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# Hodge 53-47: an early O-type double-lined binary in the Small Magellanic Cloud★

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## ABSTRACT

We present a spectroscopic and photometric study of the double-lined binary Hodge 53-47 in the Small Magellanic Cloud. We determine for the binary components spectral types of O6 V + O4-5 III(f). Through a simultaneous light and radial velocity curve analysis via the Wilson–Devinney code we find absolute masses of $\sim$26 $M_{\odot}$ and $\sim$16 $M_{\odot}$ and radii of $\sim$10.1 $R_{\odot}$ and $\sim$8.4 $R_{\odot}$ for the O6 V and O4-5 III(f) components, respectively. The relatively low mass found for the O4-5 III(f) component suggests that mass transfer and loss have played a significant role in the evolution of these stars.

**Key words:** binaries: close – binaries: eclipsing – binaries: spectroscopic – stars: early-type – stars: fundamental parameters – stars: individual: Hodge 53-47.

## 1 INTRODUCTION

The study of binaries in the Magellanic Clouds (MC) offers a straightforward way of learning about the physical parameters and evolution of stars born in a different environment, of lower metallicity than that of the Milky Way. This is especially true in the case of the Small Magellanic Cloud (SMC), where the metallicity is 4 times less than solar.

Hodge 53-47 is a member of the stellar association Hodge 53 (Hodge & Wright 1974). The current designation of Hodge 53-47 is taken from Massey, Waterhouse & DeGioia-Eastwood (2000), who also provide J2000 coordinates (01:03:22.07, −72:05:38.3) and photometric information ($V = 13.56$, $B - V = -0.23$, $U - B = -1.04$) for this star.

*I*-band photometry of Hodge 53-47 is available from Udalski et al. (1998) based on observations obtained with the 1.3-m Warsaw telescope at Las Campanas Observatory (Chile) during the OGLE microlensing search program. Hodge 53-47 is labelled in the OGLE catalogue of eclipsing variable stars in the SMC as the object 175323 in the SMC SC9 region and 33878 in the SMC SC10 region, with infrared magnitude $I = 13.670$ and $V - I = -0.181$ (data from SC9) and $I = 13.681$ and $V - I = -0.184$ (data from SC10).

The binary nature of Hodge 53-47 was spectroscopically discovered by Massey et al. (2000) who classified the binary components as O4 V + O6 V and claimed that this star is one of the most bolometric luminous members of Hodge 53. Since Hodge 53-47 is an early O-type double-lined binary, we decided to obtain more spectroscopic observations in order to determine the physical parameters of its components.

Hodge 53-47 has just been discussed by Harries, Hilditch & Howarth (2002), along with other SMC systems, among the first results of a programme to obtain fundamental parameters and distances for binaries in the SMC.

In this paper we present a simultaneous radial velocity and light curve analysis, based on our own observations of Hodge 53-47, deriving fundamental parameters for this interesting system.

## 2 OBSERVATIONS AND REDUCTIONS

### 2.1 Photometry

CCD Johnson *V* frames were obtained with the 2.15-m telescope at CASLEO, Argentina, in four observing runs between 1997.9 and 2000.9 (see Table 1 for a description of each observing run). In addition, some Johnson *B* and Kron–Cousins *R* frames were obtained in the 1997 November observing run, in order to perform absolute photometry.

Our CCD images were processed using IRAF[1] routines in the usual way (bias-trimming, zero subtraction, flat-fielding).

Given that Hodge 53-47 has a bright close neighbour, 1.15 mag fainter than Hodge 53-47 at a distance of $\sim$4 arcsec, which cannot be resolved by simple profile fitting photometry in most CASLEO

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[1] IRAF software is distributed by NOAO, operated by AURA for NSF.

**Table 1.** Observing logs.

| Date | 1997, Nov. 15–21 | 1998, Dec. 2–8 | 1999, Nov. 17–22 | 2000, Nov. 11–16 |
|---|---|---|---|---|
| HJD −245 0000 | 0767–0774 | 1151–1156 | 1499–1505 | 1859–1865 |
| Number of images acquired | 28 | 10 | 14 | 16 |

images owing to poor seeing, we performed ALLFRAME profile fitting photometry (Stetson 1987, 1991). As the use at CASLEO of a focal reducer produces strong variations in the point spread function (PSF) along the observed field, a region of only 2 arcmin radius around Hodge 53-47 was selected to build a PSF for each image.

