THE ARAUCARIA PROJECT. AN ACCURATE DISTANCE TO THE LATE-TYPE DOUBLE-LINED ECLIPSING BINARY OGLE SMC113.3 4007 IN THE SMALL MAGELLANIC CLOUD[*]

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ABSTRACT

We have analyzed the long period, double-lined eclipsing binary system OGLE SMC113.3 4007 (SC10 137844) in the SMC. The binary lies in the north-eastern part of the galaxy and consists of two evolved, well detached, non-active G8 giants. The orbit is eccentric with $e = 0.311$ and the orbital period is 371.6 days. Using extensive high-resolution spectroscopic and multi-color photometric data we have determined a true distance modulus of the system of m-M=18.83 ± 0.02 (statistical) ± 0.05 (systematic) mag using a surface brightness - color relation for giant stars. This method is very insensitive to metallicity and reddening corrections and depends only very little on stellar atmosphere model assumptions. Additionally, we derived very accurate, at the level of 1%-2%, physical parameters of both giant stars, particularly their masses and radii, making our results important for comparison with stellar evolution models. Our analysis underlines the high potential of late-type, double-lined detached binary systems for accurate distance determinations to nearby galaxies.

Subject headings: binaries: eclipsing — galaxies: distances and redshifts — galaxies: individual (SMC) — stars: late-type

1. INTRODUCTION

The determination of the cosmic distance scale is one of the fundamental tasks in astronomy. Perhaps it is the most fundamental one because usually physical quantities used in astrophysics are scaled by the distance. The building of the cosmic distance ladder has proven to be a difficult, time consuming multi-step task. The first step consists of using geometrical methods to measure the distances of nearby stars and clusters. There are only a few well defined, purely geometrical methods we can use: 1) the annual trigonometric parallax, 2) the proper motions convergence point of a star cluster, 3) the orbital parallax of a spectroscopic visual binary star, 4) the kinematic parallax of a pulsar. These primary methods are currently limited to only a few hundred parsecs around the sun. In some favorable circumstances this limit can be expanded to a few kiloparsecs: examples are the distance determination to the Galactic Center via the orbital parallax of stars using adaptive optics e.g., Gillessen et al. (2009) and the annual trigonometric parallax determination of Milky Way masers using long-baseline radio interferometry e.g., Moellenbrock et al. (2009); Reid et al. (2009); Nagayama et al. (2011). To reach out beyond the

Milky Way we have to use secondary methods calibrated with the help of the primary ones, or use other direct but "near-geometrical" methods based on some astrophysical models. In the first case we are restricted quite severely by the limited volume of space where we can safely calibrate secondary distance indicators. In the latter case we are affected by the model assumptions inherent to the different methods. Additionally, these model assumptions are often based on an accepted distance scale and may produce a circular reasoning - see as an example the discussion of the Pleiades' distance modulus problem by van Leeuwen (2009).

A fundamental step in the construction of the distance ladder is the determination of accurate distances to the Magellanic Clouds, particularly to the Large Magellanic Cloud. This galaxy with its relatively simple geometrical structure and smaller than Small Magellanic Cloud depth in the line of sight is a rich astrophysical laboratory containing sizable samples of stellar distance indicators of different kinds and still remains an ideal anchor point for the distance scale (see recent review of Walker (2011)). One of the fundamental tasks of the Araucaria project is to optimize existing methods by checking on their systematic errors. We have been using red clump stars (Pietrzyński & Gieren 2002; Pietrzyński et al. 2003), Cepheid variables (Gieren et al. 2005; Storm et al. 2011a,b) and RR Lyrae stars

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[*] Based on observations obtained with the ESO NTT and 3.6m telescopes at La Silla, and with the Magellan Clay telescope at Las Campanas Observatory

(Szewczyk et al. 2008) to measure the LMC distance, with all these techniques taken to the near-infrared to minimize systematic errors due to dust extinction on the results. These different methods have yielded true LMC distance moduli in the range 18.45 - 18.58 mag, with total errors in the range 4-6%. While this work has already yielded important progress in the long-standing effort of determining a truly accurate distance to the LMC, it is desirable and necessary for precision cosmology, and in particular for the determination of an accurate (better than 5%) value of the Hubble constant, to do better and determine the LMC distance to 1%. A very encouraging step in this direction was recently made in our project with the analysis of a first late-type eclipsing binary in the LMC, OGLE-051019.64-685812.3. This detached, double-lined binary system consisting of two G4 giant stars has allowed a near-geometrical distance measurement accurate to 3% (Pietrzyński et al. 2009). We are currently observing and analyzing a number of similar systems in the LMC from which we expect to measure the LMC barycenter distance with total uncertainty better than 2.5%. We have also detected several detached, double-lined eclipsing binary systems with red giant components in the SMC which are extremely useful for a precision distance measurement to that galaxy.

