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Sub-percent binary star masses and distances from interferometric observations

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Abstract. Our knowledge of stellar evolution relies on constraints provided by measurements of the physical stellar properties such as the mass, effective temperature, and radii. The most fundamental parameter, the stellar mass, is rarely available or has a low accuracy, providing poor constraints on the stellar structure and evolution. Observing binary stars combining astrometry and spectroscopy offers the unique opportunity to measure very precise masses. In addition, double-lined spectroscopic binaries provide independent distance measurements with an extreme accuracy, allowing to test the *Gaia* parallaxes and the period-luminosity (P-L) relations. I will show that masses and distances with an accuracy level as high as 0.05% can be obtained by combining interferometric and spectroscopic observations for different types of binary systems, i.e. binary Cepheids, eclipsing and non-eclipsing binaries.

Keywords. Techniques: High angular resolution, Interferometric, Binaries (including multiple): Close, Stars: Fundamental parameters

1. Introduction

Detached binary systems are the only tool enabling direct and precise distance and mass measurements. When the spectral lines of both components can be detected, the orbital motion of the two stars can be measured via radial velocity (RV) measurements, which provides the spectroscopic orbit of the system. However, this only provides the mass ratio. With the apparent orbit from astrometry, we can measure the orbital inclination and obtain the individual masses of the system. Icing on the cake, spectroscopy provides the projected linear semi-major axis while astrometry gives its angular size, which directly provides the orbital parallax of the system. This is the only geometric and model-independent way of measuring masses and distances of stars (see, e.g., McAlister 1976; Torres et al. 2004; Pourbaix et al. 2004; Docobo and Andrade 2013; Torres et al. 2015; Gallenne et al. 2016).

Eclipsing binary (EB) systems are the main source of precise stellar parameters, combining RVs with photometric measurements during the eclipses (see, e.g., Andersen et al. 1984; Milone et al. 1992; Pietrzyński et al. 2009, 2013; Kirkby-Kent et al. 2016; Pietrzyński et al. 2019; Graczyk et al. 2020). Although a precision level of $1-3\,\%$ is routinely achieved, it is still subject to some modelling of the light curves, such as for limb darkening, oblateness, or stellar spots. To determine the distance, a surface brightness-colour relation is usually used to estimate the angular diameter of the stars, which is then combined with the linear value measured from the eclipses. EBs are a powerful tool and already provide precise masses and distances; however, this still depends on some modelling that needs to be well calibrated.

The combination of astrometry with RV is the optimum way to measure the basic stellar properties using a minimum of theoretical assumptions. An astrometric orbit can be measured using different observing techniques, from direct imaging to long-baseline interferometry (LBI). In this talk, I focused on the LBI of binary stars, which probes a different spatial scale, well below the diffraction limit of a single-dish telescope, and sensitive to orbital periods more suitable for monitoring observations (i.e., a few years at most, in contrast to direct imaging, which is sensitive to wide binaries, and therefore to systems with very long orbital periods). This technique has now proven its efficiency in terms of angular resolution and accuracy for close-in binary stars (see, e.g., Baron et al. 2012; Le Bouquin et al. 2013; Gallenne et al. 2013b, 2014b, 2015b; Pribulla et al. 2018; Gardner et al. 2018; Lester et al. 2020; Gardner et al. 2021), and it can now reach an astrometric precision of a few μas.

With the improvement of observing and analysis techniques, finer processes and stellar structures are being revealed (for instance, the limb-darkening effect has to be taken into account in the analysis of the photometric light curves of eclipsing binaries). Such observations provide a very precise determination of the stellar parameters, at $<1\%$ level. Their comparison with predicted values from stellar evolution models start to show some discrepancies between models, which in turn provides a large range of possible ages when fitting isochrones. Models differ in various ways, as for instance in the input physics, the initial chemical compositions, the treatment of convective-core overshooting, the rotational mixing or the mixing length parameter (Marigo et al. 2017; Bressan et al. 2012). With high-precision mass measurements, evolutionary models can be tightly constrained and provide a better understanding of the stellar interior physics. We are now able to check, for instance, if the input physics is incomplete, the validity of the mixing length approximation in the convective atmosphere, or the efficiency of the convective core overshooting (Higl et al. 2018; Claret and Torres 2018).

When the primary star is a Cepheid, it makes the system even more interesting because Cepheids play a particularly important role as extragalactic distance indicators thanks to the empirical relation between their pulsation period and their luminosity. Binary Cepheids offer the opportunity to measure accurate distances and masses through the combination of astrometric and spectroscopic RV measurements. They will also help to make progress in resolving the Cepheid mass problem. For many years, stellar evolutionary models have predicted Cepheid masses larger than those derived from pulsation models (Bono et al. 1999, 2006; Keller 2008; Neilson et al. 2011).

