THE ORBITAL AND PHYSICAL PARAMETERS, AND THE DISTANCE OF THE ECLIPSING BINARY SYSTEM OGLE-LMC-ECL-25658 IN THE LARGE MAGELLANIC CLOUD

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ABSTRACT

We present an analysis of a new detached eclipsing binary, OGLE-LMC-ECL-25658, in the Large Magellanic Cloud (LMC). The system consists of two late G-type giant stars on an eccentric orbit with an orbital period of ~200 days. The system shows total eclipses and the components have similar temperatures, making it ideal for a precise distance determination. Using multi-color photometric and high resolution spectroscopic data, we have performed an analysis of light and radial velocity curves simultaneously using the Wilson–Devinney code. We derived orbital and physical parameters of the binary with a high precision of <1%. The masses and surface metallicities of the components are virtually the same and equal to \(2.23 \pm 0.02\) \(M_\odot\) and [Fe/H] = \(-0.63 \pm 0.10\) dex. However, their radii and rates of rotation show a distinct trace of differential stellar evolution. The distance to the system was calculated using an infrared calibration between \(V\)–\(K\) color, leading to a distance modulus of \(m - M = 18.452 \pm 0.023\) (statistical) \(\pm 0.046\) (systematic). Because OGLE-LMC-ECL-25658 is located relatively far from the LMC barycenter, we applied a geometrical correction for its position in the LMC disk using the van der Marel et al. model of the LMC. The resulting barycenter distance to the galaxy is \(d_{\text{LMC}} = 50.30 \pm 0.53\) (stat.) kpc, and is in perfect agreement with the earlier result of Pietrzyński et al.

Key words: binaries: eclipsing – galaxies: distances and redshifts – galaxies: individual (Large Magellanic Cloud)

1. INTRODUCTION

The distance to the Large Magellanic Cloud (LMC) is of great astrophysical importance for at least two reasons. First, the LMC serves as the best anchor to establish the zero point of the extragalactic distance scale, and a variety of distance indicators, including classical Cepheids, RR Lyrae stars, red clump stars, and the tip of the red giant branch method can be calibrated in the LMC with better accuracy than in any other galaxy at the present time. Second, the LMC represents an ideal laboratory for the detailed study of different stellar populations, given its distance of about 50 kpc which is far enough to see, in a first approximation, all its objects at the same distance, and at the same time close enough to study in great detail even its faint stellar populations. Given these advantages, many astrophysical studies of LMC stars, stellar clusters, and gaseous regions have been carried out over the past century. In particular, many attempts have been made to determine a precise and accurate distance to the LMC in order to put the luminosities and sizes of its components onto an absolute scale. It has proved extremely difficult to establish an accurate and reliable distance to the LMC, given the different and often large systematic uncertainties of the different methods which have been applied to solve this problem.

A breakthrough came with the discovery of a very special and rare class of eclipsing binaries in the Magellanic Clouds by the Optical Gravitational Lensing Experiment (OGLE) project (Udalski et al. 1998; Wyrzykowski et al. 2003, 2004). These systems consist of two usually quite similar red giant components, and offer two very important advantages over the (usually brighter and thus easier-to-observe) early-type eclipsing binaries in the context of distance determination: they can be easily and precisely analyzed using standard techniques and without resorting to uncertain theoretical predictions, and the angular diameters of the component stars, and hence their distances, can be precisely determined from a surface brightness–color relation (SBCR) which is accurately determined for late-type stars (e.g., Kervella et al. 2004; Di Benedetto 2005), but not for early-type stars (e.g., Challouf et al. 2014). The first system of this class was analyzed by Pietrzyński et al. (2009) and led to a distance accurate to 3%, including the (well-determined) systematic uncertainties. Due to the hard work of the Araucaria Project team, four years later data for these hard-to-observe systems (due to their long orbital periods and relative faintness) were ready for the analysis of eight late-type systems. Their analysis led to a LMC barycenter distance accurate to 2.2% (Pietrzyński et al. 2013, hereafter P13) which currently represents the most accurate distance to the LMC ever measured.

