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

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In the era of precision cosmology, it is essential to determine the Hubble constant to an accuracy of three per cent or better1,2. At present, its uncertainty is dominated by the uncertainty in the distance to the Large Magellanic Cloud (LMC), which, being our second-closest galaxy, serves as the best anchor point for the cosmic distance scale3–7. Observations of eclipsing binaries offer a unique opportunity to measure stellar parameters and distances precisely and accurately8–11. The eclipsing-binary method was previously applied to the LMC6,7, but the accuracy of the distance results was lessened by the need to model the bright, early-type systems used in those studies. Here we report determinations of the distances to eight long-period, late-type eclipsing systems in the LMC, composed of cool, giant stars. For these systems, we can accurately measure both the linear and the angular sizes of their components and avoid the most important problems related to the hot, early-type systems. The LMC distance that we derive from these systems (49.97 ± 0.19 (statistical) ± 1.11 (systematic) kiloparsecs) is accurate to 2.2 per cent and provides a firm base for a 3-per-cent determination of the Hubble constant, with prospects for improvement to 2 per cent in the future.

The modelling of early-type eclipsing binary systems consisting of hot stars is made difficult by the problem of obtaining accurate flux calibrations for early-type stars and by the degeneracy between the stellar effective temperatures and reddening8–9. As a result, the distances determined from such systems are of limited (∼5–10%) accuracy. More-accurate distances can be obtained using binary systems composed of cool stars; however, among the frequent dwarf stars in the LMC such systems are too faint to be accurately analysed with present-day telescopes.

The Optical Gravitational Lensing Experiment (OGLE) has been monitoring around 35 million stars in the field of the LMC for more than 16 years10. Using this unique data set, we have detected a dozen extremely scarce, very long-period (60–772-d) eclipsing binary systems composed of intermediate-mass, late-type giants located in a quiet evolutionary phase on the helium-burning loop11 (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% (refs 5, 12, 13).

To do so, we observed eight of these systems (Fig. 1 shows one example) over the past 8 yr, collecting high-resolution spectra with the MIKE spectrograph at the 6.5-m Magellan Clay telescope at the Las Campanas Observatory and with the HARP 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 code12,13, in the same way as in our recent work on a similar system in the Small Magellanic Cloud9. Realistic errors in the derived parameters of our systems were obtained from extensive Monte Carlo simulations (Fig. 2). The astrophysical parameters of all the observed eclipsing binaries were determined with an accuracy of a few per cent (Supplementary Tables 2–9).

For late-type stars, we can use the very accurately calibrated (2%) relation between their surface brightness and V−K colour to determine their angular sizes from optical (V) and near-infrared (K) photometry14. From this surface-brightness/colour 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 in the distance determinations were calculated by adding quadratically the uncertainties in absolute dimensions, V−K colours, reddening and the adopted reddening law. The reddening uncertainty contributes very little (0.4%) to the total error15,16. A significant change in the reddening law (from $R_V = 3.1$ to 2.7, where $R_V$ is the ratio of total to selective absorption) causes an almost negligible contribution, at the level of 0.3%. The accuracy of the V−K colour 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. By 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 studied14. Because nearly all the eclipsing systems are located very close to the centre of the LMC and to the line of nodes (Fig. 3), we fitted the distance to the centre of the LMC disk plane, assuming its spatial orientation14. We obtained an LMC barycentre distance of 49.97 ± 0.19 kpc (Fig. 4), which is nearly identical to the simple weighted mean value. This shows that the geometrical structure of the LMC has no significant influence on our present distance determination.

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Figure 1 | Change of the brightness of the binary system OGLE-LMC-ECL-06575 together with the solution obtained using the Wilson–Devinney code. I-band light curve (1,200 epochs collected over 16 yr) of OGLE-LMC-ECL-06575 and the orbital motion of its components. a, The main panel shows the residuals of the fit (see below): observed radial velocities (O) minus the computed radial velocities (C). b, The main panel shows the I-band light curve (1,200 epochs collected over 16 yr) of OGLE-LMC-ECL-06575 together with the solution obtained using the Wilson–Devinney code. P, orbital period. 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 spectra from the Magellan Inamori Kyocera Echelle (MIKE) and High Accuracy Radial Velocity Planet Searcher (HARPS) spectrographs, yielding in all cases velocity accuracies better than 200 m s⁻¹ (error bars smaller than the plotted symbols). The orbit (mass ratio, systemic velocity, velocity amplitudes, eccentricity and periastron passage) was fitted with a least-squares method to the deviation limits of the derived distance modulus, of 18.509 mag (50.33 kpc): 1σ, 2σ and 3σ, from bottom to top.

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 root mean squared scatter in the current SBCR is 0.03 mag (ref. 13), which translates to an accuracy of 2% in the respective angular diameters of the component stars. Because the surface brightness depends only very weakly on metallicity¹⁶,¹⁷, this effect contributes to the total error budget at the level of only 0.3% (ref. 9). Both optical (V) and near-infrared (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 second-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 measurements²,³,¹⁹. Unfortunately, almost 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

Figure 2 | Error estimation of the distance for one of our target binary systems. The reduced χ² map (goodness of fit) for the system OGLE-LMC-ECL-15260 showing the dependence of the goodness of fit 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 code¹⁴,¹⁵ within a broad range of the primary and secondary radii, R₁ and R₂, the orbital inclination, i, the phase shift, φ, the secondary’s temperature, T₂, and albedo, A₂. In each case the distance, d, was calculated from the V-band surface-brightness/colour (V−K) relation¹⁶ and translated into distance modulus using m−M = 5log(d)−5, where m and M are the observed and absolute brightnesses, respectively. The horizontal lines correspond to the standard-deviation limits of the derived distance modulus, of 18.509 mag (50.33 kpc): 1σ, 2σ and 3σ, from bottom to top.

Figure 3 | Location of the observed eclipsing systems in the LMC. Most of our eight systems (circles) are located quite close to the geometrical centre of the LMC and to the line of nodes (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 in the distance determination). The effect of the geometrical structure of the LMC on the mean LMC distance reported here is therefore negligible. The background image has a field of view of 8’×8’ and is taken from the All Sky Automated Survey wide-field sky survey²⁸.
We have good reason to believe that there is significant room to improve on the high-accuracy LMC distance determination reported here, by improving the calibration of the SBCR for late-type stars\textsuperscript{12,16}, which is the dominant source of systematic error in our present determination. This work is in progress, and a determination of the distance to the LMC accurate to 1% should be possible once the SBCR calibration is refined. This will have a corresponding effect on further improving the accuracy of \(H_0\). This is similar to the accuracy of the geometrical distance to the LMC, which is to be delivered by Gaia mission in around 12 years from now. The eclipsing-binary technique will then probably provide the best opportunity to check on the future Gaia measurements for possible systematic errors.

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