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Accurate determination of binary star masses and distances using optical long-baseline interferometry

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Abstract. One of the most fundamental stellar parameters, mass, is often unavailable or measured with low accuracy, leading to weak constraints on stellar structure and evolution. Observing binary stars through a combination of interferometry and spectroscopy provides a unique opportunity to obtain highly precise dynamical mass measurements. Additionally, double-lined spectroscopic binaries offer independent distance measurements with extreme accuracy, enabling direct tests of Gaia parallaxes. I will demonstrate that by combining interferometric and spectroscopic observations, masses and distances with accuracy levels as high as 0.05% can be achieved for various types of binary systems, including binary Cepheids, eclipsing binaries, and standard binaries.

Key words: binaries: general – Stars: fundamental parameters – Stars: variables: Cepheids – Instrumentation: high angular resolution

1. Introduction

In the Araucaria project (Gieren et al., 2005), various techniques are employed to measure distances, with the goal of understanding the influence of population effects on key standard candles such as Cepheids, RR Lyrae stars, red clump stars, and the stars at the tip of the red-giant branch (Gieren et al., 2005). Binary systems play a crucial role in this effort, as highlighted by our work on eclipsing binaries, which has yielded the most accurate distance measurements for both the Large and Small Magellanic Clouds (Graczyk et al., 2020; Pietrzyński et al., 2019).

Binary stars are the only tool that enables direct and precise measurements of stellar mass and distance. In the case of double-lined spectroscopic binaries, their geometric distance can be determined, offering an independent benchmark for other methods, such as next Gaia data release (Gaia Collaboration et al., 2016). The mass is a fundamental parameter for understanding stellar structure and evolution, and accurate measurements are essential to assess consistency with theoretical models and tighten constraints. However, stellar parameters like the effective temperature (T_{eff}) and radius (R), predicted by different stellar evolution codes, can currently show discrepancies when compared to empirical values, leading to a broad range of possible ages for a given system. Comparing different evolutionary codes for a given age reveals discrepancies for both high- and low-mass stars, primarily due to the poorly constrained physics of stellar interiors (Huber, 2016). Stellar interior models vary in several aspects, initial chemical compositions, the treatment of convective core overshooting, rotational mixing, and the mixing length parameter (Marigo et al., 2017; Bressan et al., 2012; Dotter et al., 2008; Pietrinferni et al., 2004). High-precision measurements allow for tighter constraints on the evolutionary models, leading to a deeper understanding of stellar interior physics (e.g. Higl et al., 2018; Claret & Torres, 2018).

Over the years, the precision of stellar parameters ($T_{\rm eff}, R$, and M) has steadily improved through studies of eclipsing binary systems and large ground- and space-based photometric surveys (e.g., the Optical Gravitational Lensing Experiment, the Wide Angle Search for Planets, Kepler, the Large Synoptic Survey Telescope, and the Transiting Exoplanet Survey Satellite). By combining radial velocity (RV) data with photometric observations during eclipses, a precision level of approximately 1-3% is routinely achieved (e.g. Pribulla et al., 2018; Pilecki et al., 2018; Graczyk et al., 2015). However, recent studies indicate that a precision much better than 1% in stellar mass is required to reliably determine stellar interior model parameters (e.g., overshooting, initial helium abundance, etc. Higl et al., 2018; Valle et al., 2017).

Another model-independent method for measuring stellar masses and geometric distances with binary systems at sub-1% accuracy involves combining spectroscopic and astrometric observations (see e.g. Gallenne et al., 2016; Torres et al., 2009; Zwahlen et al., 2004). This technique requires no assumptions. Recently, it was applied to a Galactic binary Cepheid, yielding the most accurate distance and mass measurements for a Milky Way Cepheid (Gallenne et al., 2018a). However, astrometric measurements require the system to be spatially resolved, which can be challenging with single-dish telescopes. Optical long-baseline interferometry (LBI) offers a much better angular resolution, allowing for the detection of close binary systems (< 20 mas). LBI has proven its efficiency in providing both angular resolution and accuracy for such close binary stars (see, e.g. Pribulla et al., 2018; Gallenne et al., 2014, 2013; Le Bouquin et al., 2013).

I present my latest results using cutting-edge interferometric instruments combined with high-precision RV measurements. I will discuss three types of binary systems: eclipsing binaries (EBs), binary Cepheids, and standard binary stars. All of our systems are well-detached, which simplifies the analysis.

