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The Araucaria Project Establishes the Most Precise Benchmark for Cosmic Distances

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In the last 20 years, over the course of the Araucaria project, we have studied 20 very special eclipsing binary systems in the Large Magellanic Cloud (LMC). Based on these systems and our newly calibrated surface brightness–colour relation we have measured a distance to the LMC that is accurate to 1%. This is currently the best benchmark for cosmic distances and it will therefore impact several fields of astrophysics. In particular, it has allowed a determination of the Hubble constant with a precision of 1.9%.

Figure 1. The Large and Small Magellanic Clouds in the southern sky.

Introduction

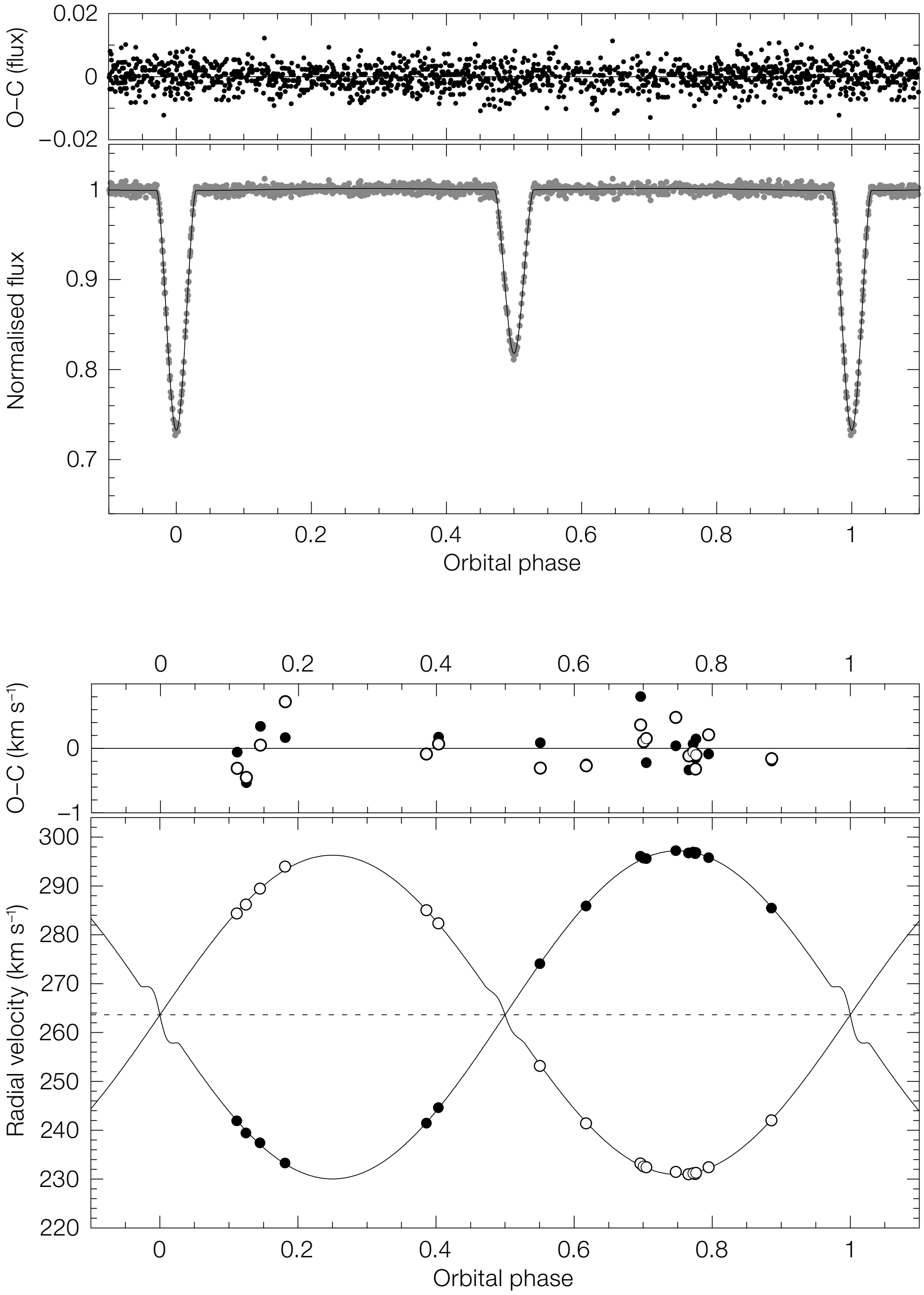
Since the earliest observations in ancient times to present-day astrophysics, the determination of distances to astrophysical objects has been one of the most important, fascinating and challenging goals in astronomy. Knowing distances is about much more than just knowing the scale; it also means knowing the physical nature of the objects in the Universe, and each significant improvement in the accuracy of the distance scale has traditionally opened up new fields of astrophysical research.