2. Binary Cepheids

Measuring the mass and the distance of a Cepheid is a challenging task because of the small angular size of the orbits, which hampers astrometric measurements using single-dish telescopes, and the high contrast between the Cepheid and its companion, which complicates the detection of the companion's spectral lines and the measurement of its RV. A number of companions of Galactic Cepheids have been detected from RV measurements and the variability of the systemic velocity of the Cepheids (see, e.g., Szabados 1989, 1991). An ultraviolet spectroscopic survey was also carried out with the International Ultraviolet Explorer (IUE), where companions were detected from low- and high-resolution spectra (Böhm-Vitense and Proffitt 1985; Evans 1992), providing us with a range of spectral types. From an evolutionary timescale point of view, most of the companions should be stars close to the main sequence, and because of the Cepheid's brightness, only bright (and hence massive) companions can be detected by photometric or spectroscopic surveys. Fainter (and hence less massive) companions have a small effect on the Cepheid's astrometry, and might be detected from high-precision radial velocity measurements. However, because of non-symmetric lines from the Cepheid's atmosphere,

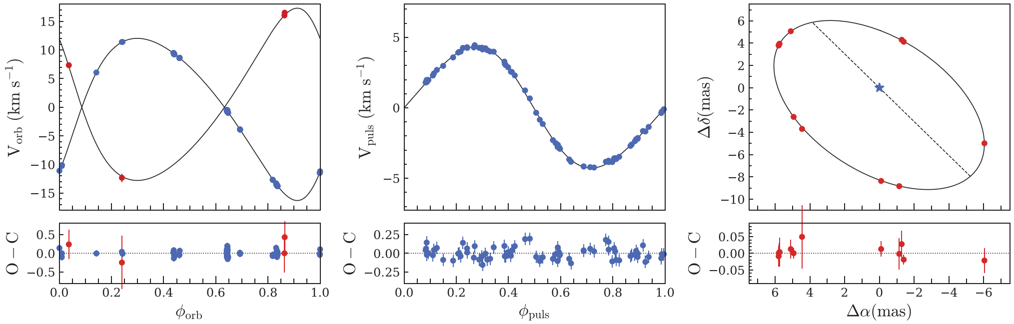

Figure 1. Left: fitted (solid lines) and extracted primary (blue dots) and secondary (red dots) orbital velocities. Middle: fitted (solid line) and extracted (blue dots) pulsation velocity. Right: modelled (black line) and measured (red points) relative astrometric orbit of V1334 Cyg Ab (Gallenne et al. 2018a).

a precision of the order of 1 m s^{-1} is not possible. So far, all binary Cepheids are single-line spectroscopic binaries (SB1) for which masses and distances are degenerate parameters.

LBI has an important impact by spatially resolving the orbiting companion and measuring its astrometric position relative to the Cepheid. First detections were reported by Gallenne et al. (2013a, 2014b,a) who combined for the first time astrometric measurements with the RVs of the Cepheids. However, only lower limits on the Cepheid mass and distance can be determined this way. In 2018, we reported the most precise mass for the Galactic Cepheid V1334 Cyg and the most precise distance to a Cepheid (Gallenne et al. 2018a) by combining astrometry, ground-based RVs for the Cepheid and new space-based RVs for the companion (Proffitt et al. 2017). We measured the mass and distance of the Cepheid at the 3 % and 1 % accuracy level, respectively. The orbital fit is shown in Figure 1.

With such precise measurements, we can do two things. First, we can compare the measured mass of the Cepheid with the predicted value from evolutionary models. Evans et al. (2018) showed that the mass is significantly lower than the prediction by fitting to evolutionary tracks in the Hertzsprung-Russell diagram, regardless of the code or rotation. Second, our measured distance can be compared to period-luminosity relations and the *Gaia* parallax (Ripepi et al. 2023). As we can see in Figure 2, only the newest relations agree with the measured value, even after correcting for the flux contamination from the companion. The latest *Gaia* measurements (Gaia Collaboration 2023) are more than 1σ away, but it is likely due to known problems with bright and pulsating stars (Gaia Collaboration 2023), which should be corrected in the next data releases.

Finally, *Gaia* will provide a unique opportunity to study binary Cepheids for which we have an astrometric orbit but no measured velocities for the companions. Assuming the distance, we will be able to measure the mass of SB1 binary systems. An example of such a system is presented in Figure 3, showing the astrometric observations of AW Per obtained during several years and combined with RVs of the Cepheid taken from the literature.