In an effort to improve the LMC distance determination even further, mostly with the aim of improving the Hubble constant to an accuracy of 1% with the Cepheid–Type Ia supernova method (e.g., Riess et al. 2011), our group is currently observing more late-type systems in the LMC. One of these systems, OGLE-LMC-ECL-25658, is particularly useful for deriving a precise distance: it is relatively bright, both components have very similar temperatures, and the deep and total eclipses allow for very precise determinations of the stellar radii and dynamical parameters. The \((V - K)\) colors of the component stars allow, in turn, for a very precise determination of their surface brightnesses and, in tandem with the radii, their distances. Some basic information on the system (coordinates,
observed magnitudes, and the orbital period) is given in Table 1. The system is different from those systems studied in P13 in the sense that its location in the LMC is quite far (3°.5) from the geometrical center of the LMC and the line of nodes (the model of van der Marel et al. 2002). We present a detailed analysis of this system, derive its orbital parameters and very accurate physical parameters for the component red giants in the system, and derive its distance which, corrected with the geometrical model of van der Marel et al., strengthens the LMC distance determination with the late-type eclipsing binaries of P13. The results also add to our database of physical parameters. Section 5 describes the distance determination, and Section 6 contains the conclusions and final remarks.

2. OBSERVATIONS

2.1. Photometry

The system was detected during the course of the OGLE III project and identified as an eclipsing binary system by Graczyk et al. (2011). Its position relative to the LMC is shown in Figure 1. Optical photometry in the Johnson–Cousins filters was obtained with the Warsaw 1.3 m telescope at Las Campanas Observatory in the course of the LMC (Udalski 2003) and fourth (Soszyński et al. 2012; Udalski et al. 2015) phase of the OGLE project (Udalski et al. 1997). 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. The zero point error of our optical photometry is 0.010 mag. The I-band light curve shows a small amount of intrinsic variability, visible as light oscillations with an amplitude of up to 0.01 mag, and a quasi-period of 50–100 days.

Near-infrared photometry was collected with the ESO NTT telescope on La Silla, equipped with the SOFI camera. In total we obtained 22 epochs of infrared photometry for our system outside eclipses. Our photometry was tied to the UKIRT system by observations of a number of JHK standards from Hawarden et al. (2001) and then transformed onto the Johnson system using the equations given by Carpenter (2001) and Bessell & Brett (1988). The zero point photometric error of our infrared photometry is 0.015 mag.

2.2. Spectroscopy

High resolution echelle spectra were collected with the Clay 6.5 m telescope at Las Campanas equipped with the MIKE spectrograph, and with the 3.6 m telescope at ESO-La Silla, equipped with the HARPS spectrograph. Details of the setup are given in Graczyk et al. (2014). In total we collected nine HARPS spectra and 15 MIKE spectra. In some cases (e.g., weak signal-to-noise ratio (S/N)) we could use only one part of a MIKE spectrum (blue or red). The HARPS spectra were reduced and calibrated with the standard on-site pipeline whereas the MIKE spectra were reduced with the pipeline software developed by D. Kelson, following Kelson (2003). In order to determine the radial velocities of the components, we employed the broadening function formalism introduced by Rucinski (1992, 1999). Radial velocities were derived using RaveSpan software (Pilecki et al. 2012). Absorption line profiles of the cooler and larger component (the secondary) are significantly rotationally broadened while the line profiles of the primary are almost Gaussian. We determined total line broadenings in terms of the rotational velocity of the components to be $v_1 \sin i = 9.5 \pm 1.0$ km s$^{-1}$ and $v_2 \sin i = 18.9 \pm 1.2$ km s$^{-1}$. During the preliminary fitting with the RaveSpan software we detected a systematic shift between the HARPS and MIKE radial velocities amounting to +0.76 km s$^{-1}$. This shift was subtracted from all radial velocities measured from MIKE spectra. Table 2 presents all our radial velocity measurements used in the subsequent analysis.

