Interferometry of Classical Pulsators

Pierre Kervella[1], Antoine Mérand[2], Alexandre Gallenne[3], Simon Borgniet[1], Boris Trahin[1], Nicolas Nardetto[4], Grzegorz Pietrzyński[5] and Wolfgang Gieren[6]

1. LESIA (UMR 8109), Observatoire de Paris, PSL Research University, CNRS, UPMC, Univ. Paris-Diderot, 5 place Jules Janssen, 92195 Meudon, France
2. European Southern Observatory, Karl-Schwarzschild-str. 2, D-85748 Garching, Germany
3. European Southern Observatory, 3107 Alonso de Córdova, Casilla 19001, Santiago 19, Chile
4. Université Côte d'Azur, Observatoire de la Côte d'Azur, CNRS, Laboratoire Lagrange, UMR 7293, Nice, France
5. Nicolaus Copernicus Astronomical Center, Bartycka 18, 00–716 Warszawa, Poland
6. Universidad de Concepción, Departamento de Astronomía, Casilla 160-C, Concepción, Chile

Long baseline interferometry at optical and infrared wavelengths can now routinely reach milliarcsecond angular resolutions, and thus resolve the apparent disk of nearby pulsating stars. We here discuss the type of pulsating stars whose angular diameter can be measured by interferometry. Their changing photospheric angular diameter is a particularly valuable observable, as it is insensitive to interstellar reddening. Angular diameter measurements thus allow for an accurate calibration of their effective temperature. We integrated the interpretation of this novel observable, together with radial velocities and photometric measurements, in the "Spectro-Photo-Interferometry of Pulsating Stars" (SPIPS) modeling tool. We briefly present the SPIPS algorithm and its application to the long period Cepheid RS Puppis.

1 Introduction

Nearby pulsating stars are classical targets for optical interferometry, as this observing technique provides accurate measurements of their changing angular diameters. We first discuss the types of pulsators that are accessible to interferometric measurements (Sect. 2). We then present the joint use of interferometric angular diameters with spectroscopy and photometry (the SPIPS algorithm) for Classical Cepheids (hereafter CCs; Sect. 3).

2 Observability of Pulsating Stars by Interferometry

2.1 Performances of optical interferometers

The current generation of optical interferometers has maximum baseline lengths, B, of 140 m (VLTI; Mérand et al., 2014) to 330 m (CHARA array; ten Brummelaar et al., 2005, 2016) and usually operates between the visible and near-infrared domains ($\lambda \approx 0.6 - 2.4 \mu$m). The future VLTI/MATISSE instrument will reach the

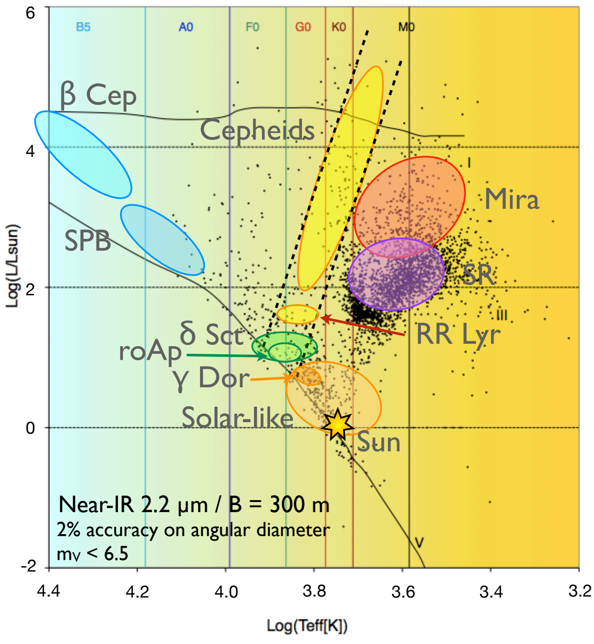

Fig. 1: Observable pulsating stars using the current generation of optical interferometers in the Hertzsprung-Russell (HR) diagram. The regions corresponding to different classes of pulsating stars are labeled, and the limits of the instability strip are represented using dashed lines. The black dots represent the stars whose angular diameter can be measured with an accuracy better than 2%.

thermal infrared domain (Matter et al., 2016; Wolf et al., 2016). This combination translates into an angular resolution λ/B of 0.3 to 3 milliarcseconds in the visible and near-infrared. To estimate the range of pulsating stars that are observable using the current interferometers, we considered the typical case of a near-infrared beam combiner ($\lambda = 2.2\,\mu$m) and a $B = 300$ m baseline length. We here assume that the instrument provides a measurement of the squared visibility, V^2, with an accuracy of 2%, which is a slightly conservative figure (Coudé du Foresto et al., 1997; Kervella et al., 2004a; ten Brummelaar et al., 2013; Gravity Collaboration et al., 2017).