There are a large number of implementations of the eclipsing binary (EB) method in the literature. They differ mostly in amount of the modeling needed to calculate the total emergent flux of a binary system. The computed flux is scaled to the observed flux at Earth to get a distance. One implementation employs stellar atmosphere models to calculate the emergent flux by fitting them to the observed spectral energy distribution (SED) obtained with the spectrophotometry. Such an approach was undertaken by E. Guinan and collaborators in the middle of 90's (Guinan et al. 1996) with the goal to obtain a precise distance to the LMC with a total uncertainty of about 2%-3%. They studied EBs with late O-type and early B-type components bright enough to obtain sufficient quality data (Guinan et al. 1998a). After, their pioneering work on the distance determination to the early type LMC binary HV 2274, with a claimed accuracy of 3.5% (Guinan et al. 1998b), it had become clear that the method has indeed a large potential. However, the extensive use of stellar atmosphere models in the fitting procedure makes such an approach very model dependent. Because absolute fluxes, especially in the UV region, predicted by atmosphere models for very early type stars can be calibrated with an accuracy of at most 5% (principally caused by the lack of a sufficient number of nearby calibrator stars with reliable geometrical parallaxes), the interpretation of the results obtained from early type systems is uncertain, e.g. Fitzpatrick et al. (2003, see their section 7) in the case of the LMC and North et al. (2010, see their section 5.6) in the case of the SMC.

A different possibility is to employ an empirical surface brightness - color relation and to use angular diameter scaling to obtain a distance to an eclipsing binary. Such relations, for different colors, are well established for dwarfs and giants with spectral types later than F0 from accurate measurements of stellar angular diameters by interferometry (Groenewegen 2004; di Benedetto 2005; Kervella & Fouqué 2008; Casagrande et al. 2010).

This approach was used by us to determine the distance to OGLE-051019.64-685812.3 in the LMC (Pietrzyński et al. 2009). Although the 1% precision of distance determination to extragalactic eclipsing binary systems envisioned by Paczyński (1997) is, in principle, possible to obtain, we are presently still hampered by the systematic uncertainty on the surface brightness-color calibration - see the section 4.1 of this paper.

In this paper we present the distance determination to the long period, well detached eclipsing binary OGLE SMC113.3 4007 ($\alpha_{2000} = 01^{\rm h}06^{\rm m}10\overset{\rm s}{.}33$; $\delta_{2000} = -72°06'25\overset{''}{.}2$) in the SMC. As this system is ideal for distance determination the distance, we show the full potential of the method and discuss all possible sources of error which can lower the robustness of our final result. The star was identified as an eclipsing binary in the catalogue published by Udalski et al. (1998) and obtained identifier SC10 137844 in the OGLE-II database. Initially, because the eccentricity of the system is close to one third and the secondary minimum appears almost exactly at orbital phase 0.67, the system was incorrectly assumed to have a circular orbit and a period of ~ 248 days. Wyithe & Wilson (2001) selected SC10 137844 as a prime distance indicator to the SMC and shortly afterwards we started obtaining high-resolution spectroscopic observations of the star. The system was identified as an eclipsing binary in the MACHO database by Faccioli et al. (2007) as MACHO 206.17005.6. In the OGLE-III photometric database the star is listed as SMC113.3 4007.

2. OBSERVATIONS AND DATA REDUCTION

Johnson-Cousins optical photometry of the system was obtained with the Warsaw 1.3 m telescope at Las Campanas Observatory in the course of the second, third and fourth phases of the OGLE project (Udalski et al. 1997; Udalski 2003) and also with the ANDICAM camera attached to the CTIO 1.3 m telescope. In total we secured 1178 I-band epochs and 168 V-band epochs. Because of the long orbital period consecutive epochs were taken usually on different nights. The time span of the I-band observations is 5119 days (from JD 2450627 to JD 2455746). The raw data were reduced with the image-subtraction technique (Woźniak 2000; Udalski 2003) and instrumental magnitudes were calibrated onto the standard system using Landolt standards. We did not use MACHO data for this star because OGLE I-band photometry has better eclipse coverage and better precision (smaller noise and much smaller number of outliers).

Near-infrared photometry was collected with the ESO NTT telescope on La Silla equipped with the SOFI camera. The setup of the instrument, and the reduction and calibration of the data onto the UKIRT system were essentially identical to those described in our previous paper by Pietrzyński et al. (2009). The transformation of our photometry onto the Johnson system was done using the equations given by Carpenter (2001) and Bessell & Brett (1988).

High resolution echelle spectra were collected with the Clay 6.5 m telescope at Las Campanas Observatory, equipped with the MIKE spectrograph, and with the 3.6 m telescope on ESO La Silla, equipped with the HARPS spectrograph. We employed an 5×0.7 arc sec slit with MIKE giving a spectral resolution of about 40000.
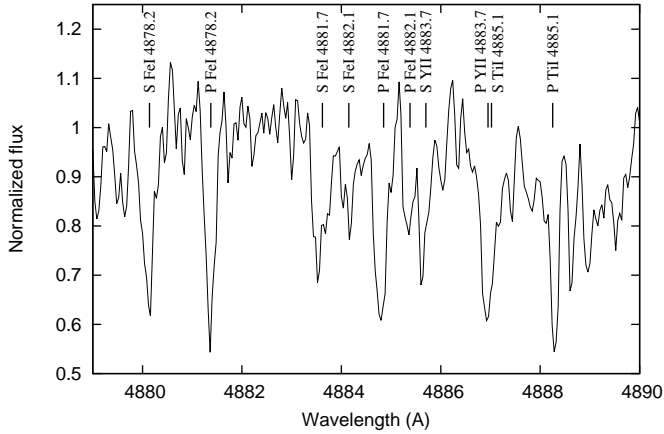
Figure 1. A MIKE spectrum of OGLE SC10 137844 taken at the third quadrature. Some absorption lines from both components are identified.

