Finding the elusive RR Lyrae companions

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No RR Lyrae in binary systems?

Textbook knowledge of binarity tell us that about half of the stars in the Universe reside in binary systems. But there is a group of stars where the situation is very different: the pulsating horizontal branch stars known as RR Lyrae (hereafter RRL), whose binary properties are almost completely unknown, even though their binary fraction, according to the mass of their progenitors in the main sequence, should approach 45% (Raghavan et al. 2010).

Even though the number of RRL candidates in binary systems has grown significantly in the past ~ 5 years (Hajdu et al. 2015; Kervella et al. 2019), *confirmed* RRL in binary systems can be counted with one hand... actually with one finger! (TU UMa; Liška et al. 2016).

The most traditional method for searching for binarity, radial velocity variations, fails because of two main reasons: a) the complications of disentangling the any orbital RV signal from the one associated to pulsation and, most importantly, b) RV searches are biased towards close binaries. The problem with close binaries is that if they become contact binaries at some point, the mass transfer will break the fragile stellar structure that produces pulsations in the horizontal branch, and therefore close binaries will not produce RRL, and one is left with the more challenging task of searching for wide binaries.

The ingenious and most successful method so far is that of the light travel time effect (LTTE, Irwin 1952), where the timing of the maximum of the pulsation cycle changes in the presence of companion given the different paths the light from the RRL has to travel (Prudil et al. 2019; Hajdu et al. 2021). One problem is that a similar effect can happen simply by secular variations in RRL (Skarka et al. 2018).

A yet unexplored avenue for searching RRL in wide binaries is speckle interferometry.

Speckle interferometry at Gemini

Speckle interferometry (Labeyrie 1970) is based on the idea that the atmospheric turbulence can be "frozen" when obtaining very short exposures. In these very short exposures, stars look actually like a collection of little small spots, or speckles, where each of these speckles has the size of the diffraction limit of the telescope. When taking many of these exposures, and using a clever mathematical approach, these speckles can be reconstructed to form the true image of the source, removing the effect of turbulence.

'Alopeke and Zorro (Hawaiian and Spanish for "fox") are identical fast, low-noise, dual-channel, and dual-plate-scale imagers based on the Differential Speckle Survey Instrument (DSSI, Horch et al. 2009). Both instruments are permanently mounted at Gemini North and Gemini South. In speckle mode they provide simultaneous two-color diffraction-limited optical imaging (FWHM$\sim 0.02''$ at 650nm) of targets as faint as $V \sim 17$ over a 6.7" field of view. Wide-field mode provides simultaneous two-color imaging in standard *ugriz* SDSS filters over a 60" field of view.