Distance determinations to galaxies led to the discovery of the expansion of the Universe, one the most important breakthroughs in astrophysics. Since then the precise and accurate measurement of distances to galaxies provides the basis for determining the famous "Hubble constant" (H_0) which describes the expansion rate of the Universe and has become a central problem in astrophysics.

After the detection of the accelerated expansion of the Universe and the introduction of an enigmatic dark energy component to the matter-energy content of the Universe, the physical explanation of the nature of dark energy has become a major challenge for astronomers and physicists. Recent empirical determinations of H_0 have further complicated our understanding of the Universe. The most precise empirical determination of H_0 to date is 74.03 ± 1.42 km s^{-1} Mpc^{-1} and is based on Cepheids and Type Ia supernovae (Riess et al., 2019). The value obtained differs by about 4σ from the value predicted by the Planck Collaboration et al. (2016), which is based on a ΛCDM model and the Planck CMB data (66.93 ± 0.62 km s^{-1} Mpc^{-1}). This discrepancy between the two values of H_0 is sometimes called a crisis, and may indicate the need for new physics beyond the standard cosmological model. A significant improvement in the accuracy of the measurement of H_0 by the Cepheid-supernova Ia method is therefore of paramount importance for deciding if the current discrepancy between it and the Planck H_0 value does indeed exist. This is critical for cosmology in general, and necessary to drive truly significant progress towards the understanding of the dark energy phenomenon.

After about 100 years of intensive work on the empirical determination of the Hubble constant, it is evident that any significant reduction in its uncertainty can now only be achieved by improving the accuracy of the absolute calibration of the Cepheid method, which constitutes the largest contribution to the total error budget of the H_0 determination (see, for example, Riess et al., 2018).

Figure 2. The light curve and radial velocity curve and corresponding residuals obtained for one of our target eclipsing binaries in the LMC, demonstrating the high quality of the data. Based on observations such as these we obtained stellar physical parameters with a very good precision of 1–2%.



The Large Magellanic Cloud as a perfect astrophysical laboratory

The Large Magellanic Cloud (LMC), which can be seen with the naked eye in the southern sky (Figure 1) is our closest neighbour galaxy and provides the road to calibrating Cepheids and other distance indicators. Indeed, it possesses a large population of Cepheids (Soszynski et al., 2017), has a relatively simple geometry (see, for example, van der Marel et al., 2002), and relatively small extinction (Gorski et al., 2020). Exquisite period–luminosity relations have already been obtained based on the LMC Cepheids in both optical and near-infrared bands (Soszynski et al., 2017; Persson et al., 2004).

The LMC is also the perfect laboratory with which to study many different processes and objects. Therefore, a precise geometrical distance to this galaxy is extremely important, not only for cosmology, but also for many different fields of modern astrophysics. For this reason, more than 600 distance determinations to the LMC can be found in the literature (with the NED database, Mazzarella & the NED team, 2007). However, their relatively low precision and lack of control of systematic errors prevent the use of the LMC distance to significantly improve the determination of H_0.

Eclipsing binaries as precise and accurate distance indicators

Detached eclipsing double-lined spectroscopic binaries offer a unique opportunity to measure directly, and very accurately, stellar parameters like mass, luminosity, and radius, and consequently the distance (Graczyk et al., 2014; see also Kruszewski and Semeniuk, 1999 for a very detailed historical review).