3. Binary stars: general case

Binary Cepheids are challenging systems, but in general, a lot more binary stars with a more favourable contrast enable easier spectroscopic and interferometric observations. Accurate mass determinations in binary systems in different evolutionary stages serve as benchmarks for calibrating theoretical stellar models and improving our understanding of the physical processes occurring within stars. In addition, they can be used as benchmark

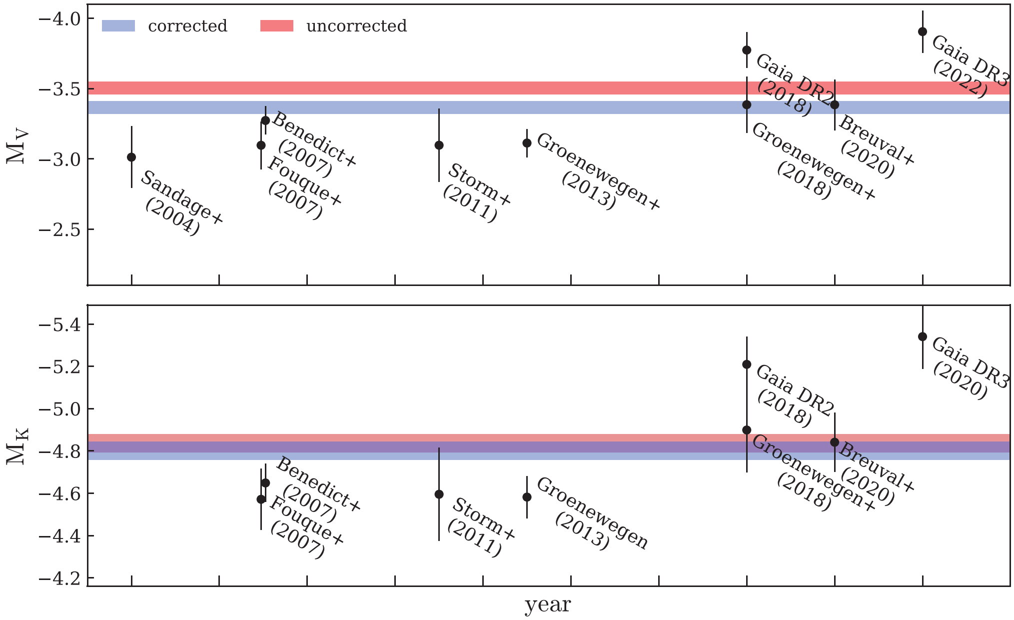

Figure 2. Comparison between the absolute magnitudes of V1334 Cyg predicted from literature P-L relations (black dots) and the present distance measurement (red and blue areas) in the *V* and *K* photometric bands (upper and bottom panels, respectively). The blue and red areas represent the measured absolute magnitude with and without the subtraction of the companion's flux contamination, respectively. In the K band, these two regions overlap as the contribution of the companion is smaller (updated from Gallenne et al. 2018a).

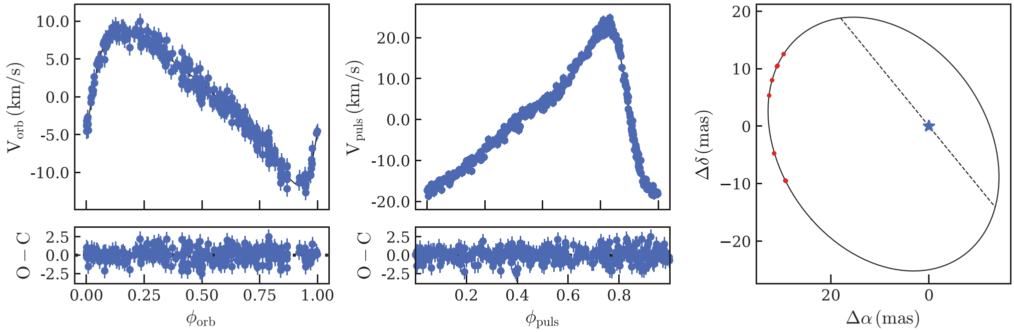

Figure 3. Same as Figure 1 but for the Cepheid AW Per. RVs are taken from Griffin et al. (2016) and the CHARA/MIRC interferometric astrometry from Gallenne et al. (2015b, updated).

systems to check or validate the *Gaia* parallaxes. Previous works show that combining spectroscopy and interferometry provides very precise and accurate measurements (see, e.g., Hummel et al. 2001; Konacki et al. 2010). However, to constrain stellar interior parameters and double-check *Gaia*, it requires an observational precision at a sub-percent level, which is rarely achieved (e.g., *Gaia* provides parallaxes at the μas level).

