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HIGH-CONTRAST COMPANIONS AROUND GALACTIC CEPHEIDS

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RESUMEN

La masa de las Cefeidas es un parámetro fundamental para estudiar la pulsación y la evolución de las estrellas de masa intermedia. Sin embargo, la determinación de las mismas sigue siendo un problema desde hace décadas. La mayoría de las masas son derivadas usando modelos de evolución estelar o de pulsación, pero estas difieren entre sí en un 10-20 %. Las Cefeidas binarias dan la oportunidad de progresar en la resolución de esta discrepancia de masa, pero hasta ahora, solo algunas Cefeidas tienen una medida dinámica de su masa. El primer problema en el estudio de las Cefeidas binarias es que la estrella pulsante brilla más que su compañera de secuencia principal en las longitudes de onda más largas que 0.5 μm. Además, debido a la órbita cercana de la compañera (< 40 mas), el sistema no puede ser resuelto espacialmente con un telescopio de clase 10 m. Nosotros usamos interferometría de larga base como una potente herramienta para lograr un alto rango dinámico (~ 1 % in H) y una alta resolución espacial. La posición astrométrica de las compañeras puede ser medida en varias épocas de la órbita, y después combinada con observaciones espectroscópicas, para medir todos los elementos orbitales, masa, y distancia de las Cefeidas.

ABSTRACT

Cepheid masses are a fundamental parameter for studying the pulsation and evolution of intermediate-mass stars, however the determination of their values is a long-standing problem since decades. Most of Cepheid masses are derived using stellar evolution or pulsation models, but they differ by 10-20 %. Binary Cepheids offer the unique opportunity to make progress in resolving this mass discrepancy, but so far, only a few Cepheids have a dynamical measurement of their mass. The first problem in studying binary Cepheids is that the pulsating star outshines its hot main-sequence companion at wavelengths longer than 0.5 μm. In addition, because of the close orbit of the companions (< 40 mas), the system cannot be spatially resolved with a single-dish 10 m-class telescope. We are using long-baseline interferometry as a powerful tool to reach a high dynamic range (~ 1 % in H) and high spatial resolution. The astrometric position of the Cepheid companions can be measured at several orbital epochs, and then later combined with spectroscopic measurements to derive all the orbital elements, the mass and the distance of the Cepheids.

Key Words: binaries: close — stars: variables: Cepheids — techniques: interferometric

1. INTRODUCTION

The mass of Cepheids is a long-standing problem since decades. First noticed by Christy (1968) and Stobie (1969), the discrepancy between the masses predicted from stellar evolution and pulsation models is not well understood, although convective core overshooting in the Cepheid's main-sequence progenitor and mass-loss during the Cepheid phase seem to be possible solutions. The only way to constrain both models is to directly measure the Cepheid masses, by studying binary Cepheids.

So far, a few dynamical masses have been measured, two eclipsing binaries including a Cepheid in the Large Magellanic Cloud (Pietrzyński et al. 2010, 2011), and only one - Polaris - in our Galaxy, using astrometric observations with the Hubble space telescope (Evans et al. 2008). The main problems in spatially resolving Galactic binary Cepheids are the contrast between the components and the apparent close orbit of the companions. The only way to spatially resolve such high-contrast systems is to use interferometric techniques. We have recently started a unique long-term interferometric observing campaign that aims at detecting and characterizing physical parameters of the Cepheid companions, to determine accurate masses and geometric distances.

2. THE HIGH-CONTRAST COMPANIONS OF CEPHEID STARS

A number of companions of Galactic Cepheids were detected from the variability of the γ-velocity (see e.g. Moore 1929; Herbig & Moore 1952; Abt 1959; Szabados 1989, 1991, and references therein). An ultraviolet survey was also carried out with the

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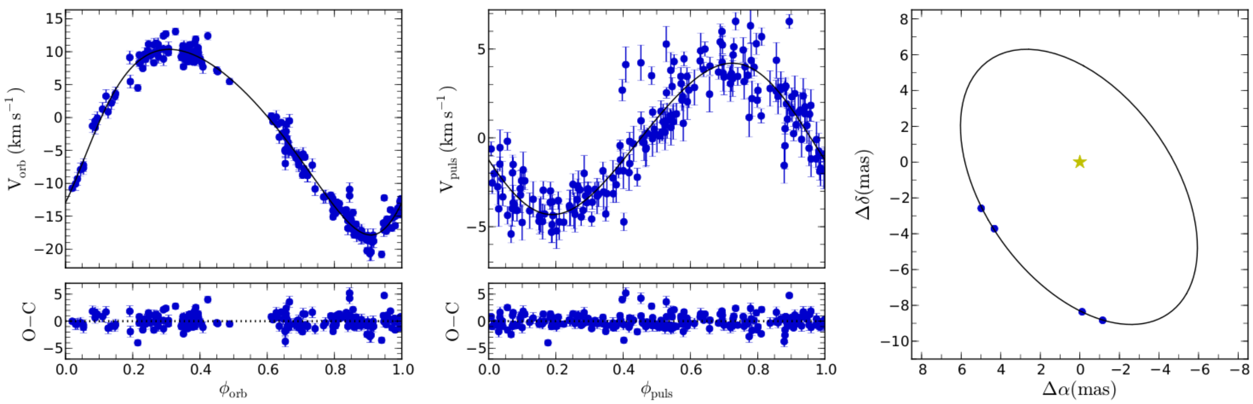

Fig. 1. *Left*: fitted (solid line) and measured orbital velocity. *Middle*: fitted (solid line) and measured pulsation velocity. *Right*: orbit of V1334 Cyg Ab. The blue data points are the MIRC observations of 2012 and 2013.