In the case of HARPS we used the EGGS mode yielding a resolution of about 80000. In our analysis we used 8 HARPS spectra, 16 MIKE blue region and 14 MIKE red region spectra (25 epochs; 13 times blue and red MIKE spectra were taken simultaneously). The typical S/N at $\sim$5000 Å was about 20 and 10 for MIKE and HARPS spectra, respectively. Figure 1 shows a small part of a MIKE blue region spectrum taken close to the third quadrature (JD 2454816.6).

Before further analysis all the spectra were shifted to the Solar System Barycenter. In order to derive radial velocities of the system's components we employed the Broadening Function (BF) formalism (Rucinski 1992, 1999) and the two-dimensional cross-correlation method TODCOR by Mazeh & Zucker (1994). We used numerous metallic lines in the wavelength regions 4125-4230, 4245-4320, 4350-4840, 4880-5000, 5350-5850, 5920-6250, 6300-6390, 6600-6800 Å. As templates we used synthetic spectra from a library computed by Coelho et al. (2005). The templates were chosen to closely match the atmospheric properties of the stars in a grid of $T_{\rm eff}$ and $\log g$. We iterated the radial velocity determination a few times each time updating the template according to the latest solution. Usually the difference between velocities derived by TODCOR and BF was smaller than 100 m s^{-1} and we adopted the mean value of both as final measurement. We detected a linear trend in velocities derived from MIKE spectra taken between HJD 2454000 and 2454800 equal to about -0.6 m s^{-1} per day. After removing the trend we accounted also, during the mentioned period of time, for a zero point shift between the MIKE and HARPS spectrographs of 0.344 km s^{-1}. The individual RV measurements are listed in Table 1.

3. MODEL OF THE SYSTEM

To derive absolute fundamental parameters for the system we used two codes for the analysis of the eclipsing binary stars: the Wilson-Devinney (WD) program, version 2007 (Wilson & Devinney 1971; Wilson 1979, 1990; van Hamme & Wilson 2007) equipped with the automated Differential Correction (DC) optimizing subroutine; and the JKTEBOP program (Southworth et al. 2004a,b) based on the EBOP code (Popper & Etzel 1981). The WD code allows to simultaneously solve for

Table 1
Radial Velocity Measurements for SC10 137844

HJD -2450000	V_1 km s^{-1}	V_2 km s^{-1}	HJD -2450000	V_1 km s^{-1}	V_2 km s^{-1}
2946.65112†	183.85	110.99	4648.92647†	129.83	164.94
4004.71811	157.44	134.47	4648.92647	130.16	165.14
4004.71812†	157.44	134.82	4655.93369	131.01	164.06
4010.72315	159.90	133.69	4655.93375†	131.15	164.08
4010.72315†	160.50	133.67	4656.87817†	130.92	163.75
4065.70091	185.64	111.32	4656.87817	131.00	163.61
4065.70093†	184.75	111.06	4671.91268*	133.38	160.74
4314.88758†	137.63	157.86	4686.79155*	137.42	157.33
4314.89337	137.13	157.53	4689.91736	138.86	157.30
4316.88748	138.02	157.37	4698.85661*	140.75	154.99
4329.86296†	141.33	154.28	4808.54742*	185.18	111.22
4329.86296	141.90	154.61	4809.54221*	185.02	110.64
4395.64368*	166.57	129.13	4816.56866	185.83	109.75
4412.54544	175.60	120.99	4816.56866†	185.85	110.18
4419.59240*	178.64	117.33	4854.52282†	165.48	130.05
4424.63882	180.62	114.55	4854.52282	165.49	129.52
4424.63882†	180.76	114.64	5087.61078*	145.58	149.79
4470.53847†	175.79	120.98	5589.53163	172.55	123.44
4470.53847	176.07	119.67	5589.53168†	172.78	123.16

* HARPS spectra
† MIKE red spectra

radial velocity and multi-band light curves recommended as the best way to obtain a consistent model of a binary system, e.g., Wilson (1979), while use of JKTEBOP allows for a reliable determination of the errors by Monte Carlo simulations. The WD code is based on Roche-lobe geometry and employs quite a sophisticated treatment of stellar surface physics, while in the JKTEBOP code stellar surfaces are approximated by biaxial ellipsoids, and simpler description of stellar physics is used. As our system is well detached it is meaningful to compare the results from both programs.

3.1. Parameter Choice

The choice of adjustable parameters has crucial impact on the final solution and parameters of the model. We tried to estimate and fix as many parameters as possible. The preliminary orbital period was calculated with the string-length method giving $P = 371.71$ days. The moment of the primary minimum was estimated to be $T_0 = 2450776.684$ from the I-band light curve and fixed during the later analysis. In this paper we will refer to the primary as the star which is eclipsed in the deeper, primary minimum. The average temperature of the primary was estimated as follows. We determined the reddening in the direction of our target to be E$(B-V)$= 0.06 ± 0.03 using the OGLE-II reddening maps (Udalski et al. 1999) and OGLE-III reddening maps (Haschke et al. 2011). Average out-of-eclipse magnitudes were calculated from all observations taken outside minima: $V(15\overset{\rm m}{.}807)$, $I(14\overset{\rm m}{.}722)$, $J(14\overset{\rm m}{.}020)$, $K(13\overset{\rm m}{.}317)$. These magnitudes were dereddened using the interstellar extinction law given by Schlegel et al. (1998) and assuming R$_V = 3.1$. From combined preliminary solutions obtained from RaVeSpAn software written by B. Pilecki and from JKTEBOP code we obtained the surface gravities: $\log g_1 = 1.7$ and $\log g_2 = 1.6$, the eccentricity $e = 0.31$ and $T_2 - T_1 \sim 10$ K. The metallicity was assumed to be [Fe/H]= -0.5 appropriate for a