2. Eclipsing Binaries

In our quest for precise and accurate distance measurements for the Araucaria Project (Gieren et al., 2005), EBs serve as a very powerful tool. By combining contemporaneous radial velocities and photometric measurements, we can determine very precise linear radii. When these are paired with angular radii obtained from a well-calibrated surface brightness-colour relation (SBCR), the result is precise distance measurements. In 2019, we used EBs and a newly calibrated SBCR to determine the distance to the LMC with 1% accuracy (Pietrzyński et al., 2019; Gallenne et al., 2018b) and to the SMC with 2% (Graczyk et al., 2020).

Our newly calibrated SBCR (Pietrzyński et al., 2019) was specifically tailored to our LMC EBs with a colour range $2 < V - K < 2.8$. I am currently working on extending this range to include EBs of different spectral types. This extended SBCR will undergo rigorous validation through independent observing methods. The only alternative approach for precisely and accurately measuring EB distances involves combining RV data with astrometry. However, the small angular separations between EB components make astrometric measurements with single-dish telescopes impossible. Interferometry remains the only technique capable of spatially resolving their orbital motion.

I used LBI to observe nearby eclipsing systems and determine their astrometric orbits. By combining these observations with high-precision RV, as shown in Fig. 1, I achieved very accurate distance measurements. The first system I observed, TZ For, was studied with the VLTI/PIONIER instrument in 2015, yielding a distance measurement with 0.4% precision (Gallenne et al., 2016, 2018b). Five additional systems were subsequently observed (Gallenne et al., 2019) delivering the same level of precision. This level of accuracy is directly competitive with Gaia and will serve as a benchmark for parallax validation and for testing the accuracy of the extended SBCR.

During this work, I achieved stellar mass measurements with an as good as 0.04%. Such precise mass determinations are remarkable and can be used to test and calibrate stellar evolution models. As mentioned earlier, different evolutionary codes yield discrepant mass predictions for high- and low-mass stars, while they generally agree for solar-type stars, which is expected since the Sun is used to calibrate these models.

Achieving greater precision and accuracy in distance measurements was not possible due to the primary source of error being the systematic uncertainty from PIONIER's wavelength calibration (0.35%). To overcome this limitation, I transitioned the project to the VLTI/GRAVITY instrument and expanded the sample to include standard binary stars of various spectral types. Thanks to a dedicated internal reference laser source, this instrument is expected to achieve a wavelength calibration accuracy of approximately 0.02% in high-resolution spectral mode.

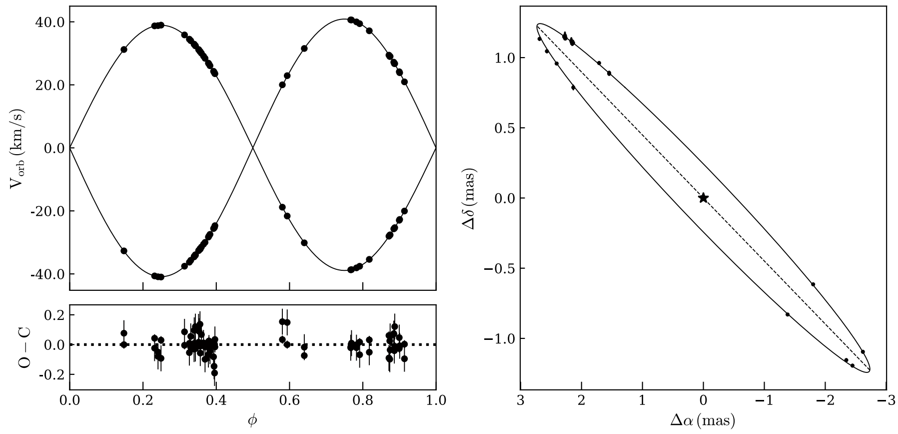

Figure 1. Left: radial velocities of the primary and the secondary star in the TZ For system. Right: astrometric orbit of the secondary component relative to the primary.

3. Standard Binary stars

Given the remarkable initial results on eclipsing binaries, it became evident to me that the sample of stars should be expanded to include non-eclipsing systems. Obtaining extremely precise masses for stars of various spectral types is essential for calibrating models at various evolutionary stages, as mentioned earlier. Moreover, there are no reference stars with the required distance precision and accuracy to validate Gaia parallaxes.

