyzed by Zhu et al. (2004); a cyclic oscillation with a period of 53.24 yr and an amplitude of about 0.133 days were aperiodic from the values of van Hamme (1993): \( x_{1bol} = 0.108, x_{2bol} = 0.167, y_{1bol} = 0.615, y_{2bol} = 0.553, x_{1I} = 0.224, x_{2I} = 0.428, y_{1I} = 0.658, y_{2I} = 0.462, x_{1V} = 0.083, x_{2V} = 0.190, y_{1V} = 0.710, y_{2V} = 0.640, x_{1R} = -0.017, x_{2R} = 0.075, y_{1R} = 0.717, y_{2R} = 0.667, x_{1J} = -0.075, x_{2J} = 0.005, y_{1J} = 0.679, \) and \( y_{2J} = 0.640. \) Following Lucy (1967) and Ruciński (1969), gravity-darkening coefficients of \( g_{1I} = 0.32 \) and bolometric albedo coefficients of \( A_{1I} = 0.5 \) were set, which are appropriate for stars with convective envelopes. During our solutions, the adjustable parameters were as follows: the orbital inclination \( i, \) the mass ratio \( q, \) the effective temperature of the secondary component \( T_2, \) the monochromatic times are \( 30 \) s for the \( B \) band, \( 20 \) s for the \( V \) band, \( 10 \) s for the \( R \) band, and \( 8 \) s for the \( I \) band, respectively. The comparison and check stars are shown in Figure 1; they are near the target and have similar spectral types and visual magnitudes. The observed images were processed using the Image Reduction (IMRED) and Aperture Photometry (APPHOT) packages in the Image Reduction and Analysis Facility (IRAF\(^4\)) in standard fashion. The errors of individual points do not exceed 0.01 mag. The observed four color light curves are displayed in Figure 2. EB-type light curves can be clearly seen. Three new times of minimum light (2456574.0514, 2456575.0720, and 2456604.0014) are obtained.

3. THE FIRST PHOTOMETRIC ANALYSIS

The observed four color light curves of IR Cas were simultaneously analyzed by using the fourth version of the W-D program (Wilson & Devinney 1971; Wilson 1990, 1994). The symmetric light curves and nearly flat secondary minimum indicate that we can determine very precise photometric results. According to the fourth edition of the GCVS (Kholopov 1987), the spectral type of IR Cas is F4. Therefore, the mean temperature for Star 1 was chosen as \( T_1 = 6750 \) K. The square root law bolometric and bandpass limb-darkening coefficients were interpolated from the values of van Hamme (1993): \( x_{1bol} = 0.108, x_{2bol} = 0.167, y_{1bol} = 0.615, y_{2bol} = 0.553, x_{1I} = 0.224, x_{2I} = 0.428, y_{1I} = 0.658, y_{2I} = 0.462, x_{1V} = 0.083, x_{2V} = 0.190, y_{1V} = 0.710, y_{2V} = 0.640, x_{1R} = -0.017, x_{2R} = 0.075, y_{1R} = 0.717, y_{2R} = 0.667, x_{1J} = -0.075, x_{2J} = 0.005, y_{1J} = 0.679, \) and \( y_{2J} = 0.640. \) Following Lucy (1967) and Ruciński (1969), gravity-darkening coefficients of \( g_{1I} = 0.32 \) and bolometric albedo coefficients of \( A_{1I} = 0.5 \) were set, which are appropriate for stars with convective envelopes. During our solutions, the adjustable parameters were as follows: the orbital inclination \( i, \) the mass ratio \( q, \) the effective temperature of the secondary component \( T_2, \) the monochromatic

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Figure 1. Image of IR Cas observed by the 1 m telescope. V marks the target IR Cas, C represents the comparison star, and CH shows the check star. North is up and east is to the left.

Figure 2. Observed four color light curves of IR Cas. Crosses, open squares, circles, and triangles represent the light curves observed on October 8 and 9, and November 4 and 7, respectively. The phases are calculated using the linear ephemeris: Min. $I = \text{HJD 2456574.0514} + 0.680686E$.

Figure 3. $\sum -$ $q$ curves for IR Cas. The small insert figure is an enlargement for $q$ from 0.75 to 1.00.

Figure 4. Theoretical light curves computed with these photometric elements.