Table 2
Effective Temperatures Derived from the Dereddened Colors

$T_{eff}(K)$	Calibration	Color Index
4732	di Benedetto (1998)	$V - K$
4763	Alonso et al. (1999)	$V - K$
4799	Houdashelt et al. (2000)	$V - K$
4717	Ramírez & Meléndez (2005)	$V-I, V-K$
4830	Masana et al. (2006)	$V - K$
4847	González H. & Bonifacio (2009)	$V - K$
4899	Casagrande et al. (2010)	$V-I, V-K$
4812	Worthey & Lee (2011)	$J-K, V-I, V-K$
4803		**mean**

Table 3
Photometric Parameters

Parameter	WD[a]	JKTEBOP[b]
Eccentricity e	0.3112 ± 0.0012	0.3064 ± 0.0010
Argument of Per. ω (deg)	30.2 ± 0.4	28.5 ± 0.5
Phase Shift ϕ	0.07557 ± 0.00009	not adjusted
Orbital Inclination i (deg)	88.19 ± 0.02	88.18 ± 0.02
Sec. Temperature T_2 (K)	4813 ± 3	not adjusted
Fractional Radius r_1	0.1097 ± 0.0007	0.1145 ± 0.0016
Fractional Radius r_2	0.1160 ± 0.0007	0.1117 ± 0.0016
$(r1 + r2)$	0.2257	0.2262 ± 0.0004
$k = r2/r1$	1.057	0.975 ± 0.028
Observed Period P_{obs} (d)	371.768 ± 0.002	371.768 ± 0.002
$(L2/L1)_V$	1.135 ± 0.011	not adjusted
$(L2/L1)_I$	1.131 ± 0.012	0.976 ± 0.052
$(L2/L1)_J$	1.125[c]	–
$(L2/L1)_K$	1.120[c]	–
Third Light I_3	0.0	not adjusted

[a] Simultaneous solution of V-band and I-band light curves, and radial velocity curves of both componets. Uncertainties quoted are the standard errors from DC subroutine.
[b] Only I-band light curve solution. Uncertainties quoted are from Monte Carlo simulations.
[c] Extrapolated from the model.

young (age ~ 200 Myr) population of stars in the SMC: e.g. Dias et al. (2010) from integral spectroscopy of clusters for a cluster NGC 458 (it lies very close to our star) derived [Fe/H]$= -0.4$ and age about 100-200 Myr (similar to age of our star). To derive an average effective temperature of the binary we employed a number of empirical calibrations published during last thirteen years (Table 2). The resulting average effective temperature was set as a temperature of the primary $T_1 = 4800 \pm 100$ K. It corresponds to a spectral type G8 giant star according to the calibration by Alonso et al. (1999). The lower metallicity e.g., [Fe/H]$= -0.7$ has only minor effect on the temperature (it is lower by 10 K).

Using BF we estimated the velocity broadening to be 8.4 km s^{-1} and 10.8 km s^{-1} for the primary and the secondary, respectively, with errors ± 1.0 km s^{-1}. These velocities are *lower* than the appropriate semi-synchronous velocities expected if the components are in tidal locking during periastron passage, 12.5 km s^{-1} and 13.2 km s^{-1}, respectively. If we account for the macroturbulence velocity field typical for a G type giant atmosphere described by $\zeta_{RT} = 5.4$ km s^{-1} (Gray 2005, Table B.2), the primary velocity broadening is consistent with synchronous rotation: $v \sin i = 6.4$ km s^{-1}. However, the secondary seems to rotate super-synchronously with the rotational velocity $v \sin i$ being by a factor of 1.4 larger than the synchronous one. Accordingly we set the star rotation parameters $F_1 = 1.0$ and $F_2 = 1.4$.

The albedo parameter was set to 0.5 and the gravity brightening to 0.32, both values appropriate for a cool, convective atmosphere. The limb darkening coefficients were calculated internally by the WD code according to the logarithmic law of Klinglesmith & Sobieski (1970) during each iteration of DC using tabulated data computed by van Hamme (1993). With the help of BF we tried to detect any signature of a tertiary component in the spectra at different orbital phases but we failed, and thus set the third light parameter to $l_3 = 0$.

As free parameters of the WD model we chose the semi-major axis a, the orbital eccentricity e, the argument of periastron ω, the phase shift of the primary spectroscopic conjunction ϕ, the systemic radial velocity γ, the orbital inclination i, the secondary star average surface temperature T_2, the modified surface potential of both components Ω_1, Ω_2, the mass ratio $q = M2/M1$, the observed orbital period P_{obs}, and the relative monochromatic luminosity of the primary star in the two bands $L1_V$, $L1_I$. It is worth noticing that within the WD code there is no possibility to directly adjust the radial velocity semiamplitudes K_1 and K_2, instead the semimajor axis and

the mass ratio are adjusted simultaneously.