I observed 35 binary systems with GRAVITY and also acquired new high signal-to-noise ratio spectra with the VLTI/UVES spectrograph. In Gallenne et al. (2023), we published the results for 10 of these systems, achieving a precision of as good as 0.03% for both masses and distances, thanks to high-precision RVs($\sim$ 200 m s^{-1}) and astrometry ($\sim$ 20μas). Fig. 2 illustrates the high-precision orbit derived from my dataset.

This work yielded two key findings. First, we confronted our precise mass measurements, along with other observables (e.g., $T_{\rm eff}$, radii, ...), with four stellar evolution models. Theoretical predictions fail in matching observations of two components with a single isochrone, suggesting that further refinement of stellar models is necessary, especially when dealing with non-solar-type stars, as the models are often tailored to match solar characteristics. Second, we also compared our orbital parallaxes with Gaia and showed that for half of the stars, Gaia measurements deviate by more than 1σ, despite their RUWE value being below the commonly accepted cutoff of 1.4 for reliable Gaia astrometry. Further analysis suggests a correlation between this discrepancy and the brightness of the systems, the brighter the star, the larger the deviation. Since these stars have $G < 10$, the discrepancy could be related to saturation effects.

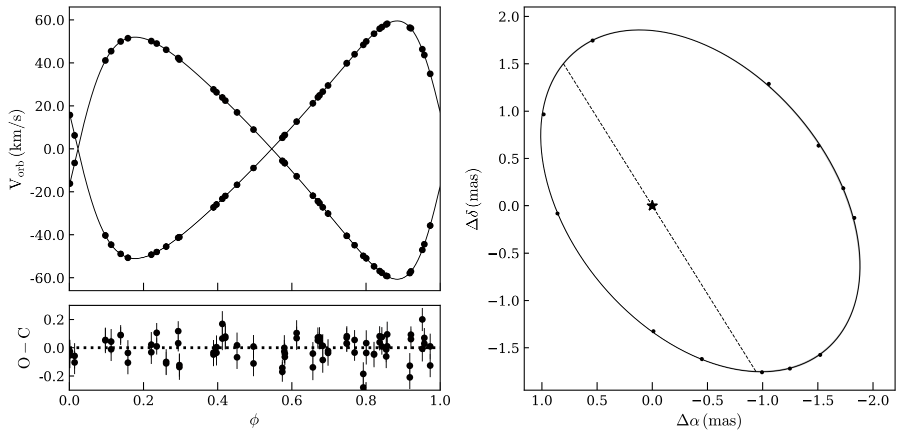

Figure 2. Left: radial velocities of the primary and the secondary components of the HD224974 system. Right: GRAVITY astrometric orbit of the secondary relative to the primary.

4. Binary Cepheids

LBI is also a powerful technique for studying binary Cepheids. In the context of the extragalactic distance scale, Cepheids are essential primary distance indicators due to their period-luminosity relation (PLR). However, calibrating this PLR can be challenging since it requires direct distance measurements. Prior to Gaia, the calibration was partially based on 19 Galactic Cepheids with trigonometric parallax measurements (Benedict et al., 2007; Kervella et al., 2014; Riess et al., 2018). However, their average accuracy was limited to 9%, making it difficult to achieve the 1% precision required for a reliable luminosity calibration. With Gaia, the geometric calibration of 75 Cepheid luminosities seems to be precise to 1% (Riess et al., 2021). However, the accuracy still needs to be assessed. Gaia is still affected by a variable parallax offset (Lindegren et al., 2021) that depends on ecliptic latitude, chromatic effects due to colour variations during pulsation, and the influence of binarity. As a result, precise and accurate independent distance measurements are essential to verify Gaia's accuracy. Observing binary Cepheids is the only method able to deliver precise and accurate independent distance measurements.

Most known companions are too close to the Cepheid (< 40 mas) to be observed with an 8-meter class telescope. While orbits for several Cepheids have been determined through RV measurements, LBI is the only method capable of spatially resolving these systems. In 2012, I initiated an interferometric observing campaign targeting the brightest northern and southern binary Cepheids. The aim of this project is to monitor the astrometric orbits of their companions and to measure dynamical masses and distances.

