

Hunting for binary Cepheids using lucky imaging technique

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Detecting companions to Cepheids is difficult. In most cases the bright pulsator overshines the fainter secondary. Since Cepheids play a key role in determining the cosmic distance scale it is crucial to find binaries among the calibrating stars of the period-luminosity relation. Here we present an ongoing observing project of searching for faint and close companions of Galactic Cepheids using lucky imaging technique.

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1 Introduction

Cepheids are radially pulsating supergiant variable stars. They are located in the instability strip on the Hertzsprung-Russell diagram. According to stellar evolution theories stars between 4 and 20 solar masses cross this region during the He-burning phase in the core. More than 50% of the Galactic Cepheids are members in binary or multiple systems (Szabados 2003). The fainter the target, the more difficult to detect its even fainter companion(s). This is clearly seen in the form of an observational selection effect in Fig. 1.

Undetected companions can significantly modify the relations based on Cepheids. One of the most important is the well known period-luminosity-color (P-L-C) relationship. The binaries contribute to the dispersion of the relation via the increase of the apparent brightness and the change of the observed color. Therefore, the accuracy of distance determination is not at the point yet we want to achieve. To improve the accuracy of the extragalactic distance scale we have to omit these binaries from the calibrating sample. For an overview of the importance of binary Cepheids see Szabados & Klagyivik (2012).

From another point of view binary Cepheids play a very important role. Cepheids in eclipsing binary systems are key objects for the determination of stellar masses and for the solution of the long-standing problem of Cepheid mass discrepancy (Christy 1968; Stobie 1969). This discrepancy was mainly resolved with new opacity tables (Moskalik et al. 1992), but there is still a $17 \pm 5\%$ difference between the masses determined from the evolutionary models and the pulsation models (Keller 2008). The list of Cepheids belonging to eclipsing binaries in the Magellanic Clouds can be found in Szabados & Nehéz (2012). In our

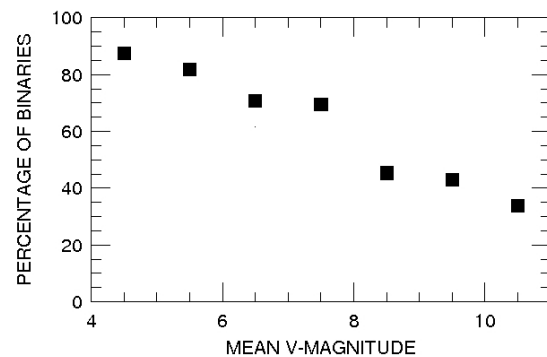


Fig. 1 Observed frequency of binaries among Galactic Cepheids as a function of the mean apparent brightness (Szabados et al. 2011). The trend seen in the diagram is the result of the observational selection effect.

Galaxy there is only one known eclipsing binary containing a Cepheid component (Sipahi et al. 2013).

There are many different ways to detect companions around Cepheids. Here we present a survey of searching for close visual companions of Galactic classical Cepheids using lucky imaging technique.

In Section 2 we overview the binary Cepheid searching methods, in Sect. 3 we describe shortly the lucky imaging technique, in Sect. 4 we present the details of our observing project. In the last part we present the first results and we look into the practicalities of this survey.

2 Binary Cepheid searching methods

The most effective way of binary detection is the spectroscopic investigation. Since the pulsation and the orbital periods are independent from each other the variability due to the two phenomena can be properly separated.

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Binary detection using photometric methods are based on the fact that if the companion has a different surface temperature than the Cepheid, then the impact depends on the wavelength of the observation. Klagyivik & Szabados (2009) developed various methods to detect binary Cepheids based on the peak-to-peak amplitudes observed in different photometric bands. These methods are less effective than the radial velocity observations but they can be used for faint stars as well. If we are not able to correct for the photometric contribution of the companion owing to the lack of brightness and color information we have to exclude these Cepheids from the calibrations.

In the case of Cepheids bright outliers of the PL-relation can be unrecognised binaries or blends (Fig. 6 in Soszyński et al. 2008).