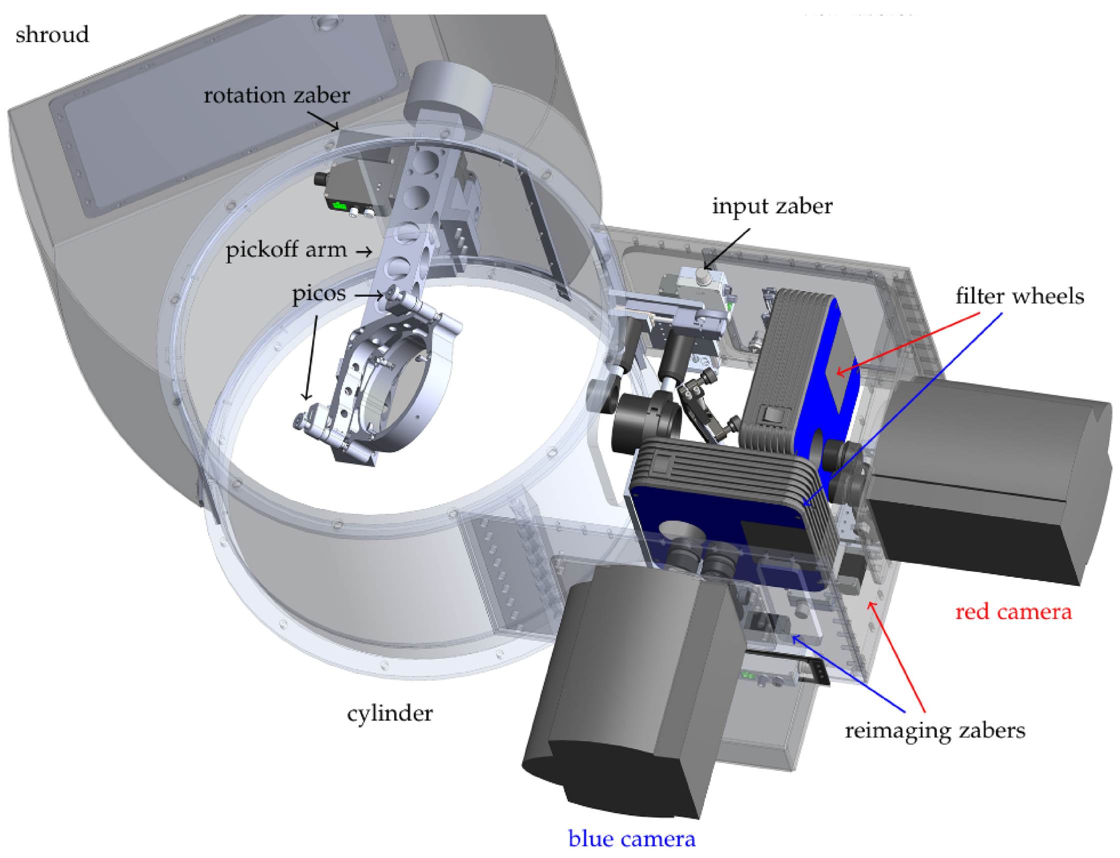

Figure 1: A schematic view of Zorro and 'Alopeke. The light coming from the tertiary mirror is captured by a retractable flat mirror into the instrument. Inside the instrument, a dichroic separates the light at 674 nm, into the blue and red cameras equipped with Andor EMCCDs. Adapted from Scott et al. (2021).

Zorro/'Alopeke observations of RRL

Speckle observations of 70 RRL were conducted with Zorro and 'Alopeke (Gemini programs: GS-2019A-SV-401, GN-2020B-FT-115, GN-2020B-LP-105, GS-2021A-Q-220, GN-2021B-Q-309, GS-2021B-Q-315), selected from the solar neighborhood sample of Prudil et al. (2019). Every RRL was observed with the same exposure time of $8 \times 1000 \times 60$ ms with medium band filters centered at 562nm and 832nm. The exposure time was set with the goal of obtaining a Δ mag of 7, which would imply detection of main sequence stars down to a mass of $\sim 0.4 M_{\odot}$. Observations were conducted near the RRLs minimum light in order to push down the contrast with any putative companions.

Following Howell et al. (2011), we combined all images subjected to Fourier analysis to produce the speckle re-constructed imagery from which the 5-σ contrast curves are derived in each passband.