With current observational facilities, and the application of an appropriate surface brightness-colour relation, eclipsing binaries have the potential to yield the most direct (one-step), and the most accurate (~ 1%) distance to the LMC. Indeed, the distances to individual systems can be obtained from the simple equation:

$$d(pc) = 9.2984 \times \frac{R(R_\odot)}{\varphi(mas)}$$

The linear radii of the components of the binary systems R are determined from the standard, well known modelling of radial velocities and photometric light curves, while angular diameters are derived from the surface brightness-colour relation. The surface brightness is defined as $S_V = V_0 + 5\log(\varphi)$, where V_0 is the V-band magnitude corrected for the reddening and φ is the stellar angular

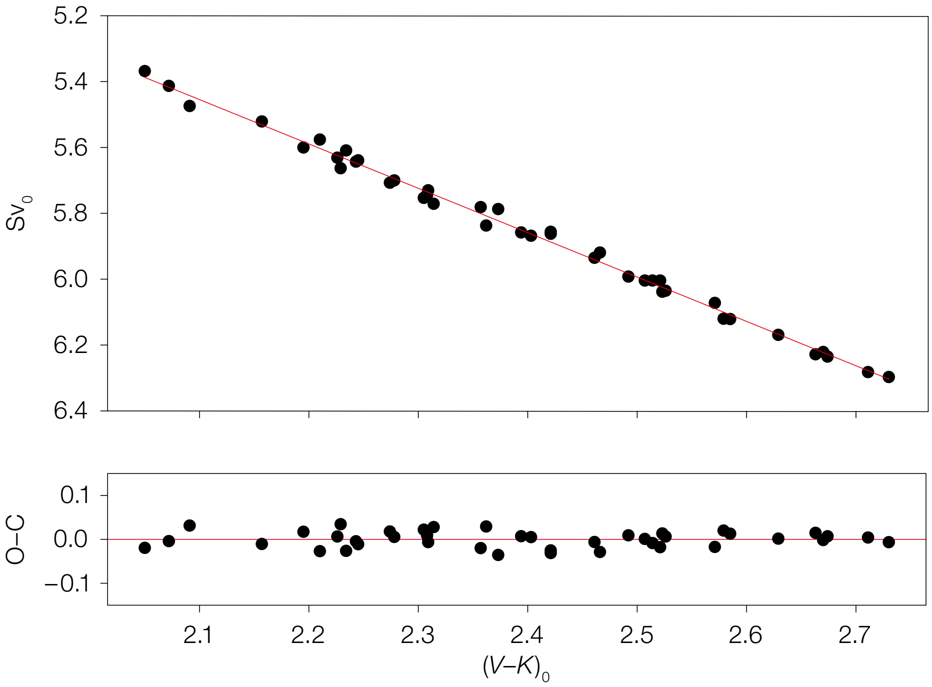


Figure 3. The new surface brightness–colour relationship obtained over the course of the Araucaria project based on interferometric observations with the VLTI and PIONIER and photometric data from the literature. The rms scatter on this relation is 0.018 magnitudes, which corresponds to 0.8% precision in stellar angular diameters.

diameter. An empirical surface brightness-colour relation is very well established for stars with spectral types later than A5, coming from accurate determinations of stellar angular diameters using interferometry (Di Benedetto, 2005; Kervella et al., 2004; Pietrzyński et al., 2019).

The only concern in using this approach was that late-type main sequence binaries located in the LMC are too faint to secure accurate high-resolution spectra even with the biggest telescopes. For a long time, it had not been possible to use the full potential of eclipsing binaries to determine the distance to the LMC because of the lack of suitable systems. This situation changed when microlensing teams, in particular the Optical Gravitational Lensing Experiment (OGLE), provided an enormous amount of precise photometric data for about 35 million stars in the LMC obtained over around 20 years. Based on these data a few dozen extremely rare binaries composed of helium-burning giants were detected (Graczyk et al., 2011). The orbital periods of such systems are very long, typically several hundred days, and the eclipses are very narrow, which explains why they are extremely difficult to discover.

The Araucaria project delivers a 1% geometrical distance to the LMC

About 20 years ago we began a long-term study called the Araucaria project with the aim of improving the calibration of major stellar distance indicators, and, as a result, the determination of the Hubble constant (Gieren et al., 2005; Pietrzyński et al., 2019). The eclipsing binaries were a very important part of this from the very beginning. In particular, we selected a sample of binaries composed of helium-burning giants in the LMC and we have collected high-quality spectroscopic data with the MIKE, HARPS and UVES high-resolution spectrographs, and near-infrared photometry with the SOFI camera at ESO's La Silla Observatory (see Figure 2). We then used these data together with OGLE photometry to determine very precise astrophysical parameters for the systems (1–3% masses, radii, temperatures, etc.).