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Table 1

| Parameters | Photometric Elements | Errors |
|------------|----------------------|--------|
| $q$ ($M_2/M_1$) | 0.851 ± 0.005 |
| $T_2$ (K) | 5992 ± 4 |
| $i$ (deg) | 86.8 ± 0.2 |
| $\Omega_1$ | 3.5034 |
| $\Omega_2$ | 3.7601 ± 0.0145 |
| $L_{1B}/L_B$ | 0.7457 ± 0.0003 |
| $L_{1V}/L_V$ | 0.7113 ± 0.0004 |
| $L_{1R}/L_R$ | 0.6901 ± 0.0004 |
| $L_{1I}/L_I$ | 0.6732 ± 0.0005 |
| $r_1$ (pole) | 0.3696 ± 0.0005 |
| $r_1$ (side) | 0.3891 ± 0.0005 |
| $r_1$ (back) | 0.4194 ± 0.0005 |
| $r_1$ (mean) | 0.3932 ± 0.0006 |
| $r_2$ (pole) | 0.3116 ± 0.0017 |
| $r_2$ (point) | 0.3601 ± 0.0037 |
| $r_2$ (side) | 0.3226 ± 0.0020 |
| $r_2$ (back) | 0.3417 ± 0.0026 |
| $r_2$ (mean) | 0.3345 ± 0.0045 |

The derived photometric elements are listed in Table 1 (the errors are formal errors only and have no real meaning for the uncertainties). Figure 4 shows the theoretical light curves computed with these photometric elements.

4. PERIOD VARIATION

The orbital period variation of IR Cas has been analyzed by Zhu et al. (2004). Based on 313 minima, they found that the orbital period of IR Cas is secularly decreasing at a rate of $dp/dt = -1.18 \times 10^{-7}$ days yr$^{-1}$, while it undergoes cyclic oscillation with a period of 53.24 yr and an amplitude of about 0.133 days. Among the 313 minima, only six are photometric and CCD minima; the others are visual and photographic minima. Therefore, the results determined by Zhu et al. (2004) are possibly not reliable.

We reanalyzed the orbital period variation of IR Cas by collecting all available visual, photographic, photometric, and CCD minima. Using the same linear ephemeris
we computed the \((O - C)\) values for these times of minimum light and listed them in Table 2. The corresponding \((O - C)\) curve was displayed in Figure 5. One minimum light time, 2441178.3580 (BBSAG 31), was discarded because of the very large scatter from other data. It is found that a secular decrease as \(O\) gateway,\(^5\)

\[
\text{Min. } I = 2446332.4510 + 0.680686E,
\]

we generally applied to fit the \((O - C)\) curve, displayed in Figure 5. One minimum light time, 2441178.3580 (BBSAG 31), was discarded because of the very large scatter from other data. It is found that a secular decrease and a cyclic variation lead to a satisfactory fit to the \((O - C)\) curve. Therefore, a second-order polynomial superimposed on a light travel-time effect due to a third body in an elliptical orbit (Irwin 1952), was generally applied to fit the \((O - C)\) curve,

\[
(O - C)_1 = T_0 + \Delta T_0 + (P_0 + \Delta P_0)E + \frac{\beta}{2} E^2 + A \left[ (1 - e^2) \left( \frac{\sin (\nu + \omega)}{1 + e \cos \nu} \right) + e \sin \omega \right],
\]

where \(T_0\) is the initial epoch and \(P_0\) is the orbital period. Other parameters are taken from Irwin (1952). In this calculation, different weights were adopted: 8 for the photoelectric and CCD minima and 1 for the visual and photographic minima. The fitted parameters are shown in Table 3. The \((O - C)_2\) values from the quadratic term are plotted in the middle panel of Figure 5. The residuals from the full terms of Equation (2) are displayed in the lower panel of Figure 5. As seen in Figure 5, it is clear that the orbital period of IR Cas, superimposed on the long-term downward parabolic variation, varies in a cyclic way. The rate of the secular period decrease is determined to be \(-1.28(\pm 0.09) \times 10^{-7}\) days yr\(^{-1}\). According to the light travel-time effect term of Equation (2), the period of the cyclic oscillation is about 39.7 yr, and its amplitude is about 0.0153 days. The results are different from that determined by Zhu et al. (2004).