Thanks to the Gaia astrometric satellite (to be launched in October 2013) many stars will be marked expectedly as astrometric binaries during the next decade. The accuracy of the positions of Hipparcos (10^{-3} arcsec) was not able to resolve the orbits of binary Cepheids, but the precision of Gaia (10^{-6} arcsec) will be sufficient in many cases to reach this goal. Unresolved binaries however falsify the calculated parallaxes as it was demonstrated by Szabados et al. (2011). All the negative parallax values of Hipparcos for Cepheids within 2 kpc belong to known binary Cepheids.

Finding unknown visual (either optical or physical) binaries a very good spatial resolution is needed. In some cases this is the only way to discover the secondary source. High spatial resolution optical imaging can be achieved in many ways. The main problem is the turbulent behaviour of the terrestrial atmosphere. Space telescopes are beyond this problem, the spatial resolution depends only on the size of the mirror and the observing wavelength. Adaptive optics are excellent tools to eliminate this adverse atmospheric effect, but these instruments are too expensive for smaller observatories. Lucky imaging is a good opportunity to reach nearly diffraction limited spatial resolution even from observing sites with average seeing.

Analysing $O - C$ diagrams, or radial velocity curves are also viable methods to detect unknown companions. But these techniques need gravitationally bound binary system and either short orbital period or long term observations (e.g. Szabados et al. 2012).

Interferometry is also a plausible solution, it has better spatial resolution than the lucky imaging technique, but it can be applied in the case of the brightest targets.

3 Lucky imaging

Long exposure time observations from the ground are always affected by the atmospheric blurring. Therefore the real spatial resolution is far from the diffraction limited one. Exposing thousands of images with very short exposure times there will be some 'lucky' frames on which the random fluctuations of the atmospheric turbulence are smaller and the image seems stable in the small field of view of the

camera. The fraction of such frames depends on both the aperture of the telescope and the seeing. Tip-tilt correcting and adding the sharpest images much better spatial resolution can be achieved than by using long exposure times. In ideal cases the improvement of the image quality can reach a factor of ~ 4 (Smith et al. 2009). The resulting point spread function is a diffuse halo around the stars with a distinct, sharp core.

This technique, nowadays widely used by amateur astronomers observing planets, is now used by professional astronomers, too. For example in exoplanetary researches it is a very interesting question how a companion star affects the planet formation. Searching for close and faint companions can help to answer this question (Ginski et al. 2012, Bergfors et al. 2012).

The lucky imaging technique requires a usable fraction ($\sim 1-20\%$) of undistorted images. Above 2.5 m in diameter this fraction is effectively zero due to the size of the turbulent cells of the atmosphere. More details of the technique can be found in Law et al. (2006).

Modern EMCCD (electron multiplying CCD) cameras are excellent instruments for this technique (e.g. Smith et al. 2004). This technology allows very short readout of CCDs with almost negligible noise.

4 The observing project

Although binary Cepheids are key objects in the calibration of the cosmic distance scale we have insufficient information about the companions of Cepheid type stars. In many cases we know only the existence of the companion without additional information about its physical properties (luminosity, temperature, etc.).

We launched an observing project at the Konkoly Observatory searching for faint companions close to Galactic Cepheids brighter than 13th mag in I_C band using lucky imaging technique. Our goal is to determine the fraction of visual binaries among Cepheids and to measure the brightness and colors of the companions.

4.1 Observations

The observations are obtained at the Piskéstető Mountain Station of the Konkoly Observatory using the 50 cm Cassegrain telescope. The observatory is located 100 km far from Budapest to the northeast. The seeing at an average night is $3-4''$, but at an excellent night it is near $1''$.

The lucky imaging camera is an Andor iXon + 888 back-illuminated EMCCD camera. This camera has 1024×1024 active pixels with $13 \times 13 \mu\text{m}$ pixel size. These parameters result in a 6.88×6.88 arcmin field of view and a $0.40''/\text{px}$ pixel scale. The maximum readout rate is 10 MHz, while the frame rate is 8.9 frame per second at full frame without binning. The peak quantum efficiency is 92.5% at 575 nm. The EM gain multiplication can be varied linearly

between 1 and 1000. Using this EM gain multiplication the readout noise is less than $1e^-$.

During the observations we used the camera in 14 bit mode with 10 MHz horizontal readout speed. The EM gain varied between 100 and 300. The exposure times were between 10-40 ms. For each star we obtained 15000 - 30000 exposures mostly in the I_C band.