The observations were reduced to a unique instrumental system using for comparison a group of neighbouring stars, in the way described in Ostrov, Lapasset & Morrell (2000). The instrumental magnitudes were then transformed to the standard system (see results in Table 2).

Standard stars from the selected areas SA92 and SA98, (Landolt 1992) were also observed in order to derive transformation equations to the standard system, on the nights 1997 November 15 and 20. Unfortunately the photometric quality of the night of 1997 November 15 (during which we acquired the $B$ frames) was suspect, and therefore, our $B-V$ measurements should be considered with caution (see Ostrov 2001 for details).

We finally obtain for Hodge 53-47 the following visual magnitude and colours, computed for phase 0.75:

$V = 13.517 \pm 0.02,$
$B - V = -0.185,$
$V - R = -0.081 \pm 0.02.$

Our $V$ magnitude lies within 1–2$\sigma$ of the value reported by the OGLE team for 9-175323 (13.489) and for 10-33878 (13.479), both for quadrature phases.

## 2.2 Spectroscopy

Three CCD spectra of Hodge 53-47 were obtained with the Cassegrain spectrograph at the CTIO 4-m telescope in 1999 January.[2] The reciprocal dispersion of these spectrograms is 0.41 Å pixel$^{-1}$ and their signal-to-noise ratio is between 50 and 100. The detector used was a Loral 3k CCD. These data cover the spectral region from 3700–5000 Å.

14 Cassegrain CCD spectra of Hodge 53-47 were obtained at CASLEO, using the REOSC spectrograph[3] in its single dispersion mode between 1999 December and 2000 June. For 3 of them (observing run 1999 December–2000 January) we used a 400 groove mm$^{-1}$ grating giving a reciprocal dispersion of 2.5 Å pixel$^{-1}$ in the wavelength region from 3700 to 6200 Å. For the other runs we used a 600 grooves mm$^{-1}$ grating, obtaining a reciprocal dispersion of 1.63 Å pixel$^{-1}$. These spectrograms cover the wavelength region approximately between 3870 Å and 5500 Å. The signal-to-noise ratio of the REOSC spectra is typically 50. We used a 1024 × 1024 Tek CCD as detector.

The usual sets of bias, dark and flat-field frames were also acquired during each observing night. All the spectroscopic data were processed and analysed using IRAF routines.

[2] CTIO: Cerro Tololo Inter-American Observatory, operated by AURA, Inc., for NSF.
[3] The REOSC spectrograph is at CASLEO on long term loan from the Liège Observatory.

# 3 RESULTS

## 3.1 Ephemeris

The first ephemeris for Hodge 53-47 was determined as part of the results of the OGLE project (Udalski et al. 1998) giving for this system $T_0$ = 2450630.65120 + 2.20596E (9 175323) and $T_0$ = 2450665.93497 + 2.20626E (10 33878).

Independently, $V$ light variations with an amplitude of ∼0.2 mag were found in Hodge 53-47 by one of us (PO) when analysing direct CCD frames of the Hodge 53 field.

From the study of the complete set of photometric data, a period of 2.20604 ± 0.00002 d was found to better fit the light variations of Hodge 53-47. The corresponding time of primary minimum is $T_0$ JD 2451861.643 ± 0.015. These values were adopted in the subsequent calculations.

## 3.2 Spectral types

The spectrum of Hodge 53-47 is illustrated in Fig. 1. Spectral types were determined for the Hodge 53-47 components through careful inspection of our CCD spectra obtained at binary phases that allow maximum separation of the double lines. In the classification process we used the criteria described by Walborn & Fitzpatrick (1990).

Both components show He II absorption lines that are stronger than those of He I, corresponding to early O types.

The primary star shows no observable emission lines in our data and its H absorption lines are somewhat less conspicuous than those of its companion. Nevertheless, the radial velocity measurements proved this star to be the more massive component in the system. From the relative intensities of He II 4542 to He I 4471 and the relatively large equivalent width of He II 4686, we determine a spectral type of O6 V for this binary component.