3. MODELING STRATEGY

In order to derive absolute fundamental parameters for the system we used the Wilson–Devinney (hereafter WD) code version 2007 (Wilson & Devinney 1971; Wilson 1979, 1990; van Hamme & Wilson 2007) which allows us to analyze multiband light curves and radial velocity curves simultaneously.
The mean error of radial velocity determination is 300 m s⁻¹. This code also implements the automated differential correction (DC) optimizing subroutine, helping us to obtain an optimal model of our binary system. As the system is well detached we utilized the JKTEBOP program (Southworth et al. 2004a, 2004b), based on the EBOP code (Popper & Etzel 1981), to obtain a reliable determination of the statistical errors by Monte Carlo (MC) simulations.

We follow the methodology from Graczyk et al. (2014). The first step of the analysis uses the information obtained from the combined light and radial velocity curves plus a first reddening estimate to estimate the basic physical parameters (e.g., surface temperature) and subsequently decompose the components' spectra. The second step utilizes information obtained from an atmospheric analysis of the decomposed spectra in order to obtain a full set of internally consistent parameters of the system.

### 3.1. Initial Parameters

The detached configuration (Mode 2) was chosen during the whole analysis and a simple reflection treatment (MREF = 1, NREF = 1) was employed. A stellar atmosphere formulation was selected for both stars (IFAT = 1). Level dependent weighting was applied (NOISE = 1), and curve dependent weightings (SIGMA) were calculated after each iteration. A logarithmic limb darkening law was used (Klinglesmith & Sobieski 1970) with coefficients automatically computed from the Van Hamme (1993) tables (option LD = -2). The orbital period P and epoch of the primary minimum were taken from the OGLE III catalog of eclipsing binaries in the LMC (Graczyk et al. 2011). Initially we assumed a temperature of \( T_1 = 5000 \) K for the primary component (i.e., component eclipsed during primary minimum). The albedos \( A_{1,2} \) and the gravity brightenings \( g_{1,2} \) were set to standard values expected for a cool convective atmosphere. The rotation parameter of the two components was set to \( f_{i,2} = 1 \), i.e., synchronous rotation. The orbit is significantly eccentric and using the LC module of the WD code we computed a number of trial light curves and radial velocity curves to obtain good starting values for the stellar radii and the orbital parameters. As the eclipses are total, and the separation of the components is relatively large, the orbital inclination \( i \) must be close to 90°.

#### 3.2. Initial Fitting

We fitted simultaneously two optical light curves (\( V \)- and \( I \)-bands) and two radial velocity curves corresponding to each of the components. After each iteration the curve dependent weights were updated. As free parameters of the WD model we chose the semimajor axis \( a \), the orbital eccentricity \( e \), the argument of periapsis \( \omega \), the phase shift \( \phi \), the systemic radial velocity \( \gamma \), the orbital inclination \( i \), the secondary star average surface temperature \( T_2 \), the modified Roche lobe surface potential of both components \( \Omega_{1,2} \), the mass ratio \( q = M_2/M_1 \), the observed orbital period \( P_{\text{obs}} \), and the relative monochromatic luminosity of the primary star in the two bands \( L_1, L_1' \). It is worth noting that within the WD code there is no possibility to directly adjust the radial velocity semiamplitudes \( K1 \) and \( K2 \); instead, the semimajor axis and the mass ratio are adjusted simultaneously. For all fitted parameters we use a parameter increment, required by the DC procedure, equal to 0.7% of the nominal value.