The diffraction limit of the telescope is $0.40''$ in I_C band, $0.33''$ in R_C and $0.27''$ in V band, but at shorter wavelength the seeing is much worse. So in V and R_C bands the pixel scale of the camera is larger than the diffraction limit. Therefore if we want to reach nearly diffraction limited spatial resolution the I_C band is the appropriate filter for lucky imaging observations. Comparing the results we sometimes observed in other filters, too.

We plan to use the 1m RCC telescope also located at the Piskésetető Mountain Station. Suspected binaries are planned to be confirmed with an even larger telescope.

5 First results

So far we have observed 76 northern Galactic Cepheids of our 120 program stars. For this technique the best targets are near the zenith. The zenith distance of our program stars at culmination should not exceed 30° , which corresponds to a declination range of $18^\circ < \delta < 78^\circ$. The brightness of the targets is between 7th and 13th mag in I band. The data reduction pipeline is in the test phase.

5.1 CE Cas

CE Cas is a unique object in our target list. It is located in the NGC 7790 open cluster. Both components of this binary system are Cepheids. The pulsation periods of the components are 5.141 (CE Cas A) and 4.479 days (CE Cas B). The apparent mean visual magnitudes of the components are 10.90 and 11.02 mag, respectively in V band. The separation is $2.5''$, so on the nights of good seeing they can be separated even in long exposure time images.

On 4 October 2011 we obtained 15000 images in V , R_C and I_C bands with 30 ms, 30 ms and 40 ms exposure times, respectively. The seeing was $3''$. After the standard image reduction steps – bias, dark and flat corrections – we selected differential number of images, shifted them to each other and added. Each pixel was upsampled to 4×4 pixels. The result is shown on the right side of Fig. 2. In the top left panel we just summarized all the images only with tip-tilt correction and without any selection. In the top right panel we selected the best 750 (5%) of the frames. In the bottom panels we added 300 (2%) images, but on the right side the best images were taken, while putting in context in the left side we selected the frames randomly. The pictures clearly show that the selection is working efficiently. Random selection results in the same image as no selection (left panels). There is only marginal difference between the 5% and

the 2% selection. But using the best 10% the result is significantly worse.

Table 1 Average FWHM values in the field of CE Cas in V , R_C and I_C bands after tip-tilt correction with and without lucky imaging. The improvement ratios were calculated as the ratio of the FWHM without and with lucky imaging. During the lucky imaging the best 300 frames were selected.

Band	FWHM ($''$)		improvement ratio
	no lucky	with lucky	
V	1.32	1.14	1.16
R_C	1.54	1.15	1.34
I_C	1.68	1.11	1.51

The spatial resolution increased by a factor of 1.5 in I_C band (Table 1 and Table 2), while the brightness of the central peak of the stars is doubled. The data reduction pipeline is under development, so there is still potential to improve the spatial resolution. The pipeline will be published soon (Regály, in prep.).

We found no more optical stellar companion in the system of CE Cas.

Since the observations and data reductions are ongoing, calculation of limits of separation and magnitude difference for the detectability of companions is left for the future.

Table 2 Tip-tilt corrected FWHM values in I_C band for different number of selected images.

%	FWHM ($''$)
100%	1.68
10%	1.53
5%	1.17
2%	1.11

6 Conclusion

Lucky imaging is a powerful tool detecting faint and/or close companions around bright stars which are not detectable with other techniques. The period-luminosity relation of Cepheids is one of the most important relations in the field of the cosmic distance scale, but binaries disturb the calibration. It is indispensable to exclude these systems even if the companion is faint.

The first results with the 50 cm Cassegrain telescope at Piskésetető Mountain Station and the EMCCD camera are promising. On an average night with $3''$ seeing we reached almost three times better spatial resolution than using long exposure time images. On much better nights we should reach nearly the diffraction limited resolution.

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Fig. 2 Comparison of CE Cas with (right) and without (left) lucky imaging technique. Top left panel: sum of all the images only with tip-tilt correction, bottom left panel: sum of 300 randomly selected images, top right panel: sum of the best 750 (5%) frames, bottom right panel: sum of the best 300 (2%) images.

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