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A spectro-interferometric view of ℓ Carinae's modulated pulsations

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Abstract. Classical Cepheids are radially pulsating stars that enable important tests of stellar evolution and play a crucial role in the calibration of the local Hubble constant. ℓ Carinae is a particularly well-known distance calibrator, being the closest long-period ($P \sim 35.5$ d) Cepheid and subtending the largest angular diameter. We have carried out an unprecedented observing program to investigate whether recently discovered cycle-to-cycle changes (modulations) of ℓ Carinae's radial velocity (RV) variability are mirrored by its variability in angular size. To this end, we have secured a fully contemporaneous dataset of high-precision RVs and high-precision angular diameters. Here we provide a concise summary of our project and report preliminary results. We confirm the modulated nature of the RV variability and find tentative evidence of cycle-to-cycle differences in ℓ Car's maximal angular diameter. Our analysis is exploring the limits of state-of-the-art instrumentation and reveals additional complexity in the pulsations of Cepheids. If confirmed, our result suggests a previously unknown pulsation cycle dependence of projection factors required for determining Cepheid distances via the Baade-Wesselink technique.

Keywords. stars: oscillations, Cepheids, stars: distances, techniques: radial velocities, techniques: interferometric

1. Introduction

Classical Cepheid variable stars are often considered to be very stable radial pulsators. Moreover, Cepheids are high-sensitivity probes of stellar evolution and crucial calibrators of the cosmic distance scale (e.g. Riess *et al.* 2011). Thanks to recent advances in instrumentation, it is becoming increasingly clear that Cepheids exhibit time-dependent variability, ranging from erratic cycle-to-cycle variations to (semi-)periodic modulations that are often likened to the Blažko (1907) effect.

The most commonly observed time-dependence of Cepheid variability is related to pulsation periods. Since Eddington (1919) it is known that Cepheids exhibit long-term (secular) trends that provide an important test of stellar evolution (Turner *et al.* 2006). However, long-term monitoring of Cepheids in the Magellanic Clouds (Poleski 2008, Süveges *et al.*, this volume) as well as space-based photometry (Derekas *et al.* 2012, Evans *et al.* 2015) are revealing ubiquitous, irregular low-level fluctuations of pulsation periods on time-scales much shorter than the secular trends caused by stellar evolution.

Recently, Anderson (2014) discovered the modulated nature of Cepheid radial velocity (RV) variability. One of the stars in the sample showing RV curve modulation was

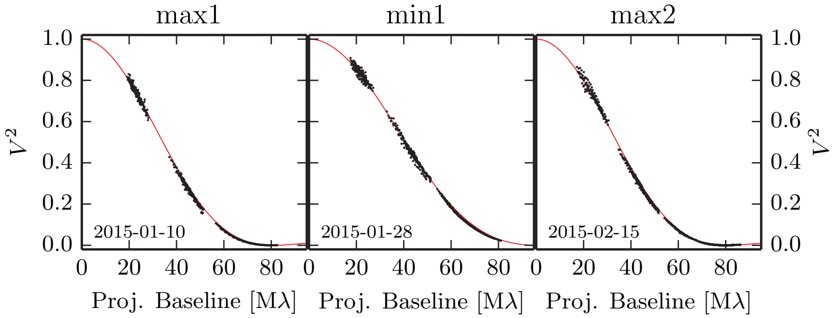

Figure 1. Squared visibility versus projected baseline as observed during the nights (as indicated) nearest to epochs of first maximum (max1), minimum (min1), and second maximum (max2) diameter. Fitted models for uniform disk diameters are shown as solid red curves. At maximum radius, the first zero is resolved, while this is not the case for the minimum.

ℓ Carinae (HD84810), the Cepheid with the largest known angular diameter (Kervella *et al.* 2004). In practice, RV modulation can lead to a systematic uncertainty in the determination of geometric distances via Baade-Wesselink techniques (Baade 1926, Wesselink 1946), since distance $d \propto \Delta R/\Delta\Theta$, where $\Delta R = p \int v_r d\phi$ is the linear radius variation determined using the projection factor p and the RV curve v_r, and $\Delta\Theta$ is the angular diameter variation.