3.2. *Fitting Procedure*

We fitted simultaneously two light curves, in the I-band and V-band, and two radial velocity curves using the DC subroutine of the WD code. The detached configuration (Mode 2) was chosen during all the analyses and a simple reflection treatment (MREF=1, NREF=1) was employed. A stellar atmosphere formulation was selected to both stars (IFAT=1). A level dependent weighting was applied (NOISE=1) and curve dependent weightings (SIGMA) were calculated after each iteration. The initial input solution was found using the JKTEBOP code. Convergence was defined to have been achieved if the parameter corrections given by DC were smaller than their standard errors on three consecutive iterations. The grid size was initially set to N=40 for both stars but other grids were checked. It was found that very fine grids (N> 50) produced some numerical instability and no convergence, in the sense defined above, could be obtained. We did not break the adjustable parameter set up into subsets, but instead we adjusted all free parameters at each iteration.
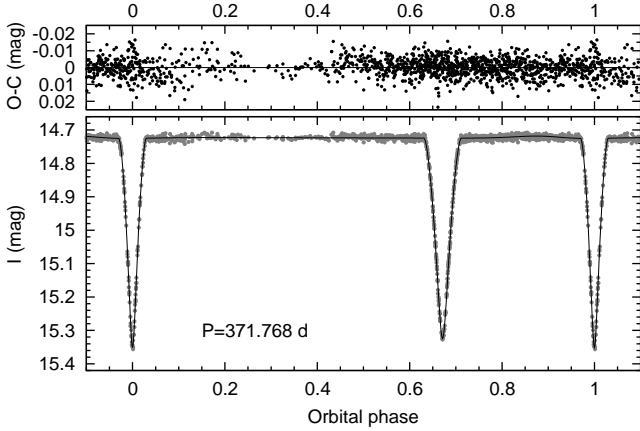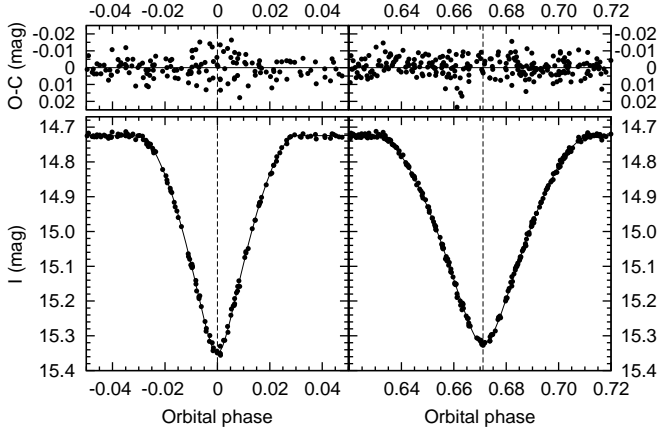
At the end of the fitting procedure we additionally adjusted the third light I_3 to find its impact on the solution: the third light corrections were invariably negative suggesting an unphysical solution, and we therefore set $I_3 = 0$ in our final solution.

The I-band light curve solution obtained with the WD code is presented in Figures 2 and 3. This solution was compared with the solution resulting from the application of the JKTEBOP code. Using JKTEBOP we fitted only the I-band light curve, and values of the mass ratio and the limb darkening coefficients were set according to the final WD solution. The errors of the parameters were calculated from ten thousand Monte Carlo simulations (Mode 8 of JKTEBOP code). It turned out that the parameters obtained from both solutions are consistent with each other within 2σ errors with one exception: the individual fractional radii of the components. The WD
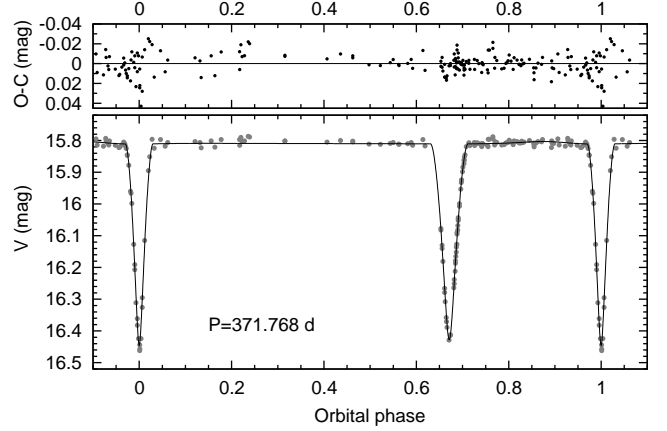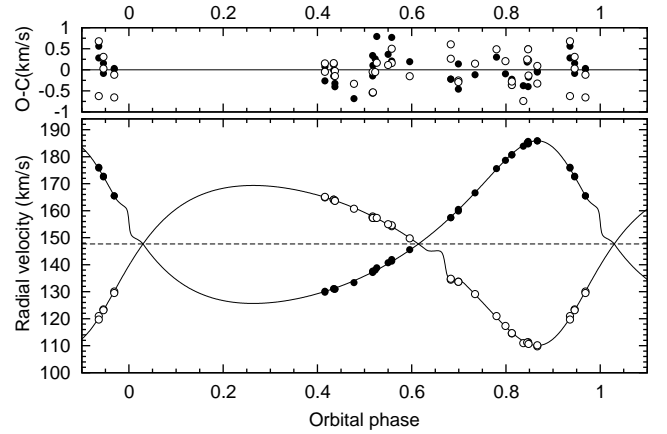
Table 4
Orbital Parameters