Regarding the secondary component, blueshifted in Fig. 1, it displays He II lines much stronger than He I, moderate N III 4634-40-42 emission, and He II 4686 absorption weaker than other He II lines, indicative of the presence of emission filling this line profile. Considering this fact, and the relative strength of He II 4542 relative to He I 4471 we classify this binary component as O4-5 III(f). As this is the earliest type star in the system, and it displays slightly stronger H lines than its companion, we formerly thought it was the primary, more massive component, but this assumption was proved to be false from the radial velocity analysis.

## 3.3 Radial velocities

The spectra of Hodge 53-47 were measured for radial velocity determinations. These measurements were carried out through double Gaussian fitting using standard IRAF routines. Then we computed the radial velocities as the average of He II lines. The journal of the spectroscopic observations along with the radial velocity measurements is presented in Table 3 where, in successive columns we quote the Heliocentric Julian Date of each observation, the orbital phase, and the radial velocities for the primary and secondary components. As our radial velocities are averages of only 3 or 4 individual lines, we

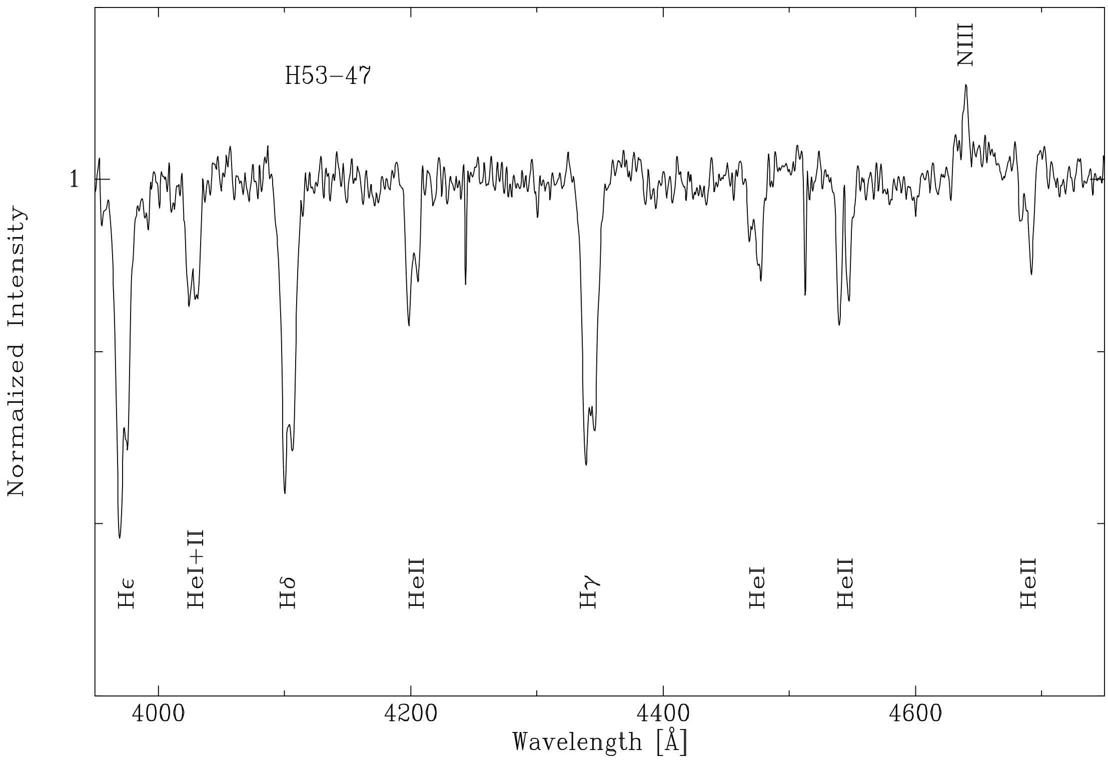


**Figure 1.** Spectrum of Hodge 53-47 obtained at the CTIO 4-m R-C spectrograph.

**Table 2.** Observed *V* values.

| HJD 2450000+ | *V* | $\sigma_i$ | FWHM arcsec | *X* | HJD 245 0000+ | *V* | $\sigma_i$ | FWHM arcsec | *X* |
|---|---|---|---|---|---|---|---|---|---|
| 767.519 | 13.684 | 0.005 | 2.23 | 1.35 | 1500.515 | 13.524 | 0.005 | 3.27 | 1.35 |
| 767.551 | 13.648 | 0.015 | 4.18 | 1.32 | 1500.551 | 13.530 | 0.008 | 3.71 | 1.32 |
| 767.581 | 13.650 | 0.005 | 2.19 | 1.31 | 1500.626 | 13.559 | 0.005 | 3.37 | 1.33 |
| 767.613 | 13.633 | 0.007 | 2.41 | 1.32 | 1500.694 | 13.581 | 0.005 | 4.08 | 1.43 |
| 767.659 | 13.619 | 0.011 | 3.86 | 1.36 | 1501.523 | 13.522 | 0.004 | 2.87 | 1.33 |
