Stars and their variability observed from space
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THE DISTANCE OF THE LONG-PERIOD CEPHEID RS PUPPIS FROM ITS REMARKABLE LIGHT ECHOES

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Abstract. The Milky Way Cepheid RS Puppis is a particularly important calibrator for the Leavitt law (the Period–Luminosity relation). It is a rare long-period pulsator ($P = 41.5$ days), and a good analogue of the Cepheids observed in distant galaxies. It is the only known Cepheid that is embedded in a large (≈ 0.5 pc) dusty nebula which scatters the light from the pulsating star. DOwing to the light travel time-delay introduced by scattering on the dust, the brightness and colour variations of the Cepheid imprint spectacular light echoes on the nebula. This brief overview of the studies of this phenomenon focus in particular on polarimetric imaging obtained with the HST/ACS camera. These observations enabled us to determine the geometry of the nebula and the distance of RS Pup. That distance determination is important in the context of calibrating both the Baade-Wesselink technique and the Leavitt law.

Keywords: stars: distances, distance scale, variables: Cepheids, techniques: polarimetric, scattering, photometric

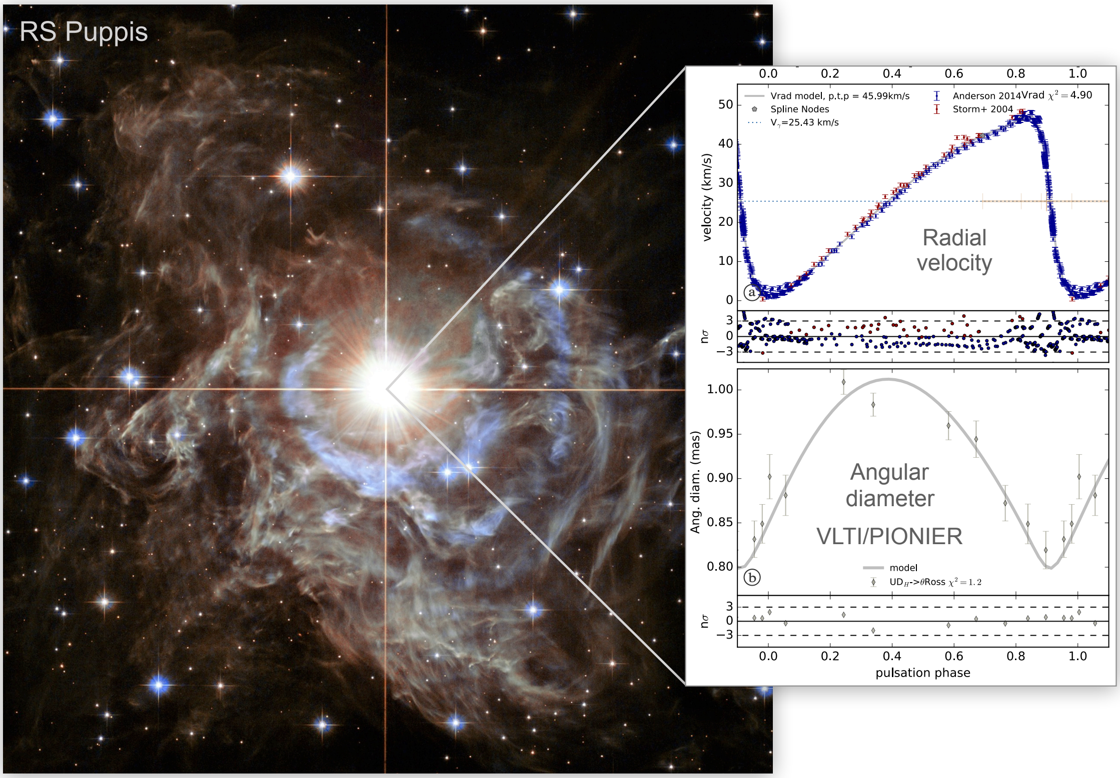
1 Introduction

The high intrinsic brightness and the tight relation between period and luminosity established by the Leavitt law (Leavitt 1908; Leavitt & Pickering 1912) make long-period Cepheids the most precise standard candles for the determination of extragalactic distances. Their relatively high mass ($m \approx 10 - 15\,M_\odot$) together with the brevity of their passage across the instability strip combine to make them very rare stars. As a result, only a handful of long-period Cepheids ($P > 30$ d) are located within a few kiloparsecs of the Sun. RS Puppis (HD 68860) (period $P = 41.5$ d) is among the most luminous Cepheids in the Milky Way. This article presents the remarkable light echoes that occur in its circumstellar nebula, and how the distance to the Cepheid can be derived from observating them. It also describes how modelling of the pulsation of RS Pup, and the calibration of the Baade-Wesselink projection factor have been carried out.