The aim of this work is to test whether cycle-to-cycle differences of ΔR have analogs in $\Delta\Theta$. The detailed analysis and results of this study are about to be submitted (Anderson *et al.*, in prep.). Here, we present an overview of the project and some preliminary results.

2. Observations

To search for modulated variability, we observed ℓ Carinae between late December 2014 and May 2015. We determined 361 high-precision (median individual measurement uncertainty $\sim 3.1\,\mathrm{ms}^{-1}$) RVs from optical spectra taken with the high-resolution spectrograph *Coralie* mounted to the Swiss 1.2 m *Euler* telescope situated at La Silla Observatory, Chile. During a period of three months (until late March), we achieved nearly uninterrupted nightly RV monitoring.

Contemporaneously, we obtained three epochs of long-baseline near-infrared interferometric observations with the *PIONIER* instrument (Le Bouquin *et al.* 2011) at ESO's Very Large Telescope Interferometer under program ID `094.D-0583`. These three epochs were chosen to be near successive maximal (max1, early January 2015), minimal (late Jan), and maximal (max2, mid February 2015) diameters. Figure 1 shows the visibility curves nearest to the epochs of both maxima and single minimum.

We determine angular diameters Θ from the calibrated visibility curves, adopting both uniform disk and limb-darkened models. We employ the RV data to provide timing estimates of maximal and minimal diameters, and track the linear radius variations ΔR as well as their cycle-to-cycle variability.

3. Results

We confirm the presence of RV modulation from the new RV data. Figure 2 shows a direct comparison between the earlier data by Anderson (2014) and the new data. We find a significantly weaker RV curve modulation in 2015 compared to the year before,

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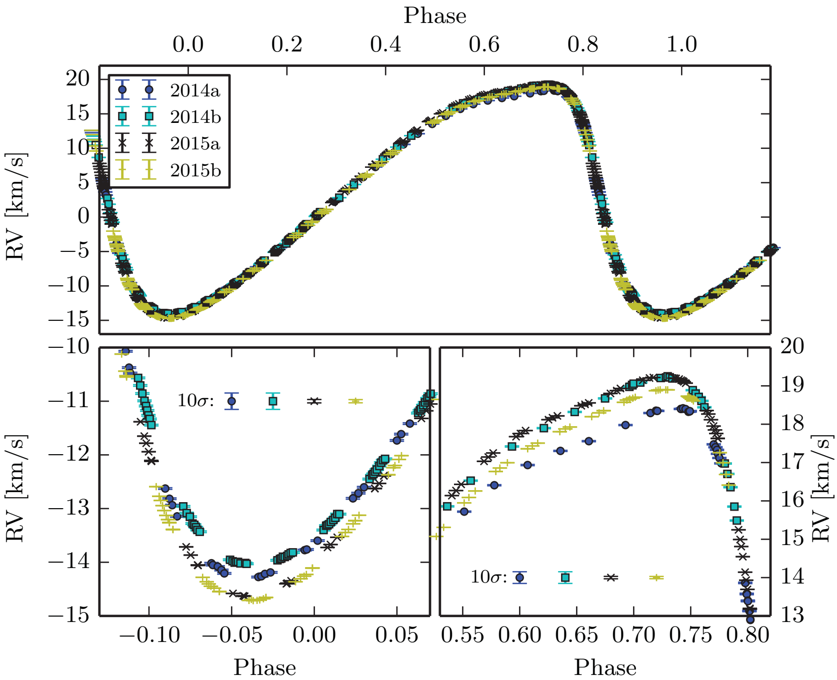

Figure 2. Confirmation of RV curve modulation and comparison of RV modulation in 2015 with the data from Anderson (2014). RV curve modulation was significantly stronger in 2014, see below panels that provide a close-up of minimum and maximum RV. Ten-fold median uncertainties for each dataset are indicated. 2015 data are more precise due to different observing mode (interlaced ThAr spectra to correct for instrumental drifts during the night).

although peak-to-peak RV amplitude was larger in 2015. This points to an erratic, irregular modulation, which occurs on the timescale of the pulsation period. For the time being, we cannot determine whether there is a longer-term periodicity to the modulation; continued RV observations are required to this end.