From the initial fitting it was clear that the orbital inclination is so close to 90° that it causes numerical instability and some problems with a solution convergence. We had to repeat the fitting with different increments of \( i \) until we could find a satisfactory solution. The temperature of the secondary star \( T_2 \) was found to be very similar to \( T_1 \). We updated the temperature estimate of the primary \( T_1 \) as follows. We determined the temperature ratio of the components to be equal to \( T_2/T_1 = 0.972 \). The extinction in the direction of our system was estimated from reddening maps of the Magellanic Clouds (Hasczke et al. 2011). We calculated \( E(B-V) = 0.091 \pm 0.030 \) mag using the equation:

\[
E(B-V) = \frac{E(V-I)}{1.3} + 0.057
\]

where \( E(V-I) \) is the color excess from the reddening map, the denominator of 1.3 is adopted from Bessell et al. (1998), and \( \Delta(B-V) = 0.057 \) mag is the foreground galactic reddening in the direction of the system as derived from the dust maps of Schlafly & Finkbeiner (2011). Then we corrected the \( V \)-, \( I \)-, and \( K \)-band infrared magnitudes of the system for extinction using the interstellar extinction law given by Cardelli et al. (1989) and O’Donnell (1994) assuming \( R_V = 3.1 \). Using a number of calibrations between \( (V-I) \), \( (V-K) \) colors and temperature (Di Bedetto 1998; Alonso et al. 1999; Houdasht et al. 2000; Ramírez & Meléndez 2005; González Hernández & Bonifacio 2009; Casagrande et al. 2010; Worthey & Lee 2011), and temperature ratio, after a few iterations we determined \( T_1 = 4825 \) K. A model of the system with this adopted temperature was subsequently utilized in obtaining the components’ decomposed spectra.

### Table 2

Radial Velocities of OGLE-LMC-ECL-25658

| HJD       | RV1     | RV2     | Spectrograph |
|-----------|---------|---------|--------------|
| 2454784.82235 | 288.315 | 226.897 | MIKE         |
| 2454809.75120 | 279.247 | 235.338 | HARPS        |
| 2454816.71919 | 275.228 | 238.456 | MIKE         |
| 2454883.63273 | 239.947 | 274.251 | MIKE         |
| 2454887.73001 | 238.783 | 276.555 | HARPS        |
| 2454887.71727 | 237.623 | 276.534 | HARPS        |
| 2454889.72089 | 237.440 | 277.668 | HARPS        |
| 2455088.89846 | 234.038 | 281.724 | HARPS        |
| 2455185.82555 | 283.472 | 230.683 | HARPS        |
| 2455218.85162 | 267.462 | 247.605 | MIKE-Blue    |
| 2455219.85556 | 267.605 | 248.489 | MIKE-Blue    |
| 2455272.74222 | 238.997 | 275.949 | MIKE-Red     |
| 2455449.89368 | 247.642 | 267.928 | HARPS        |
| 2455470.80855 | 235.760 | 279.769 | HARPS        |
| 2455502.73785 | 223.229 | 291.191 | HARPS        |
| 2455557.60017 | 287.778 | 226.300 | MIKE         |
| 2455590.70444 | 274.517 | 240.392 | MIKE         |
| 2455591.70406 | 274.386 | 241.211 | MIKE         |
| 2455882.83047 | 223.689 | 291.153 | MIKE         |
| 2455883.74846 | 222.711 | 290.662 | MIKE         |
| 2455950.75924 | 285.780 | 229.107 | MIKE         |
| 2455952.74407 | 285.202 | 229.428 | MIKE         |
| 2455964.78753 | 280.053 | 235.016 | MIKE-Red     |

Note. The mean error of radial velocity determination is 300 m s⁻¹ for HARPS and 350 m s⁻¹ for MIKE.
3.3. Spectral Disentangling Process