Using the PIONIER instrument (Precision Integrated-Optics Near-infrared Imaging ExpeRiment, Le Bouquin et al. 2011) at the Very Large Telescope Interferometer (Haguenauer et al. 2010), we collected interferometric measurements of the eclipsing binary system TZ For with an average astrometric precision of 50μas. Combining the astrometry with new precise radial velocities, we were able to measure the mass of each

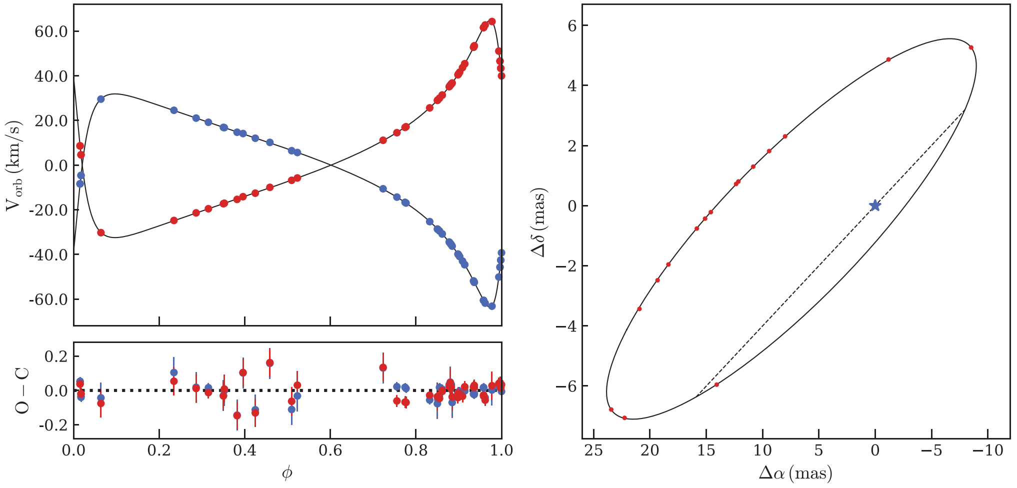

Figure 4. Combined fit of HD188088. Upper left: radial velocities of the primary (blue) and the secondary (red) star. Lower left: Residuals of the velocities. Right: modelled (black) and measured (red) GRAVITY astrometric orbit. The shaded grey area represents the 1σ orbit (Gallenne et al. 2023).

component with a precision and an accuracy of 0.05 % and the distance to the system at 0.4 % precision and accuracy levels (Gallenne et al. 2016). These are the most precise and accurate masses available in the literature. We then observed additional eclipsing systems for which we obtained the same level of precision and accuracy (Gallenne et al. 2019). However, due to the internal calibration of the instrument wavelength scale, we had a limited accuracy on any dimensional measurements of ∼ 0.4 % (Gallenne et al. 2018b).

The purpose of observing eclipsing binaries with PIONIER was to check the calibration of the surface brightness-colour relation (Pietrzyński et al. 2019; Gallenne et al. 2018b), but it also resulted in very accurate mass and distance determinations. In light of these unprecedented results, I decided to start a new project for any type of "simple" detached binary stars with the interferometric instrument GRAVITY (Eisenhauer et al. 2011). This instrument provides a much better accuracy of the wavelength calibration thanks to a dedicated internal reference laser source. The goal is to have a large sample of benchmark stars with high-accuracy mass and distance measurements to test stellar evolutionary models and the *Gaia* parallaxes. First results were published in Gallenne et al. (2023), where we demonstrated that extremely precise and accurate (i.e., at the 0.03 % level) dynamical masses and orbital parallaxes can be determined. We display an example of one fitted orbit in Figure 4, for which we obtained an astrometric residual scatter of ∼ 20 μas. For this project, we combined our new interferometric measurements with new spectroscopic observations from VLT/UVES (UV Echelle Spectrograph, Dekker et al. 2000) in order to achieve the best possible accuracy.

We confronted our measurements with four stellar evolution models and we showed that with this level of precision on individual masses theory is clearly deficient for most of the systems when simultaneously fitting stellar parameters (T_{eff}, R, L, and M). This stresses the importance of precise stellar measurements for stellar evolution modelling and its calibration. Unfortunately, with precomputed isochrones (and predefined evolution parameters) and without more precise and accurate measurements of the metallicity and temperature, it is impossible to conclude which specific evolution model is more appropriate.