International Ultraviolet Exporer (IUE), where companions were detected from low- and high-resolution spectra (Böhm-Vitense & Proffitt 1985; Evans 1992), and their spectral type was provided. From an evolutionary time-scale 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 from photometric or spectroscopic surveys. Fainter (and hence less massive) companions have a small effect on the Cepheid's position, making their detection difficult even from high-precision radial velocity measurements. In addition, all measured binary Cepheids are single-line spectroscopic binaries so far. We therefore have started a spectroscopic observing campaign both in visible and ultraviolet wavelengths, whose the objectives are 1) to measure the radial velocity of the companions from high signal-to-noise ratio spectra, and 2) to complete archival spectroscopic data in order to have a large time coverage of the orbital periods which usually span years.

In addition, most of the companions are located too close to the Cepheid (< 40 mas) to be observed with 10-m class telescopes. So far, only five companions have been imaged, Polaris, η Aql, δ Cep, V659 Cen and S Nor (Evans et al. 2013, 2008), at an angular projected separation greater than $0.6''$. All other companions have an estimated projected semi-major axis less than 40 mas. But such angular separations are only reachable using long-baseline interferometry. We started in 2012 a new and unique long-term interferometric program that aims at measuring astrometric positions of the brightest companions. The first goal is to determine the angular separation and the apparent brightness ratio from the interferometric visibility and closure phase measurements. Our long-term objective, which needs a good sampling of the orbital period, is to determine the full set of orbital elements (including a, i and Ω, unknown from single-line radial velocity measurements), absolute masses and geometric distances.

3. RESULTS FROM LONG-BASELINE INTERFEROMETRIC OBSERVATIONS

We use the two unique interferometric recombiners that allow the detection of such high-contrast companions. In the northern hemisphere, we use MIRC (Michigan Infrared Beam Combiner Monnier et al. 2004, 2010), installed at the Center for High Angular Resolution Astronomy array (CHARA, Mount Wilson, California), which can combine the light coming from six 1-m aperture telescopes with baselines ranging from 34 m to 331 m, providing an angular resolution down to ~ 0.5 mas in H. MIRC works in the K or H bands, with three spectral resolutions ($R = 42, 150$ and 400). The recombination of six telescopes gives simultaneously 15 fringe squared visibilities and 20 closure phase measurements for each spectral channel. In the southern hemisphere, we use PIONIER (Le Bouquin et al. 2011), installed at the Very Large Telescope Interferometer (VLTI, Cerro Paranal, Chile), which can combine light coming from the four 8-m unit telescopes or the four 1.8-m auxiliary ones, whose baselines range from 11 m to 140 m, providing an angular resolution down to ~ 1 mas in H. It also offers spectral dispersion in 1 (broad band), 3 or 7 channels, and provides simultaneously 6 visibilities and 4 closure phase signals per spectral channel.

The first observed Cepheid was V1334 Cyg where the companion was detected at more than 25σ (Gallenne et al. 2013). We measured its astrometric position and flux ratio with an accuracy better than

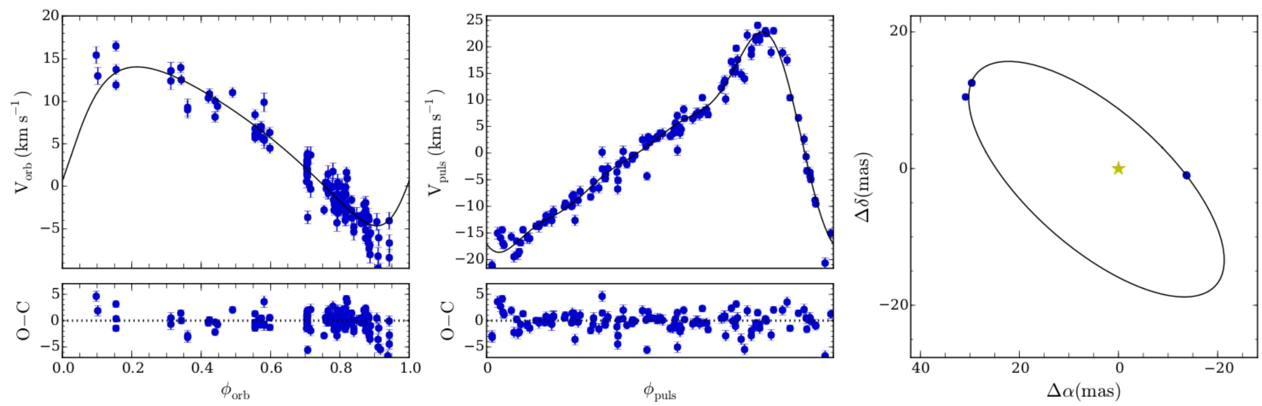

Fig. 2. *Left*: fitted (solid line) and measured orbital velocity. *Middle*: fitted (solid line) and measured pulsation velocity. *Right*: orbit of AW Per Ab. The blue data points are the MIRC observations of 2012, 2013 and the HST measurement of 2001.