Parameter	Value
Periastron Passage (HJD)	2451114.80
Orbital Period P (d)	$371.585 \pm 0.002^{\mathrm{a}}$
Semimajor Axis a ($R_\odot$)	417.49 ± 0.79
Systemic Velocity γ (km s^{-1})	147.68 ± 0.05
Prim. Velocity Semiamplitude K_1 (km s^{-1})	29.93 ± 0.10
Sec. Velocity Semiamplitude K_2 (km s^{-1})	29.46 ± 0.11
Mass Ratio q	1.016 ± 0.005

[a] Corrected for the radial movement of the centre of the system mass in respect to Solar System Barycenter - see Section 3.3.

Figure 2. The I-band light curve solution to OGLE SC10 137844 from the WD code.

Figure 3. Zoom into the I-band light curve solution to OGLE SC10 137844. Left panel presents the primary minimum, the right panel shows the secondary minimum.

solution prefers the secondary star being the larger and more luminous of the two stars, while the JKTEBOP solution prefers the opposite. It underlines the old problem of determining univocally stellar radii for eclipsing binaries having partial eclipses. To distinguish between the solutions we investigated integrated CCF and BF power profiles of both stars to derive their spectroscopic light ratio. The calculated secondary to primary light ratio from CCF and BF turned out to be about 1.1. Thus, for consistency of the model, we decided to adopt the radii delivered by the WD code but with uncertainties

Figure 4. The V-band light curve solution to OGLE SC10 137844 from the WD code.

Figure 5. The radial velocity curve solution to OGLE SC10 137844 from the WD code. Filled black circles denote the primary's velocities. The dashed line marks the systemic velocity. The deviation of the secondary radial velocities from the Keplerian motion near the orbital phase 0.69 indicates the Rossiter-McLaughlin effect.

as returned from the JKTEBOP code. The resulting ephemeris for the primary minimum is:

$$T_0(\mathrm{HJD}) = 2450776.68(\pm0.01) + E \times 371.7684(\pm0.0017)$$

The V-band solution is shown in Figure 4, and the radial velocity curve solution in Figure 5. The photometric and orbital parameters of the final solution are given in Table 3 and Table 4, respectively. We note that the systemic velocity of our system is in excellent agreement with the mean radial velocity of the red giant branch stars derived by Harris & Zaritsky (2006) from their IMACS field 3. As that field encompasses the eclipsing binary, the systemic velocity independently confirms that our target belongs to the SMC.

Two of our spectra were taken during secondary eclipse egress and have allowed an approximate modeling of the Rossiter-McLaughlin effect. The observed moderate profile (see Figure 5) was fitted by adjusting the secondary star rotation parameter and we obtained $F_2 = 1.3 \pm 0.1$. This value seems to confirm that the secondary rotates super-synchronously and it is in accordance with the initial value $F_2 = 1.4$ derived from the BF analysis.

Table 5
Physical Properties of the OGLE SC10 137844
System

Property[a,b]	The Primary	The Secondary
Spectral Type	G8 II-III	G8 II-III
V (mag)	16.630	16.493
$V-I$ (mag)	1.087	1.083
$V-K$ (mag)	2.498	2.483
$J-K$ (mag)	0.705	0.701
Radius ($R_\odot$)	45.8 ± 0.7	48.4 ± 0.7
Mass ($M_\odot$)	3.504 ± 0.028	3.561 ± 0.025
$\log g$ (cgs)	1.660 ± 0.017	1.620 ± 0.016
$T_{\rm eff}$ (K)	4800 ± 100	4813 ± 100
$v \sin i$ (km s^{-1})	6.4 ± 1.0	8.7 ± 1.2
Luminosity ($L_\odot$)	1000 ± 80	1130 ± 80
M_{bol} (mag)	-2.75	-2.88
M_V (mag)	-2.40	-2.54
Fe/H	-0.5 dex (assumed)	
E($B-V$)	0.06 ± 0.03	

[a] Absolute dimensions were calculated assuming: $G = 6.673 \cdot 10^{-8}$ cm^{3}g^{-1}s^{-2}, $R_\odot = 6.9551 \cdot 10^{10}$ cm, $M_\odot = 1.9888 \cdot 10^{33}$ g, $M_{bol,\odot} = +4.75$.

[b] The magnitudes and colors are observed values.

3.3. Absolute Dimensions

The observed orbital period of the system P_{obs} and the true orbital period P are linked through a relation:

$$P_{obs} = P(1 + \frac{\gamma}{c}), \qquad (1)$$

where c is the velocity of light. The corrected period P is listed in Table 4 and is used to calculate semimajor axis of the system. Although the correction is small it is much larger than our precision of period determination.