| 767.736 | 13.581 | 0.011 | 3.97 | 1.53 | 1501.704 | 13.557 | 0.003 | 3.49 | 1.46 |
| 768.521 | 13.697 | 0.005 | 2.09 | 1.34 | 1502.519 | 13.519 | 0.004 | 2.20 | 1.34 |
| 768.565 | 13.700 | 0.005 | 2.25 | 1.31 | 1502.664 | 13.503 | 0.005 | 1.95 | 1.38 |
| 768.602 | 13.691 | 0.005 | 2.37 | 1.31 | 1502.721 | 13.519 | 0.007 | 2.04 | 1.52 |
| 768.662 | 13.664 | 0.007 | 2.70 | 1.37 | 1502.761 | 13.525 | 0.006 | 2.32 | 1.66 |
| 768.713 | 13.634 | 0.005 | 3.46 | 1.47 | 1503.517 | 13.561 | 0.004 | 2.74 | 1.34 |
| 769.528 | 13.672 | 0.006 | 2.91 | 1.33 | 1503.767 | 13.525 | 0.007 | 2.74 | 1.70 |
| 769.561 | 13.690 | 0.009 | 3.15 | 1.31 | 1504.523 | 13.596 | 0.005 | 2.81 | 1.33 |
| 770.528 | 13.602 | 0.003 | 2.34 | 1.33 | 1859.555 | 13.674 | 0.007 | 3.61 | 1.33 |
| 770.583 | 13.625 | 0.002 | 2.59 | 1.31 | 1859.674 | 13.589 | 0.004 | 3.22 | 1.37 |
| 770.645 | 13.669 | 0.007 | 2.11 | 1.35 | 1860.513 | 13.691 | 0.006 | 2.66 | 1.37 |
| 771.645 | 13.601 | 0.012 | 2.03 | 1.35 | 1860.547 | 13.699 | 0.004 | 2.73 | 1.33 |
| 772.522 | 13.527 | 0.003 | 2.74 | 1.33 | 1860.560 | 13.696 | 0.004 | 2.86 | 1.32 |
| 773.537 | 13.515 | 0.004 | 2.41 | 1.32 | 1861.523 | 13.667 | 0.004 | 2.63 | 1.35 |
| 1151.551 | 13.592 | 0.006 | 1.60 | 1.31 | 1861.547 | 13.680 | 0.006 | 3.12 | 1.33 |
| 1151.632 | 13.551 | 0.006 | 1.81 | 1.40 | 1861.633 | 13.709 | 0.005 | 3.52 | 1.33 |
| 1151.681 | 13.534 | 0.006 | 1.96 | 1.52 | 1862.523 | 13.604 | 0.005 | 3.73 | 1.35 |
| 1152.635 | 13.607 | 0.005 | 1.85 | 1.41 | 1862.545 | 13.614 | 0.005 | 2.97 | 1.33 |
| 1152.676 | 13.583 | 0.006 | 1.97 | 1.51 | 1862.611 | 13.651 | 0.004 | 3.03 | 1.31 |
| 1153.622 | 13.660 | 0.008 | 1.80 | 1.39 | 1863.512 | 13.568 | 0.005 | 2.30 | 1.36 |
| 1153.654 | 13.637 | 0.006 | 1.85 | 1.46 | 1863.528 | 13.574 | 0.004 | 2.01 | 1.34 |
| 1154.622 | 13.714 | 0.016 | 2.20 | 1.40 | 1863.591 | 13.600 | 0.006 | 2.27 | 1.31 |
| 1155.611 | 13.694 | 0.016 | 2.20 | 1.38 | 1864.521 | 13.530 | 0.005 | 2.71 | 1.34 |
| 1155.690 | 13.701 | 0.007 | 1.97 | 1.58 | 1864.639 | 13.558 | 0.004 | 1.79 | 1.34 |
| 1499.762 | 13.685 | 0.005 | 2.42 | 1.62 | | | | | |