Based on the interferometric measurements, we find *tentative* evidence for different maximal angular diameters measured from the two consecutive epochs near maximum (one pulsation period apart). While the dispersion of the measurements suggests a significant difference between the two maximal diameters, possible significant *systematic* uncertainties may question the reality of that difference. These systematics include, e.g. the stability/reproducibility of the wavelength calibration, possible companions of calibrator stars or ℓ Car (we find no such evidence), asymmetry due to ablation, and other instrumental effects, such as pupil stability. Tests carried out to identify the contributions of such effects have been carried out and gave negative results, although we have not been able to rule out all possible sources of systematic error that could mimic cycle-to-cycle variations of Θ.

We determine that linear radius variations ΔR suggest a *decrease* in radius of approximately $0.22\,R_\odot$ between epochs max1 and max2. Contemporaneously, we determine an *increase* in maximal angular diameter of approximately $23\,\mu$arcseconds from our interferometric observation. If not caused by systematic effects, this difference suggests that modulation affects the motion of *gas* (traced by RVs) and *optical* layers (traced by interferometry) differently. This would imply a previously unknown time-dependence (varying between pulsation cycles) of the projection factor p, which can be decomposed as

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(cf. Nardetto *et al.* 2007): $p = p_0 f_{o-g} f_{grad}$, where f_{o-g} accounts for differently moving *optical* and *gas* layers, and f_{grad} for velocity gradients in the atmosphere.

4. Conclusions

Our study explores the limits of state-of-the-art interferometric methods for determining angular diameter variations over timescales of over a month, thereby revealing additional complexity in the pulsations of classical Cepheid variable stars. We confirm the presence of cycle-to-cycle differences in the RV curves of the long-period Cepheid ℓ Carinae and find tentative evidence of modulated angular diameter variability, measured contemporaneously. If interpreted as real, the morphology of the modulation suggests that *optical* and *gas* layers exhibit different types of cycle-to-cycle modulations, introducing a possibly erratic pulsation-cycle dependence of projection factors.

We will continue this effort to investigate and characterize the modulated variability of ℓ Carinae and other Cepheids using the most precise instruments available. In doing so, we seek to provide additional insight into the pulsations of Cepheids, providing constraints on possible non-linear pulsations, pulsation-convection coupling, granulation, or other relevant effects. Moreover, we seek to improve the accuracy of Baade-Wesselink distances, which will benefit the distance scale.

References

Anderson, R. I. 2014, *A&A*, 566, L10
Baade, W. 1926, *Astronomische Nachrichten*, 228, 359
Blažko 1907, *Astronomische Nachrichten*, 175, 325
Derekas, A., Szabó, G. M., Berdnikov, L., *et al.* 2012, *MNRAS*, 425, 1312
Eddington, A. S. 1919, *The Observatory*, 42, 338
Evans, N. R., Szabó, R., Derekas, A., *et al.* 2015, *MNRAS*, 446, 4008
Kervella, P., Fouqué, P., Storm, J., *et al.* 2004, *ApJ Letters*, 604, L113
Le Bouquin, J.-B., Berger, J.-P., & Lazareff, B., *et al.* 2011, *A&A*, 535, A67
Nardetto, N., Mourard, D., Mathias, P., *et al.* 2007, *A&A*, 471, 661
Poleski, R. 2008, *Acta Astron.*, 58, 313
Riess, A. G., Macri, L., Casertano, S., *et al.* 2011, *ApJ*, 730, 119
Süveges, M., Anderson, R. I., & Eyer, L., 2015, *Focus on Astronomy* (CUP), **Focus Meeting 17 (this volume)**
Turner, D. G., Abdel-Sabour Abdel-Latif, M., & Berdnikov, L. N. 2006, *PASP*, 118, 410
Wesselink, A. J. 1946, *Bull. Astron. Inst. Netherlands*, 10, 91