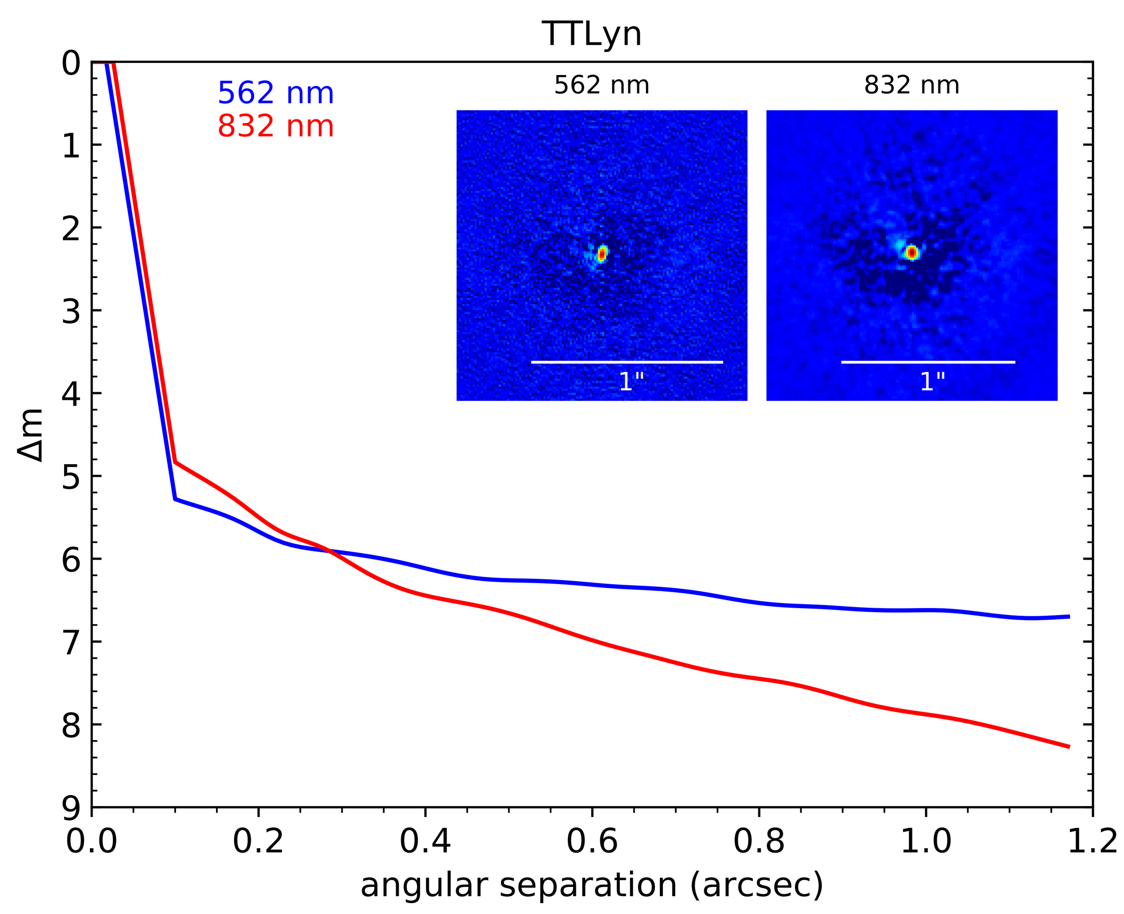

Figure 2: The summary of the 'Alopeke observation results for one of our targets, TT Lyn. The blue and red lines show the obtained 5-σ contrast for the simultaneous observations at 562 and 832nm, reaching Δm=6.11, 6.44 at 0.4" and Δm =6.62, 7.87 at 1". No companions are detected within these constraints.

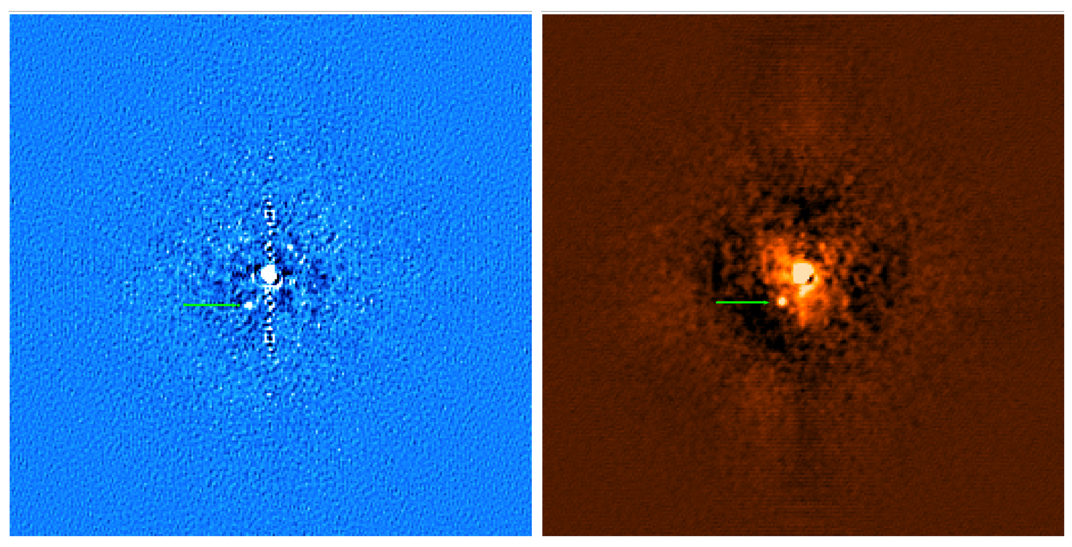

Figure 3: Reconstructed images of 'Alopeke observations of RRL RR Gem at 562nm (left) and 832nm (right). A companion is found at 172 mas from RR Gem at position angle of 145 degrees (indicated witha green arrow in both panels). The delta magnitude is 4.91 at 562nm and 4.67 at 832nm, pointing to a main sequence companion. The fact that the companion is detected with both cameras confirms that this is not speckle noise or other artifact. The field of view in both images is 2.5 arcsec a side.