2.2 Resolvable stars in the Hertzsprung-Russell diagram

In order to crudely estimate the angular diameter of each star, we used visible-infrared surface brightness-color relations (Kervella et al., 2004b). These empirically calibrated relations allow for the prediction of the angular diameter of stars with a few percent accuracy (see also Boyajian et al., 2014; Graczyk et al., 2017; Adams et al., 2018). We collected the V and K band magnitudes of the stars brighter than $m_V = 6.5$ from the Hipparcos (Perryman et al., 1997) and 2MASS (Cutri et al., 2003) catalogues. This magnitude limit corresponds to a practical feasibility limit in terms of angular resolution, as the photometric sensitivity of the instruments is usually not a limiting factor for the observation of stars. To place the stars in the HR diagram, we estimated the effective temperatures from the surface brightness-temperature relations calibrated by Kervella et al. (2004b). We considered that the observation of a given star by interferometry is scientifically useful when its angular diameter can be measured to an accuracy better than ±2%.

The resulting HR diagram is presented in Fig. 1. It is important to note that we did not individually assess the variability of each considered star, that is, we simply estimated their position in the HR diagram from their mean V and K magnitudes. This implies that the represented stars do not necessarily belong to the specified variable star classes. Another limitation is that we did not take individually into account the interstellar reddening for each star.

2.3 Cool pulsators

The distribution of observable stars is inhomogeneous, with a large number of red stars cooler than the red edge of the classical instability strip (semi-regular pulsators, Mira-like stars). This results from a combination of the statistical rarity of the hotter star classes in the solar neighborhood, and of their physical properties in terms of intrinsic brightness at infrared wavelengths and physical radius. Thanks to their favorable brightness in the near-infrared and ubiquity, red giants have been historically the subject of many interferometric studies. For instance, Lacour et al. (2009) reconstructed interferometric images of the Mira star χ Cygni at four epochs, showing the change in angular diameter over its pulsation cycle ($P = 408$ days), as well as the presence of surface inhomogeneities. Ruiz Velasco et al. (2016) recently presented a preliminary analysis of a large sample of 85 Miras observed at multiple epochs with the Palomar Testbed Interferometer. It is interesting to note that Miras and Type II Cepheids (Breitfelder et al., 2015) are the subject of a renewed interest as standard candles for the extragalactic distance scale (Macri, 2017; Bhardwaj et al., 2017). Although their environment is often more complex than that of CCs (presence of dusty envelopes), their relatively tight period-luminosity relations and high infrared brightness make them favorable targets for future observations with the JWST. The new generation of interferometric instrumentation (e.g., the GRAVITY and MATISSE instruments of the VLTI) will enable a very detailed monitoring of the pulsation cycle and close environment of these stars, potentially strengthening their reliability as distance indicators.

2.4 Cepheids and RR Lyrae

As they are massive stars that undergo a fast evolution through the instability strip, CCs are rare in the solar neighborhood, and therefore relatively distant in average. This reflects on their observability using optical interferometry, as despite their large physical radii, only approximately thirty CCs are resolvable by the current generation of interferometers (Fig. 1; see also Moskalik & Gorynya, 2006). The first interferometric observations of a Cepheid, the prototype δ Cep using the GI2T instrument at visible wavelengths, were reported twenty years ago by Mourard et al. (1997). Since this pioneering effort, the progression of the performances of optical interferometers has enabled a considerable improvement in the accuracy of the measurement of CC angular diameters (Lane et al., 2000; Nordgren et al., 2000; Kervella et al., 2004c; Mérand et al., 2005; Jacob, 2008; Mérand et al., 2015; Breitfelder et al., 2016; Kervella et al., 2017) and limb darkening (Mérand et al., 2006). Optical interferometry also allows us to probe the close environment of nearby pulsating stars for the presence of stellar companions (Gallenne et al., 2013b, 2015, 2016) or circumstellar envelopes (Kervella et al., 2009; Gallenne, 2011; Gallenne et al., 2013a).