In 2013, based on our analysis of eight eclipsing binaries and applying the surface brightness-colour relation of Di Benedetto (2005) we managed to measure a 2% distance to the LMC (Pietrzyński et al., 2013). We demonstrated that our result was only weakly affected by a number of factors, including reddening, metallicity, gravity, limb darkening and blending. Indeed, the method is very simple and powerful and provides a unique opportunity to precisely quantify all possible error contributions (Pietrzyński et al., 2013; Graczyk et al., 2014). The total error budget of this measurement is completely dominated by the error in the surface brightness-colour relation of Di Benedetto (2005). The root-mean-square (rms) scatter on this relationship is 0.03 magnitudes, which translates to 2% precision in the determination of the angular diameter. The observed scatter is mainly caused by observational errors on the *K*-band magnitudes. Another very important issue while striving for 1% accuracy of the surface brightness-colour relation calibration is to ensure that the angular diameters are measured uniformly and that all stars are at comparable evolutionary phases as the components of the LMC eclipsing binaries.

In order to provide a significantly improved calibration of the surface brightness-colour relation, we carefully selected a sample of 41 nearby red clump giants, which are in the core helium burning phase of stellar evolution. We made sure that our sample does not contain variable stars or binaries. For our sample stars we collected precise near-infrared photometry at the South African Astronomical Observatory (Laney, Joner & Pietrzyński, 2012), and angular diameters to a precision of 1% using the Precision Integrated Optics Near-infrared Imaging ExpeRiment (PIONIER) instrument on ESO's Very Large Telescope Interferometer (VLTI) (see Gallenne et al., 2018). These data are complemented with high-quality homogenous *V*-band photometry (Mermilliod, Mermilliod & Hauk, 1997). Based on these exquisite data, the following surface brightness-colour relation was obtained:

$$S_V = 1.330(\pm\, 0.017) \times [(V–K)_0 - 2.405] + 5.869(\pm\, 0.003) \text{ magnitudes},$$

with a rms scatter of 0.018 magnitudes. The relation is presented in Figure 3. It

Figure 4. Location of our 20 eclipsing binaries in the LMC. As can be seen here, all of them are located close to the centre of the LMC and to its line of nodes. The final LMC distance derived is only very weakly dependent on the geometry of this galaxy.

allows the measurement of angular diameters with a precision of 0.8%, and therefore distances to eclipsing binaries with a precision close to 1%.

We then applied our new surface brightness-colour relation to measuring distances to 20 eclipsing binaries located in the LMC. The location of the binaries is shown in Figure 4. The individual distances are precise to 1.5–2%. Combining them, the following distance measurement to the centre of the LMC was obtained: 18.477 ± 0.004 (statistical) ± 0.026 (systematic) magnitudes. With 20 precise individual distances we constrained the geometry of the central parts of the LMC and convincingly demonstrated that the geometrical extent of the galaxy has no influence on the distance measurement within the quoted errors.

To demonstrate that the method delivers, not only precise but also accurate distances, one has to compare results from independent methods. Pietrzyński et al. (2019) measured the distance to the nearby eclipsing binary TZ For at 185.1 ± 2.0 (stat) ± 1.9 (sys) pc using exactly the same approach as for the LMC systems. A very precise distance to TZ For of 186.1 ± 1.0 (stat+syst) pc was also obtained based on spectroscopic and astrometric orbits (Gallenne, 2016). These two independent geometrical distance determinations are in an excellent agreement.

With the final Gaia parallaxes expected a few years from now, a comparison between Gaia distances and distances determined for binaries with our surface brightness-colour relation will be performed for many eclipsing binaries at the 1% level. This work will allow us to definitively mutually test and verify the accuracy of our method against Gaia.

A new benchmark for cosmic distances

As can be appreciated from Figure 5, eclipsing binaries offer us an opportunity to determine stellar distances at a similar level of precision to that of Gaia at 1 kpc from the Sun, and to retain that precision out to the outskirts of the Local Group of galaxies. With the advent of the new extremely large telescopes in the near future, this will be extended even to galaxies far beyond the Local Group.