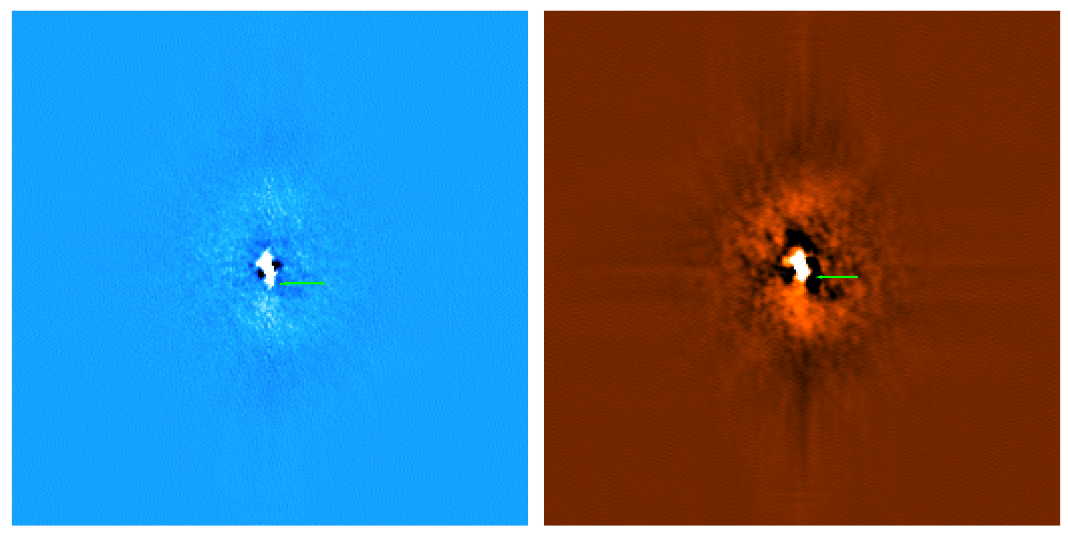

Figure 4: Reconstructed images of 'Alopeke observations of RRL BH Peg at 562nm (left) and 832nm (right). The companion is nearly blended, so appears unclear in the reconstructed image, but is detected consistently in both cameras at only 38 mas. The magnitude differences point to a RGB companion.

Finding the elusive RRL companions

Our search has revealed that 10 out of the 70 observed RRL have companions. The following table shows basic information for these findings:

Target RRL	Distance (mas)	Distance (AU)	PA (degrees)	Δm_{512}	Δm_{832}
TT Cnc	35	44	19.5	2.20	2.35
RR Gem	172	209	145	4.91	4.67
BH Peg	39	33	196	2.79	1.96
AT And	222	191	75	2.50	2.37
WZ Hya	51	50	136	–	3.41
IK Hya	22	18	100	1.73	1.92
AT Vir	32	42	220	–	1.31
V0445 Oph	35	22	221	0.45	1.23
DN Aqr	32	43	335	–	1.77
IU Car	31	54	330	–	1.93

Table 1: Column 1 is the target name. Column 2 shows the separation between RRL and companion in millliarcseconds . Column 3 shows the separation between the RRL and its companion, but this time in AU, based on Gaia EDR3 distances. Column 4 is the average position angle (between both cameras) of the companion. Columns 5 and 6 show the magnitude difference between the RRL and its detected companion for both cameras. Note that for a few targets there was a only a red detection.

Conclusions and outlook

- We have performed a speckle search with both Gemini telescopes aiming at discovering companions on a sample of 70 RRL in the solar neighborhood.
- We have detected evidence of companions on 10 out of the 70 observed RRL. This 14% is consistent with the binary fraction found by Hajdu et al. (2015) on their exploration of OGLE data towards the Galactic bulge, although all of them have separation distances of less than 5 AU. Also, none of our detections are either found by *Gaia* DR3, meaning that speckle searches are complementary to both LTTE and *Gaia*.
- Photometric calibration of our 562 and 832 contrast curves will provide mass constraints for companions in all the systems.
- Future high S/N, high-resolution spectroscopy of the RRL candidates will provide velocity difference between the primary and secondary, that in tandem with the speckle results will provide constraints on the RRL *masses*, predicted by stellar evolution, but never actually measured.

References

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