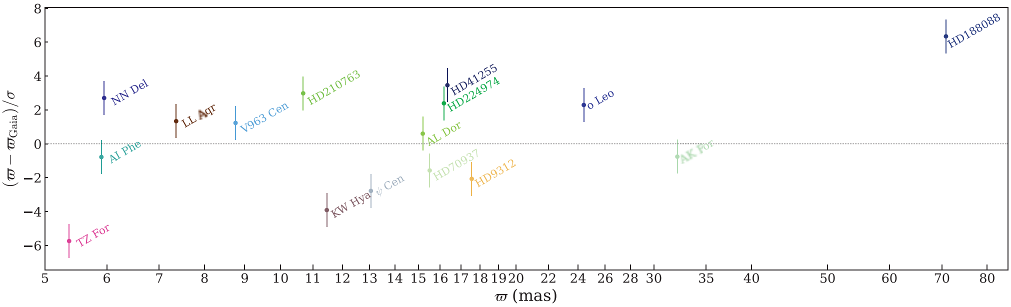

Figure 5. Comparison of our orbital parallaxes with the *Gaia* data release 3 measurements (Gallenne et al. 2023).

The very precise orbital parallaxes also provide a stringent test of *Gaia* measurements. As displayed in Figure 5, we found that 50 % (8/16 stars, including our previous works) of our sample is $> 1\sigma$ away from the *Gaia* parallax, and within the "nominal" Renormalised Unit Weight Error (RUWE) range $1 - 1.4$ (the RUWE is an astrometric quality indicator†). This can be problematic for stars with unresolved companions, which would bias the parallax. We did not see any correlation between the RUWE metric and the relative parallax difference (i.e., the relative difference between *Gaia* and our measured parallaxes), but we did confirm a correlation with the semi-major axis of the photocenter. Finally, all systems are within the bright-star magnitude range of *Gaia*, and therefore may be subject to additional systematic errors (see, e.g., Cantat-Gaudin and Brandt 2021; Lunz et al. 2022).

4. Concusions

I presented a new generation of interferometric and spectroscopic observations of binary stars, including Cepheids. I simultaneously fit the interferometric astrometry and RVs to measure stellar masses and distances with a high precision and accuracy.

In the case of binary Cepheids, I am able to measure the astrometric orbit of the close companions with a very good accuracy. When combined with Space Telescope Imaging Spectrograph (STIS) spectra on board the *Hubble Space Telescope* (HST), the mass of the Cepheid and its distance can be determined with an accuracy level better than 3 %, as demonstrated for the Cepheid V1334 Cyg. The comparison of the measured mass with prediction from evolutionary models shows that the dynamical mass is smaller than expected. The causes are still unknown, but the discrepancy may be related to a mass-loss process, the system being the product of a binary merger, or issues with evolution models. Direct and independent distance measurements of Cepheids are important and provide a stringent test of existing P-L relations and *Gaia* parallaxes. We showed that most of the relations are in marginal agreement with our value but the latest ones seem to provide a good estimate. The *Gaia* parallax is also $\sim 2 - 3\sigma$ away from our measured value, but there are known issues with bright and pulsating stars, so this is somewhat expected. Hopefully this will be solved in the next data release.

Observations of low-contrast binary systems offer a unique opportunity of measuring masses and distances with a very high precision and accuracy. New spectroscopic and interferometric instruments can now provide very precise measurements, with RVs of the order of a few m/s and interferometric astrometry as precise as a few μas. Our recent

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† `https://gea.esac.esa.int/archive/documentation/GDR2/Gaia_archive/chap_datamodel/sec_dm_main_tables/ssec_dm_ruwe.html`

works showed that uncertainties as small as 0.03 % on the distances and masses are possible. A comparison with previous studies and different datasets demonstrated that our measurements are both precise and accurate. This is possible thanks to the precision and sensitivity of the GRAVITY instrument, which provides exquisite differential astrometry ($10-20\,\mu$as). The comparison of our orbital parallaxes with *Gaia* showed differences at a $1-4\sigma$ level. A possible explanation is that all stars are in the bright-star magnitude range of the detector, and therefore possibly affected by additional systematics. Our measured masses were also used to test four isochrone models. We showed that theory is still deficient for most of the systems in fitting all observables, especially with such precision level on the masses. To reconcile the models, it is likely that a fine-tuning of the models of each star in a system is necessary, as was done by Graczyk et al. (2016). With such precise masses, stellar interior parameters such as the mixing length and envelope overshooting can now be better constrained and lead to an improved calibration of stellar evolution models.

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