All binary Cepheids are single-line spectroscopic binaries because the brightness of the Cepheid outshines the companion at optical wavelengths, leading to a degeneracy between distance and mass measurements. Since most companions are main-sequence B stars, ultraviolet (UV) wavelengths offer the best chance to detect the companion's spectral lines, which will help resolve the mass-distance degeneracy. We therefore secured HST/STIS UV observations of some binary Cepheid systems and measured RVs of their orbiting companions, despite the challenges of broad and blended spectral lines. In Gallenne et al. (2018a), we combined astrometric data from the CHARA/MIRC combiner with both space- and ground-based RV measurements to achieve the most precise distance (1%) for the Cepheid V1334 Cyg, in addition to the most precise mass (3%) for a Galactic Cepheid. Fig. 3 illustrates the highly precise orbit derived.

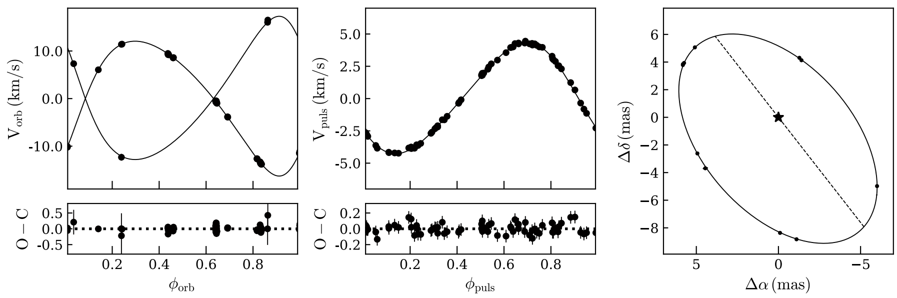

Figure 3. Left: Orbital velocity of the primary and the secondary components. Middle: Pulsation velocity of the primary (Cepheid). Right: MIRC astrometric orbit of the secondary relative to the primary.

Comparisons between our measured Cepheid mass and predictions from evolutionary models indicate that the models tend to overestimate the mass for the observed luminosity, even when factors like rotation and convective core overshooting are considered. This trend was also observed in another Cepheid system, Polaris, as reported by Evans et al. (2018).

We also compared our precise distance measurement with predictions from period-luminosity relations (PLRs). We found a discrepancy of 0.2-0.5 magnitudes when using PLRs calibrated with photometry, whereas those calibrated with direct distance measurements showed better agreement.

Recently, we conducted a similar analysis for another Cepheid, SU Cyg, for which RVs of the companion were also measured using HST/STIS spectra (Gallenne et al., 2025). We achieved even greater precision in our distance measurement, reaching a level of 0.5%, and obtained a 1% precision for the Cepheid's mass. A similar pattern to V1334 Cyg is observed, with discrepancies between our distance measurements and photometrically calibrated PLRs, as well as overestimated Cepheid mass predicted by evolutionary models.

5. Conclusions

Radial velocity measurements and interferometry offer a powerful approach to determine high-precision masses and distances of binary stars. This method is particularly efficient for close binary systems, where high angular resolution from interferometry is critical, enabling measurements of the mass with a precision as good as 0.03% and distance measurements accurate to sub-percent levels, offering crucial benchmarks for stellar models and calibration of other distance measurement techniques.

Obtaining such precise mass measurements offers a crucial test for stellar evolution models, which often fail to accurately reproduce key observables like temperature, radius, and luminosity simultaneously. Discrepancies emerge especially for non-solar-type stars, highlighting the need to refine assumptions about stellar interior, like convective core overshooting, rotation, or initial helium content. Consequently, high-precision mass data from binary systems is vital for enhancing the accuracy of these models.

There was previously no other method to verify the accuracy of Gaia parallaxes. Through this work, we achieved distance measurements with precision comparable to, or even exceeding, that of Gaia, offering a critical benchmark to identify potential biases in Gaia's data. We showed that for half of our sample, Gaia DR3 measurements deviate beyond 1σ, even though their RUWE values are below the widely accepted threshold of 1.4 for reliable Gaia astrometry. Additional analysis seems to indicate a correlation between this discrepancy and the brightness of the stars; specifically, brighter stars exhibit larger deviations. Given that these stars have $G < 10$, this discrepancy may be attributed to saturation effects, as well as the orbital motion that has not yet been considered.

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