The precise and accurate distances from this one-step geometrical method will continue to be very important for several reasons. They provide the unique possibility of measuring geometrical distances to nearby galaxies, which is very important for a wide variety of studies. As we already mentioned, independent distances to nearby eclipsing binaries will allow a cross-check with Gaia parallaxes at the level of 1%, which is extremely important for evaluating the accuracy of both techniques. Finally, the method provides an independent precise zero point for the extragalactic distance scale and the calibration of the Cepheid period-luminosity relation in different environments, paving the way for a precise determination of the Hubble constant from the combined Cepheid period-luminosity relation — supernova Ia method.

Indeed our 1% LMC distance has already allowed a precise calibration of the LMC Cepheids and, as a result, a determination of H_0 to a precision of 1.9% (Riess et al., 2019). Moreover, it has allowed a precise calibration of another interesting distance indicator, the tip of the red giant branch (Gorski et al., 2018; Freedman et al., 2020). This method was then used to obtain H_0 in an independent way (Freedman et al., 2020).

Summary and future work

Eclipsing binaries composed of late-type stars have become a unique tool for the precise measurement of distances within a volume of about 1 Mpc. We would like to highlight the role of interferometric measurements of stellar diameters in calibrating the surface brightness-colour

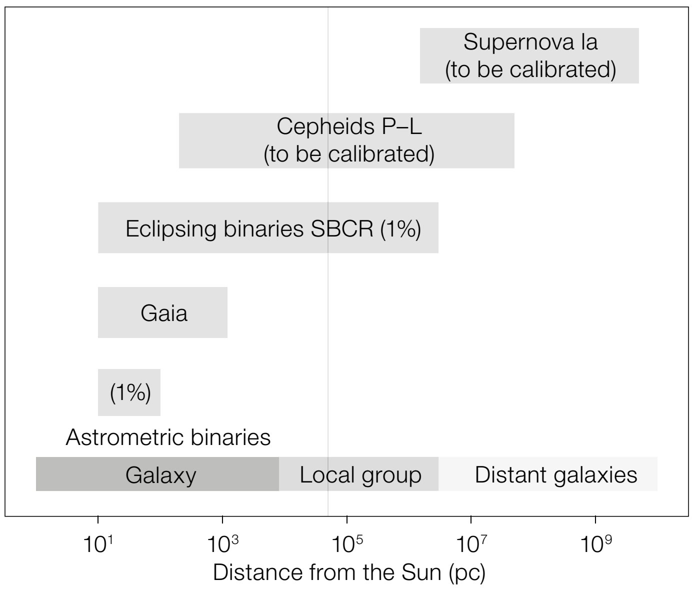


Figure 5. The methods that can be used to calibrate the Cepheid period-luminosity relation and, as a result, the brightness of Type Ia supernovae. Eclipsing binaries, together with our new relation, offer us the opportunity to determine distances competitive in precision to those with Gaia at about 1 kpc from the Sun. Contrary to Gaia parallaxes, however, they retain their high precision for distances up to 1 Mpc.

Figure 6. One of the auxiliary telescopes forming the VLTI; these telescopes were crucial in our project. Photograph taken by Grzegorz Pietrzyński during one of the team's frequent observations of the LMC eclipsing binaries at ESO's Paranal observatory.

relation, which is at the heart of this method. Thanks to this, our method is completely independent and does not require any calibrations or assumptions. It has opened up the opportunity to measure geometric distances to nearby galaxies with an accuracy of about 1%, which is very important for many fields of modern astrophysics. In particular it allows the precise calibration of secondary distance indicators like Cepheids and the tip of the red giant branch and, as a result, to significantly improve the determination of the Hubble constant.

Despite this significant progress in using eclipsing binaries as a precise and accurate distance indicator, a lot of work is still required before we can realise the full potential of eclipsing binaries and apply them to measuring cosmic distances on a larger scale. Our team has been working intensively on improvements to the surface brightness-colour relation. We are working on precision calibration of the surface brightness-colour relation for early-type stars (Taormina et al., 2019, 2020). Eclipsing binary systems composed of such stars are much easier to discover in nearby galaxies than systems composed of the late-type giants that we have studied in the LMC.

We have also been working on a very extensive verification of our method. We have already obtained astrometric orbits with the VLTI and PIONIER for more nearby eclipsing binaries (Gallenne et al., 2019). Moreover we have prepared an extended list of eclipsing binaries which can be analysed with even greater precision, and for which we expect very precise Gaia parallaxes (see, for example, Graczyk et al., 2019). These data will allow us to compare very precise (better than 1%) distances from three independent methods and verify their accuracy.

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