**Table 3.** Observed radial velocities of the double-lined binary H53-47.

| HJD $2.45 \times 10^6$ + | Phase | O6 V $V_R$ [km s$^{-1}$] | O4-5 III(f) $V_R$ [km s$^{-1}$] |
|---|---|---|---|
| 1181.629 | 0.752 | 357 | −131 |
| 1183.598 | 0.645 | 318 | −34 |
| 1185.586 | 0.546 | – | 175 |
| 1542.611 | 0.387 | −41 | 395 |
| 1545.589 | 0.737 | 273 | −53 |
| 1547.561 | 0.631 | 332 | −38 |
| 1562.566 | 0.433 | – | 184 |
| 1566.531 | 0.230 | 56 | 468 |
| 1567.551 | 0.692 | 387 | −73 |
| 1568.531 | 0.136 | −96 | 480 |
| 1569.539 | 0.593 | 273 | 32 |
| 1571.531 | 0.496 | – | 166 |
| 1572.531 | 0.950 | 300 | 89 |
| 1573.543 | 0.408 | 57 | 262 |
| 1574.527 | 0.854 | 300 | −44 |
| 1575.543 | 0.315 | 24 | 428 |
| 1718.867 | 0.284 | 20 | 498 |

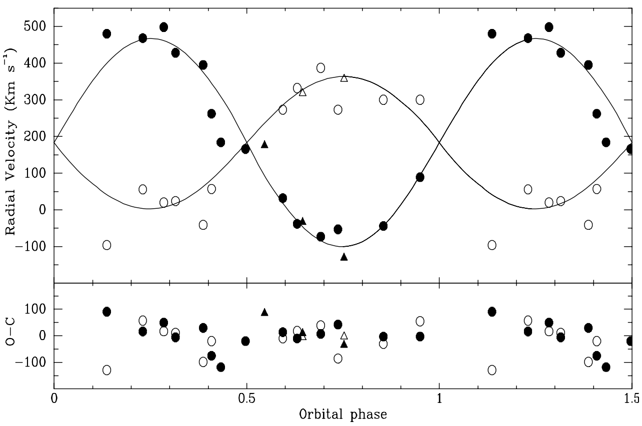


**Figure 2.** Observed and modelled radial velocity curve for Hodge 53-47 (top) and (O-C) residuals for the radial velocities (bottom). Circles and triangles represent CASLEO and CTIO spectra, respectively. Open and filled symbols refer to the primary and secondary component, respectively.

estimate the errors from the O-C of the orbital fit, instead of giving individual standard deviations which are probably less meaningful. The probable error of the orbital fit is 22 km s$^{-1}$.

In order to minimize pair blending effects we decided to use for the radial velocity solution only those spectra showing larger separations between the binary components. Although pair blending is a potential issue for the used spectral resolution, it seems not to be very important in this particular case, since the only CTIO spectrum obtained at quadrature phase agrees within the errors with the radial velocities derived from CASLEO data for similar phases. Seriously blended or very deviant observations were excluded from the solution, although all of them are plotted in Fig. 2.

We also measured radial velocities for the nebular [OIII] emission line in the CASLEO spectra of Hodge 53-47 and obtained a mean value of 173 ± 12 km s$^{-1}$.

### 3.4 Light and radial velocity curve analysis

The *V* light curve derived from our CCD photometry was analysed together with the radial velocity measurements obtained from the spectroscopic observations with the Wilson & Devinney code (Wilson & Devinney 1971; Wilson 1990).

The shape of these light curves is characteristic of ellipsoidal variations instead of eclipses, and the almost equal deepness of both minima suggests that both stars have similar surface brightness. This probably indicates that O5 III(f) is more suited for the spectral type of the secondary component than the alternative O4 III(f) because, according for example to Chlebowski & Garmany (1991), the effective temperature of a O5 III(f) is very similar to that of a O6 V, which corresponds to the primary component of Hodge 53-47.

In this analysis we adopted as standard deviations values of 0.02 and 0.04, for CASLEO and OGLE photometry, respectively, and 25 km s$^{-1}$ for spectroscopic data. The photometric observations were given unit weight, while the radial velocities were weighted according to their spectral resolution.