2 Light echoes in the nebula of RS Puppis

The circumstellar dusty nebula of RS Puppis was discovered by Westerlund (1961). This author proposed that the presence of the dusty environment results in the creation of "light echoes" of the photometric variations of the Cepheid (see, e.g., Sugerman (2003) for a review of this phenomenon). The variable illumination wavefronts emitted by the Cepheid propagate in the nebula, where they are scattered by dust grains. The additional optical path of the scattered light compared to the light coming directly from the Cepheid causes the appearance of a time delay (and therefore a phase difference) between the Cepheid cycle as observed directly and the photometric variation of the dust in the nebula.

The first detection of the light echoes of RS Pup was achieved by Havlen (1972). More than 30 years later CCD observations were collected by Kervella et al. (2008) using the EMMI imager on the 3.6-m ESO NTT. Those authors derived a distance based on the phase lag of selected dust knots with respect to the Cepheid. However, Bond & Sparks (2009) objected that the hypothesis of coplanarity of the selected dust knots was probably incorrect (see also Feast (2008)), and that a determination of the 3D structure of the dust is necessary to derive the distance using the echoes. To measure that distribution, polarimetric imaging has been shown to be a powerful technique, as applied for instance on V838 Mon by Sparks et al. (2008) (see also Sparks (1994)). Using that technique, Kervella et al. (2012) determined the structure of the nebula from ground-based observations with VLT/FORS. The dust is distributed over a relatively thin ovoidal shell, probably swept away by the strong radiation pressure from the Cepheid's light. They concluded that the mass of the dust in the



Credit: NASA, ESA, and the Hubble Heritage Team

Fig. 1. Left: HST/ACS colour image of the RS Pup nebula (Kervella et al. 2014). The light echoes of the maximum light phase are visible as irregular blue rings caused by the hotter temperature of the star at its maximum light. **Right:** Radial-velocity and angular-diameter data used for modelling the pulsation of the Cepheid (Kervella et al. 2017).

nebula is too large to be explained by mass loss from the Cepheid itself, and that the nebula is a pre-existing interstellar dust cloud in which the Cepheid is temporarily embedded.

However, the VLT/FORS polarimetric images are seeing-limited and could not provide a sufficiently detailed map of the structure of the nebula. A time-sequence of polarimetric images of RS Pup was therefore obtained by Kervella et al. (2014) using the HST/ACS. They showed in spectacular detail the structure of the nebula (Fig. 1 left panel), and the propagation of the echoes (Fig. 2; see also `https://vimeo.com/108581936` for a video of the light echoes), and the degree of linear polarization of the scattered light across the nebula.

The combination of the polarization information and the phase delay of the light echoes across the nebula result in a distance of 1910 ± 80 pc (4.2%), equivalent to a parallax of $\varpi = 0.524 \pm 0.022$ mas (Kervella et al. 2014). That value is significantly different from the parallax of RS Pup $\varpi_{\rm GDR2} = 0.613 \pm 0.026$ mas (adopting a *Gaia* parallax shift of $+29\,\mu$as) reported in the second *Gaia* data release (Gaia Collaboration et al. 2018). The parallax of a field star interacting with the RS Pup nebula (labelled S1, $\varpi[\rm S1] = 0.532 \pm 0.048$ mas; Kervella et al. (2019)) is, however, consistent with the distance of the light echo to the Cepheid.

3 Pulsation modelling and the projection factor

The classical Baade-Wesselink (BW) distance determination technique (also known as the parallax-of-pulsation) is based on a comparison of the linear amplitude of the radius variation of a pulsating star with its angular amplitude (see, e.g., Groenewegen (2008)). The SPIPS approach is a recent BW implementation presented by Mérand et al. (2015) that uses a combination of spectroscopic radial velocity, multi-band photometry and interferometric angular diameters to build a consistent model of the pulsating photosphere of the star.