5. DISCUSSION AND CONCLUSIONS

The first photometric analysis of IR Cas was carried out based on the new observed four color light curves using the 1.0 m telescope at WHOT. The new observed light curves are symmetric, and the secondary minimum is almost flat, indicating that one can determine very precise photometric solutions. It is shown that IR Cas is a semi-detached system with the primary component filling its Roche lobe and can be classified as a near contact binary since the Roche lobe filling ratio of the secondary component is about 93%. The mass ratio is \(q = 0.851\) and orbital inclination is \(i = 86.8^\circ\); the temperature difference between the two components is \(\Delta T = 758\) K. Since no spectroscopic elements have been published for IR Cas, the absolute parameters cannot be determined directly. Assuming that the primary component is a normal main-sequence star, we can estimate its mass to be \(M_1 = 1.43 M_\odot\) according to its spectral type of F4 (Cox 2000). Then, the absolute parameters for this system can be determined by combining the

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**Table 2**

| JD Hel. | Me | Type | \(\Delta E\) | \((O - C)_1\) | \((O - C)_2\) | Residuals | Reference |
|--------|----|------|-------------|---------------|---------------|-----------|-----------|
| 2417437.2600 | pg | p | -42397 | -0.1467 | -0.0338 | -0.0267 | PZ 4, 369 |
| 2417437.2707 | pg | p | -30594 | -0.1360 | -0.0231 | -0.0160 | PSMO 16, 244 |
| 2425507.4830 | pg | p | -28254 | -0.0638 | -0.0153 | -0.0114 | PSMO 16, 244 |
| 2427100.2850 | pg | p | -28224.5 | -0.0690 | -0.0206 | -0.0167 | PSMO 16, 244 |
| 2427102.3600 | pg | s | -25830 | -0.0396 | 0.0003 | 0.0063 | PSMO 16, 244 |
| 2428750.2920 | pg | p | -25247 | -0.0375 | 0.0004 | 0.0069 | PSMO 16, 244 |
| 2429147.1341 | pg | p | -24763 | -0.0341 | 0.0022 | 0.0090 | PSMO 16, 244 |

**Note.** This minimum is discarded during the fitting.

(This table is available in its entirety in machine-readable and Virtual Observatory (VO) forms in the online journal. A portion is shown here for guidance regarding its form and content.)

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**Table 3**

| Parameters | Values | Errors |
|------------|--------|--------|
| \(\Delta T_0\) (days) | 0.0085 | ±0.0014 |
| \(\Delta P_0\) (days) | 3.31 \times 10^{-7} | ±0.63 \times 10^{-7} |
| \(\beta\) (days yr\(^{-1}\)) | -1.28 \times 10^{-7} | ±0.09 \times 10^{-7} |
| \(A\) (days) | 0.0153 | ±0.0134 |
| \(e\) | 0.89 | ±0.22 |
| \(P_3\) (days) | 14497.3 | ±551.0 |
| \(\omega\) (°) | 10.5 | ±10.5 |
| \(T_P\) (HJD) | 2448184.1 | ±317.0 |
photometric solutions and its period. They are as follows: $M_2 = 1.22 \, M_\odot$, $a = 4.51 \, R_\odot$, $R_1 = 1.77 \, R_\odot$, $R_2 = 1.51 \, R_\odot$, $L_1 = 5.85 \, L_\odot$, and $L_2 = 2.63 \, L_\odot$.

Based on all available visual, photographic, photoelectric, and CCD times of minimum light, we analyzed the period variation of IR Cas. We found that the secular decrease rate of the period is $-1.28 (\pm 0.09) \times 10^{-7} \, \text{yr}^{-1}$; the period of the cyclic variation is about 39.7 yr. The continuous period decrease means that mass could be transferred from the primary component to the secondary. Assuming a conservative mass transfer and that mass could be transferred from the primary component, the mass transfer rate is $dM_1/dt = 1.13 (\pm 0.08) \times 10^{-6} \, M_\odot \, \text{yr}^{-1}$. The thermal timescale of the primary component can be estimated to be $(GM^2/RL) \sim 7.1 \times 10^6 \, \text{yr}$, which is very close to the timescale of period decrease $P/(dP/dt) \sim 5.3 \times 10^6 \, \text{yr}$. This may indicate that the mass transfer is on a thermal timescale.

The cyclic period variation could be a sign of light time-travel effect due to a third body, or of deformation of a magnetically active companion due to the Applegate mechanism (Applegate 1992). Using the relation $(\Delta P/P) = -9 (\Delta Q/Ma^2)$ (Lanza & Rodonò 2002), we can calculate the variations of the quadrupole moment $\Delta Q_{1,2}$ for both components. We determined $\Delta Q_1 = 1.4 \times 10^{49} \, \text{g cm}^2$ for the primary component and $\Delta Q_2 = 1.2 \times 10^{50} \, \text{g cm}^2$ for the secondary. Assuming conservation of the orbital angular momentum, the typical values of the variation of the quadrupole moment range from $10^{51}$ to $10^{52} \, \text{g cm}^2$ for active close binaries (Lanza & Rodonò 1999). This suggests that the Applegate mechanism cannot explain the cyclic period variation of IR Cas. Therefore, the cyclic period variation of IR Cas may be more likely caused by the light time-travel effect due to a third body.