We used for the bolometric albedos and gravity darkening coefficients the values corresponding to radiative envelopes, i.e. $A = 1.0$ (Rucinski 1969) and $g = 1.0$ (Lucy 1976). The limb darkening was modelled through a square-root law (Díaz-Cordovés & Giménez 1992), with the coefficients and tables given by Díaz-Cordovés, Claret & Giménez (1995). The binary components were supposed to be in synchronous rotation, as is usually expected for massive systems with short periods. The albedos, gravity darkening coefficients, limb darkening coefficients and rotation were kept as fixed parameters for the analysis.

The parameters to be fitted were the semimajor axis *a*, the systemic radial velocity $V_\gamma$, the orbital inclination *i*, the potential $\Omega_1$, the mass ratio *q* and the luminosity of the primary component $L_1$. To perform the fitting we followed the same procedure described in Ostrov et al. (2000).

The analysis via the Wilson–Devinney code, resulted in a semidetached, near contact configuration. From the spectral classification, the primary star has a spectral type slightly later than the secondary. Nevertheless, the solution obtained for the system suggests the secondary to be somewhat cooler than the primary (although the difference between both temperatures is within the errors).

Several attempts to adopt for the secondary O4-5 III(f) component, a temperature higher than that of the primary, resulted in light-curve fittings that were not acceptable. We finally decided to fix the primary temperature at 41 000 K (Schmidt-Kaler 1982), and leave the secondary temperature as a parameter to be determined, even if the obtained value is somewhat lower than we would expect for an O4-5 star. The fitted value of 39 400 ± 2000 K is not different within the errors from the temperature adopted for the primary component, as the similarity of the light minima would imply. Those temperature values should be considered with caution, since the temperature scale for O-type stars is currently subject to revision (Martins, Schaerer & Hillier 2002).

Our solution with the Wilson & Devinney code, presented in Tables 4 and 5 and Figs 2 and 3, results in $M_1 = 25 \pm 3$, $R_1 = 10.1 \pm 0.4$, $M_2 = 16 \pm 2$ and $R_2 = 8.4 \pm 0.3$ (these parameters expressed in solar units); an inclination of $i \approx 57^\circ$ and a semimajor axis of $a \approx 25\ R_\odot$.

The systemic radial velocity of 183 ± 6 km s$^{-1}$ agrees within the errors with the radial velocity derived for the [O III] nebular emission, and it is typical of SMC objects.

Our results are in good agreement with those found by Harries et al. (2002) using a different data set.

**Table 4.** Model parameters for H53-47.

| | |
|---|---|
| $a$ | $25 \pm 1$ $R_\odot$ |
| $K_1$ | $180 \pm 12$ km s$^{-1}$ |
| $K_2$ | $280 \pm 10$ km s$^{-1}$ |
| $V_\gamma$ | $183 \pm 6$ km s$^{-1}$ |
| $i$ | $57 \pm 3^\circ$ |
| $q$ $(M_2/M_1)$ | $0.64 \pm 0.03$ |
| $T_1$ | 41 000 K (adopted) |
| $\Omega_1$ | $3.186 \pm 0.09$ |
| $g_1$ | 1.00 (adopted) |
| $A_1$ | 1.00 (adopted) |
| $T_2$ | $39400 \pm 2000$ K |
| $\Omega_2$ | 3.143 (adopted) |
| $g_2$ | 1.00 (adopted) |
| $A_2$ | 1.00 (adopted) |

**Table 5.** Star dimensions for H53-47.

| | |
|---|---|
| $M_1$ | $25 \pm 3$ $M_\odot$ |
| $R_1$ | $10.1 \pm 0.4$ $R_\odot$ |
| $M_{bol1}$ | $-8.75 \pm 0.10$ |
| log $g_1$ [cgs] | $3.83 \pm 0.03$ |
| $M_2$ | $16 \pm 2$ $M_\odot$ |
| $R_2$ | $8.4 \pm 0.3$ $R_\odot$ |
| $M_{bol2}$ | $-8.17 \pm 0.20$ |
| log $g_2$ [cgs] | $3.80 \pm 0.01$ |