Each of our recorded spectra are composite spectra consisting of the spectral features of both components. A time series analysis of this composite spectrum can give us information about the dependence of the radial velocities of each component on the orbital phase and the spectral features of the component stars. This meaningful information is “entangled” and requires a specific process for its extraction. In order to constrain the atmospheric parameters of our binary components, in particular their surface temperatures, a spectral disentangling process was performed. We followed the method described by González & Levato (2006) to disentangle individual spectra of the binary components. The method works in the real wavelength domain. It requires a rather high S/N ratio spectrum to work properly, and thus we were restricted to using only the red part of MIKE spectra. We used the two-step method described in detail by Graczyk et al. (2014) to derive renormalized disentangled spectra. Renormalization was performed using optical light ratios calculated with the preliminary model of the system (see Section 3.2). The resulting spectra have S/N ~ 50 at 5500 Å.

3.4. Atmospheric Analysis

The decomposed spectra were used for deriving the basic atmospheric parameters such as effective temperatures $T_{\text{eff}}$, microturbulence $\nu_t$, and metallicity [Fe/H]. By measuring the equivalent widths of the iron spectral lines it is possible to obtain the iron content of the components (Marino et al. 2008; Villanova et al. 2010). Surface gravities $\log g$ of both stars were kept at values corresponding to radii and masses derived from the preliminary WD solution. The solar iron abundance chosen was $\log \epsilon$(Fe) = 7.50. Atmospheric parameters were obtained as follows. Model atmospheres were calculated using ATLAS9 (Kurucz 1970) assuming as initial estimations for $T_{\text{eff}}$ and $\nu_t$ values typical for giant stars (4800 K and 1.80 km s$^{-1}$). Lines of FeI and FeII were used for this purpose. The [Fe/H] value of the model was changed at each iteration according to the output of the abundance analysis. The typical accuracy of the parameters are 70 K, 0.10 dex, and 0.2 km s$^{-1}$ for $T_{\text{eff}}$, [Fe/H], and $\nu_t$, respectively. The resulting atmospheric parameters for our system are summarized in Table 3.

3.5. Final Solution

For the fine-tuning of the model we set the temperature of the primary to the value derived from the atmospheric analysis, $T_{\text{eff}} = 4860$ K, and we then recalculated the model. The resulting optical light ratios were in full agreement with light ratios from the preliminary solution and we do not iterate the renormalization of decomposed spectra and the atmospheric analysis. The temperature scale consistency of the system was checked by computing the distance to the system resulting from a scaling of the bolometric flux observed at Earth. To calculate the bolometric corrections, we used an average from several calibrations (Flower 1996; Alonso et al. 1999; Casagrande et al. 2010). These distances were then compared to the distance computed with an SBCR (see Section 5). The good agreement between those two distances put confidence into our adopted temperature scale.

The final tuning of the model was impeded by the notorious numerical instability of the WD code close to the 90° limit of the orbital inclination. In order to obtain a definitive value for the inclination and also to find reliable statistical errors on the photometric parameters, we ran extensive MC simulations using the JKTEBOP program (Southworth et al. 2004a, 2004b) based on the EBOP code (Popper & Etzel 1981). The system is well detached and the biaxial representation of stellar surface utilized in EBOP is sufficiently precise to not introduce systematics in the solution. The task 8 was chosen and we calculated 10,000 models based on the I-band light curve. Figure 2 shows a $\chi^2$ map for the orbital inclination and illustrates the indeterminacy of this parameter. If fact, all inclinations larger than 89°6 are allowed. The best solution returned from the MC simulations gives $i = 89°79$ and this value was adopted in our final WD runs. The solutions from the WD and JKTEBOP codes are very consistent and show only small, insignificant differences. Table 4 contains the basic parameters of our final solutions with the WD code. Resulting synthetic light and radial velocity curves and a comparison with the data are presented in Figure 3.

Also, we computed two additional sets of models by adjusting: (1) the four coefficients of the linear law of limb darkening (mode LD = +1) for both stars and both light curves and (2) the third light $l_3$ in the V- and J- bands. We checked the resulting reduced $\chi^2$ but we did not see any improvements. Moreover, the obtained third light values were consistent with zero, leading us to adopt the configuration with $l_3 = 0$ and with tabulated limb darkening coefficients for logarithmic law.