The interferometric observability of RR Lyrae stars (RRLs) is less favorable than that of CCs. Although RRLs are more common than CCs in the solar neighborhood, their small linear radius (typically a few solar radii) results in a small apparent size. The RRL that exhibits the largest angular diameter is the prototype RR Lyr. According to Trahin et al. (2017), the mean angular diameter of this star is only $\theta \approx 0.2\,\mathrm{mas}$, which is beyond the angular resolution of current interferometers. Thanks to a combination of long observing baselines and visible wavelengths, the FRIEND instrument project (Berio et al., 2014; Martinod et al., 2016) will soon make it possible to measure the angular diameter of a sample of nearby RRLs.

3 Robust Cepheid Distances Using Interferometry: the SPIPS Algorithm

The parallax-of-pulsation (PoP, or Baade-Wesselink) method is a classical way to measure Cepheid distances: by combining an angular and a linear measurement of the size variation, we can derive the distance in a quasi-geometrical way. This technique has demonstrated its potential to reach an accuracy better than 5% on the ratio d/p of the distance d and the spectroscopic projection factor p (p-factor), as shown by Mérand et al. (2005) on the prototype δ Cep. A discussion of the properties of the p-factor can be found in Nardetto et al. (2017b) and Nardetto et al. (2017a). The parameters d and p are 100% correlated and cannot be disentangled using the PoP technique alone. However, based only on interferometry and radial velocities, this simple implementation leaves out important observables. We thus developed a modeling tool to extend the robustness of the PoP technique: the *Spectro-Photo-Interferometry of Pulsating Stars* code (SPIPS; Mérand et al., 2015).

A SPIPS analysis integrates the available observables (e.g., photometry, interferometry, spectroscopic radial velocities and effective temperatures) in a consistent model of the Cepheid pulsation, from which the ratio d/p, color excess $E(B-V)$ and other parameters are derived. Instead of using only the radial velocities and the angular diameter measurements, we include, in addition, in SPIPS the photometry (in all possible systems) and other observables from the literature (e.g. T_{eff} from spectroscopy). These measurements are optional, but they make it possible to detect, for instance, the presence of infrared excess due to circumstellar emission. In this algorithm, the key advantage of interferometrically measured angular diameters is that they are independent of interstellar reddening. This means that they resolve the partial degeneracy between the color excess $E(B-V)$ and the effective temperature of the star. Within the SPIPS code, we take particular care to propagate the systematic uncertainties and the correlations between the different observables (interferometric calibrator sizes, systematic photometric biases, etc.). As a result, the derived parameter accuracy is in general not limited by statistical errors, but by well estimated systematics of various origins.

However, interferometric angular diameters alone do not resolve the degeneracy between the distance and the p-factor, and we still need an independent distance measurement for that purpose. An example of the result of a SPIPS fit on the long-period Cepheid RS Puppis is presented in Fig. 2. This star is a special case