The cyclic period and semi-amplitude are calculated to be about 39.7 yr and 0.0153 days, respectively. Using the following equation

$$\frac{\dot{P}}{P} = -3 \frac{M_1}{M_2} \left( \frac{1}{M_1} - \frac{1}{M_2} \right),$$

we determined that the mass transfer rate is $dM_1/dt = 1.13 (\pm 0.08) \times 10^{-6} \, M_\odot \, \text{yr}^{-1}$. The most impossible to detect photometrically and spectroscopically is its period. The new V-band magnitude data, which have the secular decrease from the $(O-C)$ curve, are plotted in the middle. The residuals from the full terms of Equation (2) are plotted in the lower panel. Crosses represent visual and photographic data, while filled circles refer to the photoelectric and CCD data. The open circle is a discarded minimum.

**Figure 5.** $O-C$ diagram of IR Cas. The upper panel displays the $(O - C)_1$ curve calculated with the linear ephemeris of Equation (1) based on all available times of minimum light. The $(O - C)_2$ values, which have the secular decrease from the $(O - C)_1$ curve removed, are displayed in the middle. The residuals from the full terms of Equation (2) are plotted in the lower panel. Crosses represent visual and photographic data, while filled circles refer to the photoelectric and CCD data. The open circle is a discarded minimum.

**Figure 6.** Relation between the mass and the orbital inclination for an assumed third body in IR Cas.
With the decreasing period, the mass ratio of IR Cas increases and the separation between components decreases. This system will evolve from the present semi-detached phase to the contact phase. By considering a mean period of 0.4 days for contact binary stars, it will evolve into a contact binary after $\sim 1.2 \times 10^6$ yr. Therefore, it is possible that IR Cas is a progenitor of an evolved contact binary, or is in a broken-contact stage like some interesting systems listed in Table 4. On the other hand, the theory of thermal relaxation oscillation (TRO) models (e.g., Lucy 1976; Flannery 1976; Robertson & Eggleton 1977; Lucy & Wilson 1979; Yakut & Eggleton 2005) predicted oscillation between semi-detached and slightly overcontact configurations. Each oscillation comprises a contact phase followed by a semidetached phase. As we know, these two phases predicted by TRO are quite short compared to the lifetime of the systems. Thus, a system in such phases is very rare. Systems with such configurations are important targets for investigating the evolution of close binaries. IR Cas is a promising candidate for being at this rare evolutionary stage. The photometric solution of IR Cas is only based on photometric observations. For future work, the spectroscopic and photometric observations are needed in order to obtain better understanding of the absolute dimensions and evolutionary status of IR Cas.

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Table 4
Semi-detached Binaries with the Primary Component Filling Their Inner Roche Lobes

| Star    | $P$ (days) | Sp.  | $q$  | $dP/dt$ (days yr$^{-1}$) | References |
|---------|-----------|------|------|--------------------------|------------|
| BO Peg  | 0.58043288| A7IV | 0.550| $-1.26 \times 10^{-7}$   | (1), (2)   |
| BL And  | 0.72237705| A8   | 0.387| $-3.26 \times 10^{-8}$   | (3)        |
| V473 Cas| 0.4154591 | G2   | 0.493| $-7.61 \times 10^{-8}$   | (4)        |
| BS Vul  | 0.47597147| G2   | 0.340| $-2.44 \times 10^{-8}$   | (5)        |
| CN And  | 0.46279428| F5V  | 0.390| $-1.82 \times 10^{-7}$   | (6)        |
| DM Del  | 0.8446747 | G87  | 0.550| $-2.27 \times 10^{-7}$   | (7)        |
| V388 Cyg| 0.8590372 | A3   | 0.365| $-2.06 \times 10^{-7}$   | (8)        |
| GO Cyg  | 0.71776458| A0V  | 0.428| $-1.40 \times 10^{-9}$   | (9)        |
| TT Her  | 0.91208023| F2V  | 0.439| $-1.82 \times 10^{-7}$   | (10)       |
| IR Cas  | 0.6808686 | F4   | 0.851| $-1.18 \times 10^{-7}$   | (11)       |

Notes. (1) Yamasaki & Okazaki 1986; (2) Qian 2002; (3) Zhu & Qian 2006; (4) Zhu et al. 2009; (5) Zhu et al. 2012; (6) Lee & Lee 2006; (7) He & Qian 2010; (8) Kang et al. 2001; (9) Ula¸s et al. 2012; (10) Milano et al. 1989; (11) this paper.