Once the semimajor axis a of the system is known it is possible to obtain the absolute dimensions of the stars. Table 5 gives astrophysical data about the two components. The observed individual magnitudes and colors were calculated from the out-of-eclipse mean magnitudes and the light ratios given in Table 3. The position of the disentangled components on the color-magnitude diagram (CMD) is shown in Figure 6. The physical radii of the stars result from the relation: $R = r \cdot a$, where r is the fractional radius listed in Table 3. The masses are derived from the equations:

$$M_1[M_\odot] = 1.34068 \cdot 10^{-2} \frac{1}{1+q} \frac{a^3[R_\odot]}{P^2[{\rm d}]} \qquad (2)$$

$$M_2[M_\odot] = M_1 \cdot q \qquad (3)$$

Derived absolute visual luminosities of both componets are consistent with luminosity class II-III for G-type star (Eggen 1994) and their masses lie in the mass range expected for bright giant stars which have masses from about 3 $M_\odot$ to 9 $M_\odot$.

4. DISTANCE TO THE SYSTEM

To derive the distance of our binary system we employed a surface brightness - color relation. We used the calibration of di Benedetto (2005) between V-band surface brightness and $V-K$ color relation (SBR) obtained from a number of carefully selected mixed sample of giant and dwarf stars having their angular diameters measured
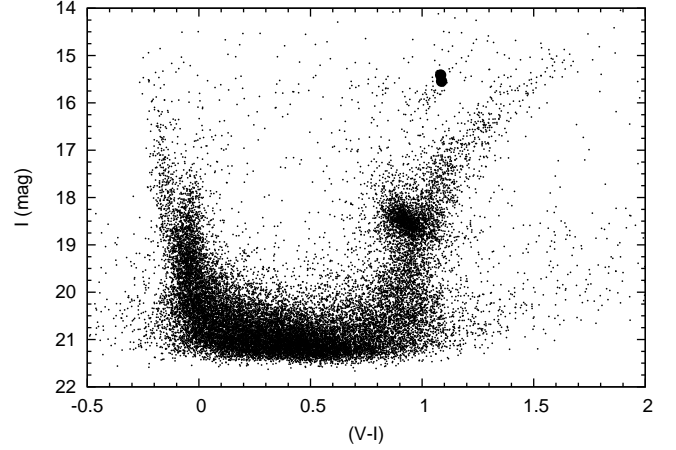

Figure 6. The observed color-magnitude diagram of the OGLE field SMC113.3 containing the eclipsing binary SC 10 137844. Superimposed (full circles) are the positions of its two giant components. Both components of our system are clump giants located at the red loop of the helium burning. At this quiet and relatively long lasting evolutionary stage stars do not show significant photometric and spectroscopic variations, which make them very good targets for precise determination of their stellar parameters.

Table 6
Distance determinations to OGLE SC10 137844 from different surface brightness-color relations

d [kpc]	Luminosity Class	Color	Reference
57.5 ± 2.0	Dwarfs+Subgiants	$V-K$	Kervella et al. (2004)
58.0 ± 2.8	Giants	$V-K$	Groenewegen (2004)
61.6 ± 4.2	Dwarfs	$V-I$	Kervella & Fouqué (2008)
60.8 ± 2.0	Dwarfs+Subgiants	$V-K$	Casagrande et al. (2010)
58.4 ± 1.8	**Giants**	$V-K$	**di Benedetto (2005)**

precisely by long baseline interferometry. The angular diameter of a star predicted by the surface brightness-color relation takes the form:

$$\phi\,[{\rm mas}] = 10^{0.2 \cdot (S-m_0)}, \qquad (4)$$

where S is the surface brightness in a given band and m_0 is the unreddened magnitude of a given star in this band. The distance in parsecs follows then directly from angular diameter scaling and is given by a simple linear equation:

$$d\,[{\rm pc}] = 9.2984 \cdot \frac{R\,[R_\odot]}{\phi\,[{\rm mas}]} \qquad (5)$$

The distance to the OGLE SC10 137844 system was calculated as the average distance to both components, and its value is 58.4 ± 1.8 kpc corresponding to a true distance modulus of 18.83 ± 0.06 mag. The distance moduli of the primary and the secondary differ by just 0.001 mag, serving as an independent check on the model consistency. We compare our result with distance estimates obtained from other recent surface brightness - color calibrations, results being summarized in Table 6. Within the errors all distances are consistent with our adopted value based on the calibration by di Benedetto (2005).

4.1. Error Budget

The systematic uncertainty on the surface brightness relation itself provides the largest contribution to the total error of 2.0%, (compare with e.g., Pietrzyński et al. (2009)). The metallicity dependence of the SBR is very weak, for our system we expect a correction of about 0.006 mag (Thompson et al. 2001; di Benedetto 1998), and we decided to add an additional error of 0.3% in the error budget. Systematic zero point uncertainties of absolute photometry are 0.7% for near infrared SOFI bands and 0.5% for the optical OGLE V band (Udalski et al. 2000). The estimated total systematic error is 2.4%.

The absolute radii are known with an accuracy of 1.5%. It would mean that the contribution to the distance error from the radius uncertainty was 1.5%. However, because of the similar diameters and temperatures of the components this contribution is much smaller and, to the first order of magnitude, equal to the uncertainty of the sum of the radii. Following Equation 5 the average distance to the system can be written as:

$$\langle d \rangle = \frac{k}{2}\left(\frac{R_1\phi_2 + R_2\phi_1}{\phi_1\phi_2}\right) = \frac{k}{2}\left(\frac{R_1+R_2}{\phi_2} + \frac{R_1}{\phi_2}\frac{\Delta\phi}{\phi_1}\right) \quad (6)$$

where index 1,2 denotes, the primary and the secondary star, respectively, $\Delta\phi = \phi_2 - \phi_1$ and $k = 9.2984$. The second term in Equation 6 constitutes, in our case, only about 3% of the first term. Regarding the error contribution from the radius uncertainties the first term gives $\sigma_{(R_1+R_2)}/(R_1+R_2) = 0.35/94.3$ i.e. about 0.4% and the second term gives 0.05%. Combining it with the semimajor axis uncertainty of 0.2% results in a total uncertainty of 0.5%.