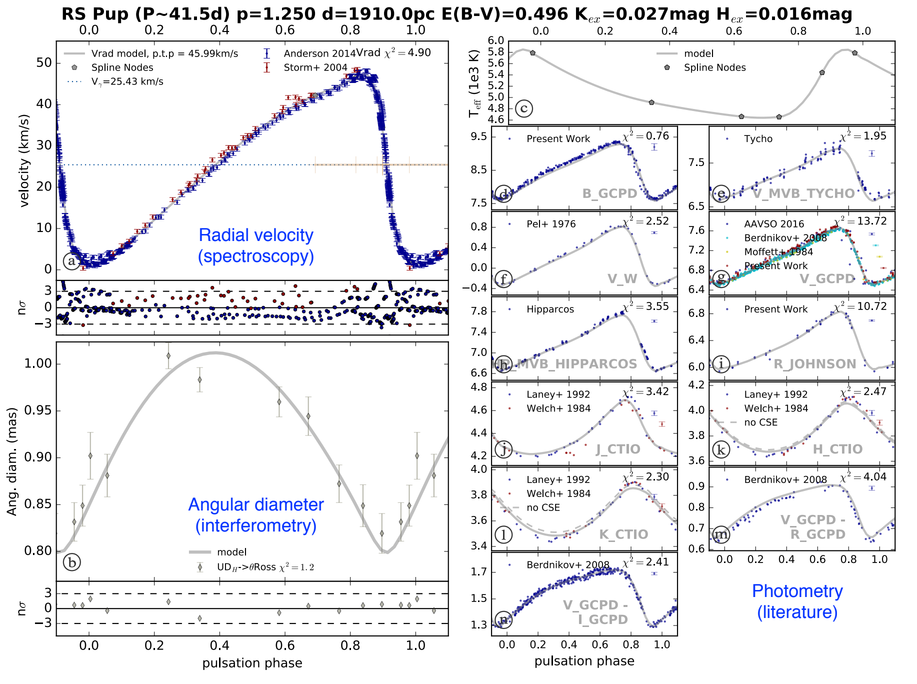

Fig. 2: SPIPS algorithm applied to the long-period Cepheid RS Pup (Kervella et al., 2017).

as its distance $d = 1910 \pm 80$ pc was measured by Kervella et al. (2014) using the spectacular light echoes that propagate in its circumstellar dusty envelope. As the distance to this star is known independently, the SPIPS fit gives access to the p-factor of the star, $p = 1.25 \pm 0.06$ (Kervella et al., 2017). Other implementations of the SPIPS algorithm, when the distance to the studied CCs is known (Breitfelder et al., 2016; Gallenne et al., 2017), as well as determinations from the modeling of eclipsing binaries (Pilecki et al., 2013; Gieren et al., 2015), point at a mild dependence of the p-factor as a function of the pulsation period. In early 2018, the publication of the second *Gaia* data release will provide a large sample of several hundred accurate parallaxes of CCs. This will allow us to determine their projection factors using the SPIPS algorithm, in particular those of the sample of nearby CCs that can be resolved by optical interferometry. This in turn will improve the reliability of the PoP technique to determine CC distances, potentially up to large distances in the local group using the coming generation of extremely large telescopes.

4 Conclusion

Optical interferometry has a strong but yet incompletely realized potential to contribute to our knowledge of pulsating stars. Miras and similar cool giant pulsators have long been studied by interferometry, and the new insights on their close environment from the new generation of beam combiners will likely improve their usability as standard candles to determine extragalactic distances. RR Lyrae stars are currently beyond the reach of interferometric measurements due to their small angular diameters, but there are good prospects that the next generation of interferometric instruments operating at visible wavelengths will measure accurately their rapidly-changing apparent size. In combination with *Gaia* parallaxes, interferometric angular diameter measurements of Classical Cepheids have the potential to establish the Parallax-of-Pulsation technique on solid foundations, making it a precision tool to measure distances to local group galaxies with extremely large telescopes.

Acknowledgements. The research leading to these results has received funding from the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation programme (grant agreement No 695099). W.G. and G.P. gratefully acknowledge financial support for this work from the BASAL Centro de Astrofisica y Tecnologias Afines (CATA) PFB-06/2007. W.G. also acknowledges financial support from the Millenium Institute of Astrophysics (MAS) of the Iniciativa Cientifica Milenio del Ministerio de Economia, Fomento y Turismo de Chile, project IC120009. The authors acknowledge the support of the French Agence Nationale de la Recherche (ANR), under grant ANR-15-CE31-0012-01 (project UnlockCepheids). We acknowledge financial support from the "Programme National de Physique Stellaire" (PNPS) of CNRS/INSU, France. We used the SIMBAD and VIZIER databases at the CDS, Strasbourg (France), and NASA's Astrophysics Data System Bibliographic Services.

References

Adams, A. D., Boyajian, T. S., von Braun, K., *MNRAS* **473**, 3608 (2018), `arXiv:1709.03902`

Berio, P., et al., in Optical and Infrared Interferometry IV, *Proc. SPIE*, volume 9146, 914616 (2014)

Bhardwaj, A., et al., *AJ* **153**, 154 (2017), `arXiv:1702.00967`

Boyajian, T. S., van Belle, G., von Braun, K., *AJ* **147**, 47 (2014), `arXiv:1311.4901`

Breitfelder, J., et al., *A&A* **576**, A64 (2015), `arXiv:1503.05176`

Breitfelder, J., et al., *A&A* **587**, A117 (2016), `arXiv:1601.04727`

Coudé du Foresto, V., Ridgway, S., Mariotti, J.-M., *A&AS* **121**, 379 (1997)

Cutri, R. M., et al., 2MASS All Sky Catalog of point sources. (2003)