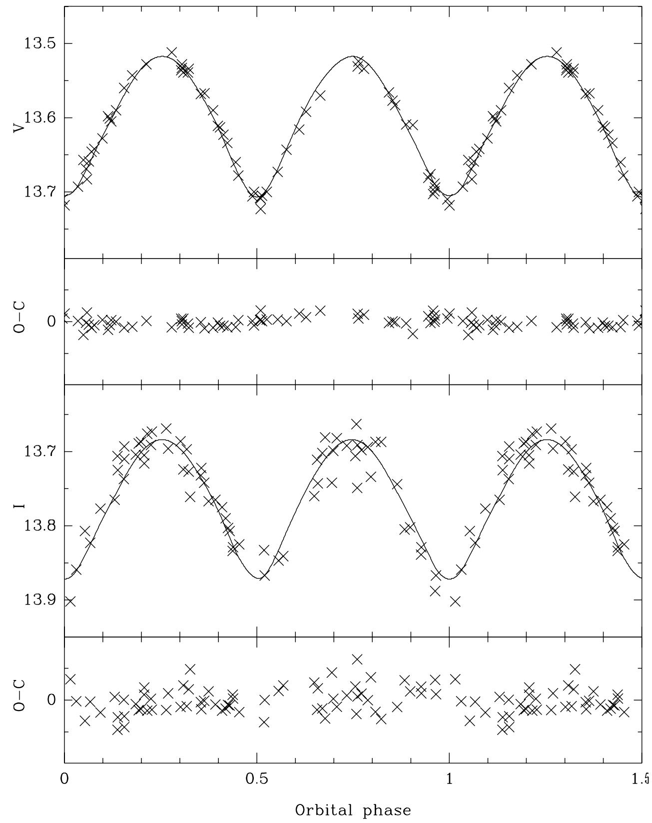


**Figure 3.** Observed and modelled light curve in the V (top, our photometry) and I (bottom, OGLE data base: SC10 33878) filters for Hodge 53-47 with their corresponding (O-C) residuals.

## 4 DISCUSSION

The position of Hodge 53-47 on the $M_{bol}$ versus log $T_{eff}$ diagram was derived by Massey et al. (2000). According to their fig. 7(b), this system's components lie near the evolutionary tracks of $\sim$50 $M_\odot$ and 35 $M_\odot$ (Schaller et al. 1992). From the present radial velocity and light-curve analysis, we determine that the components of Hodge 53-47 have much lower masses, and that the more massive component is that showing the later spectral type.

We conclude that this system has experienced a considerable amount of mass transfer, arriving at the present situation of mass inversion, with a main-sequence primary star and a more evolved secondary (originally more massive) component of higher luminosity class. As we believe we are dealing with a system where mass transfer has played an important role, and moreover one component fills its Roche lobe and the other one is very close to it, any comparison with evolutionary tracks for single stars is useless.

The spectrum of Hodge 53-47 is remarkably similar to that of the galactic system LS 3074, a luminous object in the Coal Sack region, classified as O4f + O6-7(:) by Morrell & Niemela (1990), for which a period of 2.185 d and very low minimum masses were derived from the radial velocity analysis, namely 9.5 $M_\odot$ and 10 $M_\odot$ (Niemela et al. 1992). Ellipsoidal light variations in LS 3074 were discovered and analysed by Haefner, Simon & Fiedler (1994) obtaining an inclination near 50°, which leads to absolute masses of 20 and 21 $M_\odot$ for the almost identical system components (semi-detached solution), well below the masses that could be predicted from the comparison of the luminosities of these stars with evolutionary models (Schaller et al. 1992).

Another example of this kind of system can be provided by MACHO∗81.8763.8 (= MACHO∗05:34:41.3-69:31:39) in the Large Magellanic Cloud, a short period eclipsing binary hosting an O3If primary of 'only' 41 $M_\odot$ (Ostrov 2001b).

Concerning the earliest O-type stars, a large range in masses seems to be possible for very similar spectra, depending on the evolutionary status, as stated, for example, by Walborn et al. (2002). This must be true for short-period binary systems where mass exchange processes had reversed the initial mass ratios, as seems to be the case for Hodge 53-47 and other interesting objects. Perhaps systems like Hodge 53-47, MACHO∗81.8763.8 and LS 3074 are representative of transition objects approaching a WN stage. It may be interesting to mention that Hodge 53 harbours two other binaries with WN components: AV 332 and AV 336a (Massey et al. 2000).

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