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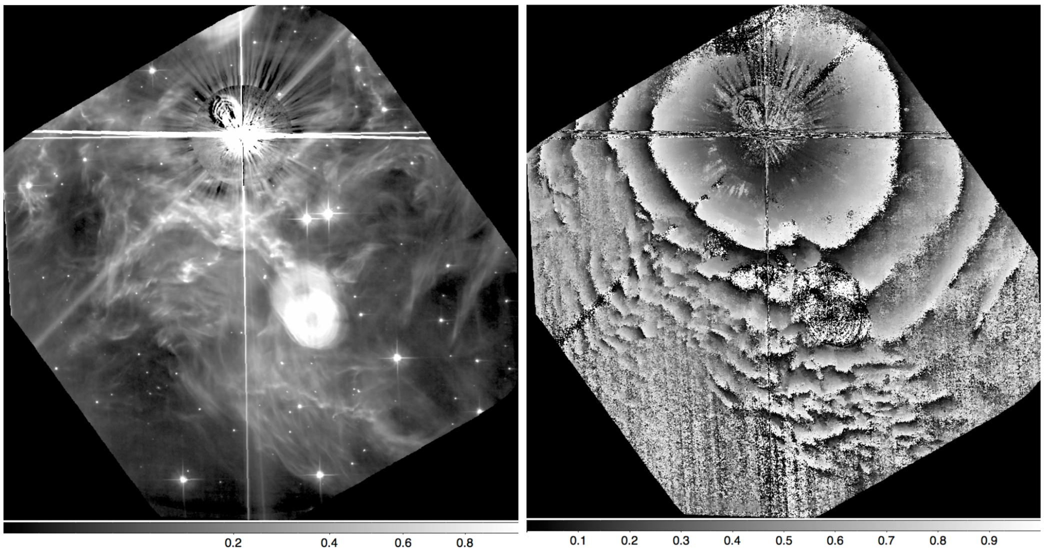

Fig. 2. Left: Mean scattered light intensity around RS Pup (Kervella et al. 2014) (arbitrary grey scale). **Right:** Phase delay of the light variation across the nebula with respect to the Cepheid cycle.

A strong limitation of the BW technique comes from the fact that the distance and the spectroscopic projection factor (p-factor) are fully degenerate. The p-factor is defined as the ratio between the photospheric velocity and the disk-integrated radial velocity measured from spectroscopy (Nardetto et al. 2014). The p-factor is presently the major limiting factor in terms of accuracy for the application of the BW technique; research is particularly active on this topic (Groenewegen 2007; Storm et al. 2011a; Ngeow et al. 2012; Pilecki et al. 2013; Breitfelder et al. 2015, 2016; Nardetto et al. 2017; Nardetto 2018). Using the VLTI/PIONIER optical interferometer, Kervella et al. (2017) measured the changing angular diameter of RS Pup over its pulsation cycle (Fig. 1, right panel). Those measurements, together with the light-echo distance from the HST/ACS observations, enabled those authors to resolve the degeneracy between the distance and the p-factor, and to obtain a p-factor value of $p = 1.25 \pm 0.06$ for RS Pup.

4 Conclusion

The determination of an accurate distance to RS Pup using its light echoes is an important step towards a reliable calibration of the Leavitt law, as it is still, even after the second *Gaia* data release (Gaia Collaboration et al. 2018), the most accurate distance estimate today to a long-period Cepheid. Moreover, this original technique is independent of the trigonometric parallax, enabling an independent validation. The light-echo distance can also be employed to calibrate the Baade-Wesselink method, especially the p-factor. A reliable calibration of this classical technique provides a solid basis for estimating the distances of Cepheids that are too far for direct trigonometric parallax measurements with *Gaia*. While BW analyses of individual Cepheids is accessible at present only out to the LMC and SMC (Storm et al. 2004, 2011b; Gallenne et al. 2017), it could soon become possible, with extremely large telescopes like the E-ELT or the TMT, to determine the distances of individual Cepheids in significantly more distant galaxies of the Local Group.

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