An eclipsing binary distance to the Large Magellanic Cloud accurate to 2 per cent

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In the era of precision cosmology it is essential to determine the Hubble Constant with an accuracy of 3% or better[1,2]. Currently, its uncertainty is dominated by the uncertainty in the distance to the Large Magellanic Cloud (LMC) which as the nearest galaxy serves as the best anchor point of the cosmic distance scale[2,3]. Observations of eclipsing binaries offer a unique opportunity to precisely and accurately measure stellar parameters and distances[4,5]. The eclipsing binary method was previously applied to the LMC[6,7] but the accuracy of the distance results was hampered by the need to model the bright, early-type systems used in these studies. Here, we present distance determinations to eight long-period, late-type eclipsing systems in the LMC composed of cool giant stars. For such systems we can accurately measure both the linear and angular sizes of their components and avoid the most important problems related to the hot early-type systems. Our LMC distance derived from these systems is demonstrably accurate to 2.2 % (49.97 ± 0.19 (statistical) ± 1.11 (systematic) kpc) providing a firm base for a 3 % determination of the Hubble Constant, with prospects for improvement to 2 % in the future.

The modelling of early-type eclipsing binary systems consisting of hot stars is made difficult by the problem to obtain accurate flux calibrations for early-type stars, and by the degeneracy between the stellar effective temperatures and reddening[8,9]. As a result, the distances determined from such systems are of limited (~5-10%) accuracy. A better distance accuracy can be obtained using binary systems composed of cool stars; such systems among the frequent dwarf stars in the LMC are however too faint for an accurate analysis with present-day telescopes.

The OGLE team has been monitoring some 35 million stars in the field of the LMC for more than 16 years[10]. Based on this unique dataset we have detected a dozen extremely scarce very long period (60 – 772 days) eclipsing binary systems composed of intermediate-mass late-type giants located in a quiet evolutionary phase on the helium burning loop[11] (see Supplementary Table 1). These well detached systems provide an opportunity to use the full potential of eclipsing binaries as precise and accurate distance indicators, and to calibrate the zero point of the cosmic distance scale with an accuracy of about 2 % [5,12,13].

In order to achieve this goal, we observed 8 of these systems (see Figure 1) over the last 8 years, collecting high-resolution spectra with the MIKE echelle spectrograph at the 6.5-m Magellan Clay telescope at the Las Campanas Observatory, and with the HARPS spectrograph attached to the 3.6-m telescope of the European Southern Observatory on La Silla, together with near infrared photometry obtained with the 3.5-m New Technology Telescope located on La Silla.

The spectroscopic and OGLE V- and I-band photometric observations of the binary systems were then analysed using the 2007 version of the standard Wilson-Devinney (WD) code[14,15], in an identical manner as in our recent work on a similar system in the Small Magellanic Cloud[9]. Realistic errors to the derived parameters of our systems were obtained from extensive Monte Carlo simulations (see Figure 2). For all observed eclipsing binaries, their astrophysical parameters were determined with an accuracy of a few percent (see Supplementary Tables 2-9).

For late-type stars we can use the very accurately calibrated (2 %) relation between their surface brightness and V-K color to determine their angular sizes from optical (V) and near-infrared (K) photometry[16]. From this surface brightness-color relation (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 distances measured with this very simple but accurate one-step method are presented in Supplementary Table 12. The statistical errors of the distance determinations were calculated adding quadratically the uncertainties on absolute dimensions, V-K colors, reddening, and the adopted reddening law. The reddening uncertainty contributes very little (0.4 %) to the total error[17,11]. A significant change of the reddening law (from Rv = 3.1 to 2.7) causes an almost negligible contribution at the level of 0.3 %. The accuracy of the V-K color for all components of our eight binary systems is better than 0.014 mag (0.7 %). The resulting statistical errors in the distances are very close to 1.5 %, and are dominated by the uncertainty in the absolute dimensions. Calculating a weighted mean from the individual distances to the eight target eclipsing binary systems, we obtain a mean LMC distance of 49.88 ± 0.13 kpc.

Our distance measurement might be affected by the geometry and depth of the LMC. Fortunately, the geometry of the LMC is simple and well studied [18]. Since nearly all the eclipsing systems are located very close to the center of the LMC and to the line of nodes (see Fig. 3) we fitted the distance to the center of the LMC disk plane assuming its spatial orientation [18]. We obtained an LMC barycenter distance of 49.97 ± 0.19 kpc (see Figure 4), nearly identical to the simple weighted mean value, which shows that the geometrical structure of the LMC has no significant influence on our present distance determination.

The systematic uncertainty in our distance measurement comes from the calibration of the SBCR and the accuracy of the zero points in our photometry. The rms scatter on the current SBCR is 0.03 mag[13], which translates to a 2 % accuracy in the respective angular diameters of the component stars. Since the surface brightness depends only very weakly on metallicity[16,17], this effect contributes to the total error budget at the level of only 0.3 % [9]. Both optical (V) and near-infared (K) photometric zero points are accurate to 0.01 mag (0.5 %). Combining these contributions quadratically we determine a total systematic error of 2.1 % in our present LMC distance determination.