The accuracy of $V - K$ color determination is about 0.015 mag adding 0.7% to the statistical error. The disentangling of individual V-magnitudes and near infrared color indexes contributes only slightly to the total error due to the similar temperatures of the stars. We recalculated the distance modulus of the system by enlarging the light ratios in the V and K bands with the error quoted in Table 3 and an error of 0.014, respectively. The resulting distance moduli differ by just 0.0005 mag. Thus we omitted this uncertainty in the error budget.

In the fitting procedure we set atmosphere model formulation in the WD code. We have checked how the distance estimate will change if we assume a blackbody approximation. We re-fitted the data setting IFAT=0 (black body) to both stars. The resulting radii and light ratios lead to a value of the distance modulus which differs by less than 0.001 mag from our adopted value.

The interstellar absorption, because of the reddening vector being almost parallel to the SBR, contributes relatively little to the total error: 0.7%. A different interstellar extinction law with $R_V = 2.7$ contributes insignificantly on the level of 0.3%. Adding the contributions of these errors on the distance determination to OGLE SC10 137844 quadratically we obtain a total statistical error of 1.1%.

We conclude that the uncertainty of the extinction and $V - K$ color determination are the main contributors to the statistical error in the distance. The calculation of the total uncertainty is a bit ambiguous because it depends on the systematic uncertainty probability distribution which we don't know a priori. We can give however the limits for the total error. The lower error limit of

Table 7
Comparison of recent distance determinations to the SMC.

$(m-M)$	Stat. Err.	Sys. Err.	Method	Ref[a]
18.91	0.04	$\sim$0.1	Eclipsing Binaries	1
18.96	0.10	?	RR Lyr	2
18.93	0.02	?	Bump Cepheids	3
18.97	0.03	0.12	RR Lyr	4
18.85	0.07	$\sim$0.1	Type-II Cepheids	5
19.11	0.03	?	Eclipsing Binaries	6
18.92	0.14	?	Classical Cepheids	7
18.83	0.02	0.05	Eclipsing Binary	8

[a] References: 1- Hilditch et al. (2005), 2- Sandage & Tammann (2006), 3 - Keller & Wood (2006), 4 - Szewczyk et al. (2009), 5 - Ciechanowska et al. (2010), 6 - North et al. (2010), 7 - Storm et al. (2011b), 8 - this paper

2.5% comes from the assumption of a gaussian distribution of the systematic uncertainty while the upper limit of 3.5% results from the assumption of a pure bias. The mean value of both was given in Table 6 corresponding to the total uncertainty of $\sim$3.0%.

5. DISCUSSION

We obtain a true distance modulus for our binary system of 18.83 ± 0.02 (statistical) ± 0.05 (systematic from the SBR) mag. Our analysis demonstrates that for such late-type systems consisting of red giant stars we can indeed measure the distances very accurately, with prospects of improving the achievable accuracy once an improved surface brightness-color relation becomes available which is the current limiting factor on the precision of the method.

In Table 7 we have compiled other recent determinations of the distance to the SMC. Our result from SC10 137844 is in good agreement with the average SMC distances derived from classical and Type-II Cepheid, and RR Lyrae star samples. The outlier is the distance of 19.11 mag reported by North et al. (2010) from an analysis of 33 eclipsing binaries in the southwest part of the galaxy. However, since the SMC is a line-of-sight elongated structure, especially towards the northeast, with a typical depth of $\sim$ 0.25 mag (e.g. Harris & Zaritsky (2006)), all the determinations in Table 7 might be compatible within their quoted errors. Also it is known that there is a distance gradient over the SMC with its northeastern part being closer to us than its southwestern part (e.g. Subramanian & Subramaniam (2011)). Indeed, the distance to the galaxy centre given by Hilditch et al. (2005) lies between our determination and the North et al. (2010) estimate which seems to be consistent with the present geometrical model of the galaxy. However, because North et al. (2010) did not give any estimate of the systematic uncertainty of their result it is not easy to compare the SMC distances obtained from eclipsing binaries.

If we assume a distance gradient over the SMC projected disc of 2-3 kpc (Hilditch et al. 2005) our star should be around $\sim$1 kpc (0.035 mag) closer to us than the optical center of the galaxy. Thus our distance would correspond to a distance modulus of 18.87 mag for the SMC center. Assuming a modulus offset between SMC and LMC equal to 0.44 (Cioni et al. 2000) it would imply a distance modulus of the LMC of 18.43 mag. This value is very close to the true LMC distance modulus derived

recently by Storm et al. (2011b) with the near-infrared Baade-Wesselink method applied to classical Cepheids.

We are currently working on a number of similar late type eclipsing systems in the Small Magellanic Cloud, and expect to determine the mean distance to the SMC with a precision better than 4%.

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