Gallenne, A., Cepheids at high angular resolution: circumstellar envelope and pulsation, Ph.D. thesis, Université Pierre et Marie Curie-Paris 6 (2011)

Gallenne, A., et al., *A&A* **558**, A140 (2013a), `arXiv:1309.0854`

Gallenne, A., et al., *A&A* **552**, A21 (2013b), `arXiv:1302.1817`

Gallenne, A., et al., *A&A* **579**, A68 (2015), `arXiv:1505.02715`

Gallenne, A., et al., *MNRAS* **461**, 1451 (2016), `arXiv:1606.01108`

Gallenne, A., et al., *A&A* **608**, A18 (2017)

Gieren, W., et al., *ApJ* **815**, 28 (2015), `arXiv:1511.02826`

Graczyk, D., et al., *ApJ* **837**, 7 (2017), `arXiv:1611.09976`

Gravity Collaboration, et al., *A&A* **602**, A94 (2017), `arXiv:1705.02345`

Jacob, A. P., Observations of Three Cepheid Stars with SUSI, Ph.D. thesis, University of Sydney (2008)

Kervella, P., Mérand, A., Gallenne, A., *A&A* **498**, 425 (2009), `arXiv:0902.1588`

Kervella, P., Ségransan, D., Coudé du Foresto, V., *A&A* **425**, 1161 (2004a), arXiv: arXiv:astro-ph/0406625

Kervella, P., Thévenin, F., Di Folco, E., Ségransan, D., *A&A* **426**, 297 (2004b), arXiv: astro-ph/0404180

Kervella, P., et al., *A&A* **416**, 941 (2004c), arXiv: astro-ph/0311525

Kervella, P., et al., *A&A* **572**, A7 (2014), arXiv: 1408.1697

Kervella, P., et al., *A&A* **600**, A127 (2017), arXiv: 1701.05192

Lacour, S., et al., *ApJ* **707**, 632 (2009), arXiv: 0910.3869

Lane, B. F., et al., *Nature* **407**, 485 (2000)

Macri, L., in European Physical Journal Web of Conferences, *European Physical Journal Web of Conferences*, volume 152, 07001 (2017)

Martinod, M. A., et al., in Optical and Infrared Interferometry and Imaging V, *Proc. SPIE*, volume 9907, 99071H (2016)

Matter, A., et al., in Optical and Infrared Interferometry and Imaging V, *Proc. SPIE*, volume 9907, 990728 (2016), arXiv: 1608.02351

Mérand, A., et al., *A&A* **438**, L9 (2005)

Mérand, A., et al., *A&A* **453**, 155 (2006)

Mérand, A., et al., in Optical and Infrared Interferometry IV, *Proc. SPIE*, volume 9146, 91460J (2014), arXiv: 1407.2785

Mérand, A., et al., *A&A* **584**, A80 (2015), arXiv: 1510.01940

Moskalik, P., Gorynya, N. A., *Mem. Soc. Astron. Italiana* **77**, 253 (2006), arXiv: astro-ph/0510139

Mourard, D., et al., *A&A* **317**, 789 (1997)

Nardetto, N., et al., *A&A* **597**, A73 (2017a), arXiv: 1701.01589

Nardetto, N., et al., in present proceedings (2017b)

Nordgren, T. E., et al., *ApJ* **543**, 972 (2000), arXiv: astro-ph/0009497

Perryman, M. A. C., et al., *A&A* **323**, L49 (1997)

Pilecki, B., et al., *MNRAS* **436**, 953 (2013), arXiv: 1308.5023

Ruiz Velasco, A., van Belle, G., Creech-Eakman, M., in 19th Cambridge Workshop on Cool Stars, Stellar Systems, and the Sun (CS19), 52 (2016)

ten Brummelaar, T. A., et al., *ApJ* **628**, 453 (2005), arXiv: astro-ph/0504082

ten Brummelaar, T. A., et al., *Journal of Astronomical Instrumentation* **2**, 1340004 (2013)

ten Brummelaar, T. A., et al., in Optical and Infrared Interferometry and Imaging V, *Proc. SPIE*, volume 9907, 990703 (2016)

Trahin, B., et al., present proceedings (2017)

Wolf, S., et al., in Optical and Infrared Interferometry and Imaging V, *Proc. SPIE*, volume 9907, 99073S (2016), arXiv: 1609.06152