### Table 3

|          | $T_{\text{eff}}$ | [Fe/H] | $\nu_t$ |
|----------|------------------|--------|--------|
| Primary  | 4860             | −0.65  | 1.70   |
| Secondary| 4730             | −0.62  | 1.80   |

4. Absolute Dimensions

A summary of the derived physical parameters of our system is given in Table 5. Spectral types of the components were estimated from temperatures using calibration by Alonso et al. (1999). The observed orbital period of the system $P_{\text{obs}}$ and the

![Figure 2](image_url)
true orbital period $P_{\text{orb}}$ are linked through a relation:

$$P_{\text{obs}} = P_{\text{orb}} \left(1 + \frac{\gamma}{c}\right)$$

where $c$ is the speed of light. The corrected period $P_{\text{orb}}$ is used to calculate the semimajor axis of the system. The masses were derived from the equations:

$$M_1 [M_{\odot}] = 1.34157 \times 10^{-2} \frac{1}{1 + q} \frac{a^3}{P^2 \text{[day]}}$$

$$M_2 [M_{\odot}] = M_1 \cdot q.$$  

Projected rotational velocities $v \sin i$ of the components were calculated from the observed line broadening taking into account the effects of the macroturbulence $\nu_T$ and the instrumental broadening $\nu_{ib}$. To estimate the macroturbulence we used the calibration given by Massarotti et al. (2008), and the instrumental profile broadening for MIKE’s resolving power of $R = 40,000$ was estimated to be $4.5 \text{ km s}^{-1}$. Comparison of the resulting $v \sin i$ values with synchronous and pseudo-synchronous rotational velocities shows that the rotation of the smaller, primary component seems to be locked to the orbital period (synchronism) while the secondary rotates much faster in accordance with the periastron rotation lock. In such a comparison we assume that both stellar axes of rotation are perpendicular to the orbital plane. However, this mismatch of rotational velocities may also mean a strong misalignment of the rotation axes, with the primary’s axis being tilted against the orbital plane by $\sim 30^\circ$.

5. DISTANCE

For late-type stars we can use the very accurately calibrated (2%) relation between their surface brightness and $(V-K)$ color (Di Benedetto 2005) to determine their angular sizes from optical $(V)$ and near-infrared $(K)$ photometry. From this SBCR we can derive angular sizes of the components of our binary systems directly from the definition of the surface brightness. Therefore the distance can be measured by combining the angular diameters of the binary components derived in this way with their corresponding linear dimensions obtained from the analysis of the spectroscopic and photometric data. The angular diameter of a star predicted by the SBCR is:

$$\theta = 10^{0.2(S-m_0)}$$

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 then follows directly from angular diameter scaling and is given by a simple linear equation:

$$d \text{[pc]} = 9.306 \frac{R_{\odot}}{\theta \text{[mas]}}. \quad (6)$$

The individual, extinction corrected magnitudes of the components were calculated using the light ratios from Table 4. To estimate the angular diameters we utilized the SBCR calibration given by Di Benedetto (2005). The distance to the OGLE-LMC-ECL-25658 system was assumed to be an average of the distances determined to both components. Its value is 49.03 kpc and it corresponds to a true distance modulus of $(m-M) = 18.452$. The difference between the components’ individual distance moduli is smaller than 0.001 mag. Because the system is located significantly away from the center of the LMC, it is necessary to calculate a geometric correction to find the distance to the barycenter of the LMC. To this end, we adopted the model of the LMC disk from van der Marel et al. (2002), i.e., the inclination of the disk to the plane of the sky $i = 28^\circ$ and the position angle of the line of nodes $\Omega = 128^\circ$. The correction corresponding to the position of the system is $\Delta d = +1.27$ kpc, translating into a barycenter distance to the LMC of $d_{\text{LMC}} = 50.30$ kpc, or a true distance modulus of $(m-M)_{\text{LMC}} = 18.508 \pm 0.023$ mag (statistical error). This value is in excellent agreement with the distance modulus to the LMC derived by P13 who reported $(m-M) = 18.493 \pm 0.008$ (stat.) $\pm 0.047$ (syst.) based on eight late-type eclipsing binaries.