3%. We then combined our astrometric data with available single-line radial velocity measurements to derive for the first time all orbital elements of the system. More particularly, we derived the orbital inclination, $i = 124.7 \pm 1.8°$, the angular semi-major axis, $a = 8.54 \pm 0.51$ mas, and the longitude of the ascending node, $\Omega = 206.3 \pm 9.4°$ which were previously unknown. The final orbital fit is shown in Fig. 1, in which we added the measurements made in 2013. The derived parameters are in very good agreement with the preliminary fit made by Gallenne et al. (2013), which included a measurement from 2012. It's estimated magnitude in H is 8.47 mag

We also detected with MIRC the companion orbiting AW Per with a detection level $> 16\sigma$. It was detected at $\rho \sim 32$ mas and $PA \sim 67°$ with a flux ratio of 1.05 % (Gallenne et al. 2015, submitted to A&A). We measured its magnitude to be $m_{\mathrm{H}} = 9.74$ mag. We present here in Fig. 2 a preliminary orbital fit using our two astrometric epochs and an additional measurement from the literature (Massa & Evans 2008). We estimated $i = 69°$, $a = 31$ mas, and $\Omega = 68°$, however additional points are necessary to fully constrain this orbit.

In the southern hemisphere, the companion orbiting AX Cir was detected with PIONIER, with a flux ratio as low as 0.75 %, and was located at $\rho \sim 29$ mas and $PA \sim 168°$. The χ^2_r map, made with our new interferometric fitting tool `CANDID` (Gallenne et al. 2015, submitted to A&A), is presented in Fig. 3. We estimated hte magnitude of the companion to be $m_{\mathrm{H}} = 9.06$ mag.

4. CONCLUSION

Thanks to the high angular resolution provided by interferometry, we are able to detect the close high-contrast companions of Cepheids. Our work, using multi-telescope recombination, provided novel physical parameters of the Cepheid companions. These innovative results also show the capabilities of long-baseline interferometry to study close and high-contrast binary systems in general.

The astrometric measurements can then be efficiently combined with radial velocity data to provide new constraints on the system properties. Further interferometric observations will be obtained in the future to cover the orbits presented here, and derive the orbital elements with a unique accuracy for our sample of binary Cepheids.

Finally, our interferometric program is complementary to an ongoing spectroscopic campaign to detect the orbital radial velocity variations of the companions. This will provide an orbital parallax and model-free masses for Galactic Cepheids, which is of crucial importance to constrain Cepheid masses and the Cepheid mass discrepancy.

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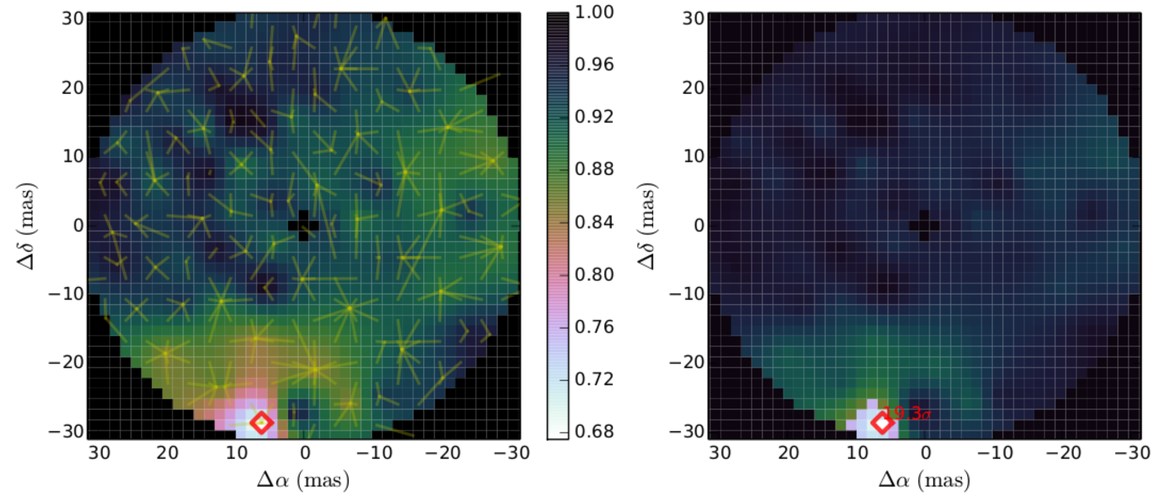

Fig. 3. χ_r^2 map (left) and detection level map (right) of AXCir. The yellow lines represent the convergence of the fit from the starting points to the final fitted position.

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