The LMC contains significant numbers of different stellar distance indicators, and being the closest galaxy to our own offers us a unique opportunity to study these indicators with the utmost precision. For this reason this galaxy has an impressive record of several hundred distance measurements which have been carried out over the years[2,3,19]. Unfortunately, virtually all LMC distance determinations are dominated by systematic errors, with each method having its own sources of uncertainties. This prevents a calculation of the true LMC distance by simply taking the mean of the reported distances resulting from different techniques. Our present LMC distance measurement of 49.97 ± 0.19 (statistical) ± 1.11 (systematic) kpc (i.e. a true distance modulus of 18.493 mag ± 0.008(statistical) ± 0.047 (systematic)) agrees well, within the combined errors, with the most recent distance determinations to the LMC[19]. Our purely empirical method allows us to estimate both statistical and systematic errors in a very reliable way, which is normally not the case, particularly in distance determinations relying in part on theoretical predictions of stellar properties and their dependences on environment. In particular, our result provides a significant improvement over previous LMC distance determinations made using observations of eclipsing binaries[7,20]. These studies were based on early-type systems for which no empirical surface brightness-color relation is available, so they had to rely on theoretical models to determine the effective temperature. Our present determination is based on many (8) binary systems and does not resort to model predictions.

The classical approach to derive the Hubble constant consists in deriving an absolute calibration of the Cepheid Period-Luminosity Relation (CPLR) which is then used to determine the distances to nearby galaxies containing Type Ia supernovae (SNIa).[21] SNIa are excellent standard candles reaching out to the region of unperturbed Hubble flow once their peak brightnesses are calibrated this way, and provide the most accurate determination of H_0.[22] A yet alternative approach to calibrate the CPLR with Cepheids in the LMC is to calibrate it in our own Milky Way galaxy using Hubble Space Telescope (HST) parallax measurements of the nearest Cepheids to the Sun[23]. However, the resulting CPLR from that approach is less accurate for two reasons: first, the Cepheid sample with HST parallaxes is very small (ten stars) as compared to the Cepheid sample in the LMC (2000 stars), which can be used to establish the CPLR once the LMC distance is known. Second, the average accuracy of the HST Cepheid parallaxes is 8%[23] and suffers from systematics which are not completely understood, including Lutz-Kelker bias[24,25]. Therefore the currently preferred route to determine the Hubble constant is clearly the one using the very abundant LMC Cepheid population whose mean distance is now known, with the result of this work, to 2.2 %. This result reduces the uncertainty on H_0 to a very firmly established 3 %.

We have good reasons to believe that there is significant room to improve on our current 2.2% distance determination to the LMC by improving the calibration of the SBCR for late-type stars,[12,16] which is the dominant source of systematic error in our present determination. We are currently embarked on such a program, and a distance determination to the LMC accurate to 1% seems within reach once the SBCR calibration is refined, with its corresponding effect on improving the accuracy of H_0 even further. This is similar to the accuracy of the geometrical distance to the LMC which is to be delivered by GAIA in some 12 years from now. The eclipsing binary technique will then likely provide the best opportunity to check on the future GAIA measurements for possible systematic errors.

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Figure 1: Change of the brightness of the binary system OGLE-LMC-ECL-06575 and the orbital motion of its components.

a, Main panel, orbital motion of the two binary components in the OGLE-LMC-ECL-06575 system. Filled and open circles, primary and secondary components, respectively. The top panel shows the residuals of the fit (see below): observed radial velocities (O) minus the computed radial velocities (C).

b, Main Panel, the I-band light curve (1200 epochs collected over 16 years) of the binary system OGLE-LMC-ECL-06575 together with the solution, as obtained with the Wilson-Devinney code. The top panel shows the residuals of the observed magnitudes from the computed orbital light curve.

All individual radial velocities were determined by the cross-correlation method using appropriate template spectra and the MIKE and HARPS spectra, yielding in all cases velocity accuracies better than 200 m/s (error bars smaller than the circles in the figure). The orbit (mass ratio, systemic velocity, velocity amplitudes, eccentricity, and periastron passage), was fitted with a least squares method to the measured velocities. The resulting parameters are presented in Supplementary Tables 2-9. The spectroscopic orbits, light curves and solutions for the remaining systems are of similar quality.

Figure 2: Error estimation of the distance for one of our target binary systems.

The reduced χ^2 map for the OGLE-LMC-ECL-15260 system showing the dependence of the fit goodness to the V-band and I-band light curves on the distance modulus of the primary component. This map was obtained from 110,000 models computed with the Wilson-Devinney code[14,15] within a broad range of the radii R_1 and R_2, the orbital inclination i, the phase shift ϕ, the secondary's temperature T_2 and the secondary's albedo A_2. In each case the distance d was calculated from the V-band surface brightness – color (V–K) relation[16] and translated into distance modulus via formula $(m-M)=5\times\log(d)-5$. The horizontal lines correspond to the standard deviation limits of the derived distance modulus of 18.509 mag (50.33 kpc), accordingly from down to up: 1σ, 2σ and 3σ.

Figure 3: Location of the observed eclipsing systems in the LMC.

Most of our eight systems (marked as filled circles) are located quite close to the geometrical center of the LMC and to the line of nodes (marked with the line), resulting in very small corrections to the individual distances for the geometrical extension of this galaxy (in all cases smaller than the corresponding statistical error on the distance determination). The effect of the geometrical structure of the LMC on the mean LMC distance reported in our Letter is therefore negligible. The background image has a field of view of 8 x 8 degrees and is taken from the ASAS wide field sky survey[26].

Figure 4: Consistency among the distance determinations for the target binary systems

Distance offsets between our particular eclipsing binary systems and the best fitted LMC disk plane, plotted against the angular distance of the systems from the LMC center. The identification of the systems is the same as in Figure 3. The error bars correspond to one sigma errors. We assumed the model of the LMC from van der Marel et al [18]. We fitted one parameter: the distance to the center of the LMC (R.A. = $5^h\ 25^m\ 06^s$, DEC = $-69^o\ 47'\ 00''$) using a fixed spatial orientation of the LMC disk: inclination i = 28 deg and a position angle of the nodes of θ = 128 deg. The resulting distance to the LMC barycenter is 49.97 ± 0.19 kpc, with a reduced χ^2 very close to unity.