5.1. Error Budget

Contributions to the statistical error on the distance modulus determination are: uncertainty on the sum of the radii $(0.012 \text{ mag})$, uncertainty on extinction $(0.013 \text{ mag})$, error of the semimajor axis $(0.008 \text{ mag})$, out-of-eclipse variability $(0.010 \text{ mag})$, and combined error on photometry $(0.006 \text{ mag})$. Combination of these contributions in quadrature yield $0.023 \text{ mag}$. We assumed this value as the total statistical uncertainty on the distance.

Table 4

| Parameter | Value |
|-----------|-------|
| Orbital period $P_{\text{orb}}$ (day) | 192.7892 ± 0.0014 |
| $T_0$ (HJD–2450000) | 3891.605 ± 0.009 |
| $a \sin i$ ($R_{\odot}$) | 231.237 ± 0.610 |
| Systemic velocity $\gamma_1$ (km s$^{-1}$) | 257.25 ± 0.06 |
| Systemic velocity $\gamma_2$ (km s$^{-1}$) | 257.58 ± 0.06 |
| Periastron longitude $\omega$ ($^\circ$) | 263.93 ± 0.22 |
| Eccentricity $e$ | 0.3731 ± 0.0046 |
| Mass ratio $M_2/M_1$ | 1.0001 ± 0.0048 |

Photometric Parameters

| Parameter | Value |
|-----------|-------|
| Orbital inclination $i$ ($^\circ$) | 89.79 ± 0.18 |
| Surface potential $\Omega_1$ | 12.394 ± 0.040 |
| Surface potential $\Omega_2$ | 9.985 ± 0.050 |
| Temperature ratio $T_2/T_1$ | 0.9714 ± 0.0012 |
| Relative radius $r_1$ | 0.0927 ± 0.0006 |
| Relative radius $r_2$ | 0.1193 ± 0.0010 |
| Light ratio $(L_2/L_1)_H$ | 1.3953 ± 0.0050 |
| Light ratio $(L_2/L_1)_K$ | 1.4681 ± 0.0046 |
| Light ratio $(L_2/L_1)_{\text{bb}}$ | 1.5365 ± 0.0047 |
| Light ratio $(L_2/L_1)_{\text{bb}}$ | 1.5964 ± 0.0047 |

Derived Quantities

| Parameter | Value |
|-----------|-------|
| Rest frame $P_{\text{orb}}$ | 192.6237 ± 0.0014 |
| Semimajor axis $a$ ($R_{\odot}$) | 231.040 ± 0.617 |
| Velocity semimajor $K_1$ (km s$^{-1}$) | 32.70 ± 0.13 |
| Velocity semimajor $K_2$ (km s$^{-1}$) | 32.70 ± 0.13 |
| $k = r_2/r_1$ | 1.287 ± 0.014 |
| $r_1 + r_2$ | 0.2120 ± 0.0011 |

Notes:

- a Epoch of the primary minimum.
- b From the MC calculations with JKTEBOP.
- c Extrapolated from the WD code.
- d Calculated from the rest frame orbital period.
The sources of systematic uncertainty in our method are the following: the uncertainty on the empirical calibration of the SBCR of Di Benedetto (2005) (0.041 mag), the uncertainty on the extinction (0.010 mag), the metallicity dependence on the SBCR (0.004 mag), and the uncertainties on the zero points of the $V$- and $K$-band photometries (0.010 mag and 0.015 mag, respectively). Combining these in quadrature, we obtain a total systematic error of 0.046 mag.

6. SUMMARY AND CONCLUSIONS

We have obtained stellar parameters for the eclipsing binary OGLE-LMC-ECL-25658. Although this is an extragalactic object the absolute dimensions of the system and the physical parameters of the component stars are determined with very high precision (better than 1%). The system is composed of two giants of equal masses and similar temperatures but having significantly different radii and rates of axial rotation. As such this is probably an interesting case of differential stellar evolution of two identical stars in which some secondary evolution parameters (like, e.g., the initial rate of rotation) have led to the observed present day differences. We leave this problem for a future study, including a detailed comparison with evolutionary models.

The distance to the system is measured to be $49.03 \pm 1.41$ kpc (total uncertainty), i.e., it has a fractional accuracy better than 3%. The eclipsing binary is located relatively far from the barycenter of the LMC and lies on the eastern side of the galaxy. Its position is exactly opposite to the systems analyzed by P13 which are located close to the barycenter, and the western part of the LMC. Because of this our distance...
Table 5

| Property | Primary | Secondary |
|----------|---------|-----------|
| Spectral Type | G8 III | G9 III |
| Mass $M_*(M_\odot)$ | $2.229 \pm 0.019$ | $2.230 \pm 0.019$ |
| Radius $R_*(R_\odot)$ | $21.41 \pm 0.15$ | $27.57 \pm 0.24$ |
| Gravity log g (g/s) | $2.125 \pm 0.006$ | $1.906 \pm 0.007$ |
| $v\sin i$ (km s$^{-1}$) | $6.7 \pm 1.4$ | $17.7 \pm 1.3$ |
| $v_{\text{mac}}$ (km s$^{-1}$) | $5.62 \pm 0.04$ | $7.24 \pm 0.06$ |
| $v_{\text{sync}}$ (km s$^{-1}$) | $13.3 \pm 0.2$ | $17.1 \pm 0.3$ |
| Temperature $T_{\text{eff}}$ (K) | $4860 \pm 70$ | $4721 \pm 75$ |
| Luminosity$^a$ ($L_\odot$) | $230 \pm 14$ | $339 \pm 22$ |
| $M_{\text{bol}}$ (mag) | $-1.15 \pm 0.06$ | $-1.58 \pm 0.07$ |
| $M_V$ (mag) | $-0.81 \pm 0.07$ | $-1.17 \pm 0.08$ |
| $\text{[Fe/H]}$ (dex) | $-0.65 \pm 0.10$ | $-0.62 \pm 0.10$ |
| $E(B − V)$ (mag) | $0.091 \pm 0.030$ | |
| $(m − M)^{ij}$ (mag) | $18.452$ | $18.453$ |
| Distance$^d$ (kpc) | $49.03 \pm 0.53$ (stat.) | $1.04$ (syst.) |
| Distance to the LMC (kpc) | $50.30 \pm 0.53$ (stat.) | |

Notes.

$^a$ Assuming $T_\odot = 5777$ K.

$^b$ Assuming the Sun’s bolometric magnitude is $+4.75$ mag.

$^c$ The distance modulus.

$^d$ Taking into account uncertain systematic in the distance modulus of 0.046 mag.

determination serves as a perfect check of the consistency of our method and the assumed spatial orientation of the LMC disk (van Marle’s model). The distance to the LMC barycenter resulting from the application of the geometrical correction corresponding to the position of the system is fully consistent with our previous result ($P_{13}$, $d_{\text{LMC}} = 49.97 \pm 1.12$ kpc).

With a further ~10 new eclipsing binaries to be analyzed by our team, we can provide very precise individual distance determinations to a total number of about 20 systems. Such a large sample of systems, in tandem with an improved SBCR our group is currently working on, will allow a significant improvement in the accuracy of the distance to the LMC, and thus improvement of the zero point of the cosmic distance scale.

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