On the binarity of the classical Cepheid X Sgr from interferometric observations*  
(Research Note)

G. Li Causi1,2, S. Antoniucci1, G. Bono3, S. Pedicelli1, D. Lorenzetti1, T. Giannini1, B. Nisini1

1 INAF-Osservatorio Astronomico di Roma, Via Frascati 33, I-00040 Monteporzio Catone (RM) - Italia
2 INAF-Istituto di Astrofisica e Planetologia Spaziale, Via Fosso del Cavaliere 100, Roma - Italia
3 Università degli Studi di Roma 'tor Vergata’, via della Ricerca Scientifica 1, I-00133 Roma - Italia

ABSTRACT

Context. Optical-infrared interferometry can provide direct geometrical measurements of the radii of Cepheids and/or reveal unknown binary companions of these stars. Such information is of great importance for a proper calibration of Period-Luminosity relations and for determining binary fraction among Cepheids.

Aims. We observed the Cepheid X Sgr with VLTI/AMBER in order to confirm or disprove the presence of the hypothesized binary companion and to directly measure the mean stellar radius, possibly detecting its variation along the pulsation cycle.

Methods. From AMBER observations in MR mode we performed a binary model fitting on the closure phase and a limb-darkened model fitting on the visibility.

Results. Our analysis indicates the presence of a point-like companion at a separation of 10.7 mas and 5.6 mag fainter than the primary, whose flux and position are sharply constrained by the data. The radius pulsation is not detected, whereas the average limb-darkened diameter results to be 1.48±0.08 mas, corresponding to 53±3 R⊙, at a distance of 333.3 pc.

Key words. Stars: variables: Cepheids – Binaries: close – Techniques: interferometric – Instrumentation: interferometers – Infrared: stars

1. Introduction

Classical Cepheids are fundamental astrophysical objects, being the most popular primary distance indicators in the nearby Universe. These pulsating stars obey well defined Period-Luminosity (PL) relations, so that it is possible to derive their distance moduli by measuring periods and apparent magnitudes.

Cepheids can be used to trace the evolutionary properties of Helium burning intermediate-mass stars, as they are crossing the instability strip along the so-called “blue loops” in the HR diagram. However, the comparison between pulsation and evolutionary masses disclosed the problem known as “Cepheid mass discrepancy” (Cox 1980), due to the pulsation masses resulting systematically smaller than the evolutionary ones (see e.g. Bono et al. (2001); Beaulieu et al. (2001); Caputo et al. (2005); Keller & Wood (2006)).

Recently two double eclipse binary Cepheids have been identified in the Large Magellanic Cloud (Pietrzyński et al. (2011), Pietrzyński et al. (2011)), providing the first measurements of the dynamical mass of classical Cepheids with 1-3% accuracy, whose values support the pulsation masses, or the Mass-Luminosity relations based on evolutionary models that account for mild convective core overshooting (Cassisi & Salaris (2011); Prada Moroni et al. (2012)).

For non-eclipsing binaries, direct orbital determination of the companion by means of optical interferometry would provide dynamical mass determinations able to disentangle the mass discrepancy problem.

The binary fraction of the Cepheids has an impact on the Cepheid distance scale in the optical bands, since the companions are typically main sequence (MS) stars. The binarity analysis has been applied to a limited sample (Szabados (2003), but current estimates indicate that the binary fraction among MS B-type stars is of the order of 60–70% (Brott et al. (2011); Chini et al. (2012)).

In order to improve the current observational scenario we have observed the Cepheid X Sgr with the VLTI. This particular target was selected because: i) its trigonometric parallax has been recently measured by Benedict et al. (2007); ii) accurate radial velocity curves are available (Mathias et al. (2006); Storm et al. (2011)), and iii) it was suggested by Szabados (1990), on the basis of temporal changes in the γ-velocity, that X Sgr might be a binary, although this finding has always been controversial (Mathias et al. (2006); Groenewegen (2008)).

2. Observations and data reduction

2.1. Data acquisition

We observed X Sgr (HD161592, R.A. 17:47:33.62, Dec. -27:49:50.83, J2000) using VLTI/AMBER (Petrov et al. (2007) with the Auxiliary Telescopes. We used medium spectral resolution in the K-band (MR, R~1500, 2.1µm) and the fringe tracker FINITO (Gai et al. (2004)) with a frame exposure time of 1 s. Observations were carried out with a maximum projected base-
Table 1. Log of the interferometric observations, with details on the SCience-CALibrators sequence used and the optimal frame selection adopted for $V^2$ and $\phi$. Magnitude and diameters of the two calibrators employed are shown.

| Date         | Target sequence | Baselines | % of frames for $V^2$ | % of frames for $\phi$ |
|--------------|-----------------|-----------|-----------------------|------------------------|
| 2011-04-24   | CAL$_2$-SCI-CAL$_2$-SCI-CAL$_1$ | D0-I-G1 | 10% | 100% |
| 2011-05-05   | CAL$_2$-SCI-CAL$_1$-SCI-CAL$_2$-SCI-CAL$_1$ | D0-A1-C1 | 30% | 100% |
| 2011-05-07   | CAL$_2$-SCI-CAL$_1$-SCI-CAL$_1$ | D0-A1-C1 | 10% | 100% |
| 2011-06-11   | CAL$_1$-SCI-CAL$_1$ | K0-A1-H1 | 50% | 100% |
| 2011-06-25   | CAL$_1$-SCI-CAL$_1$ | K0-A1-H1 | 20% | 100% |
| 2012-03-31   | CAL$_1$-SCI-CAL$_1$-SCI-CAL$_1$ | K0-A1-G1 | 20% | 100% |

| ID | Name       | $V$ | $\phi$ |
|----|------------|-----|--------|
| CAL$_1$ | HIP88339 | 2.070 | 1.881 ± 0.133 |
| CAL$_2$ | HD157919 | 3.203 | 0.947 ± 0.066 |

$^a$ Data from JMMC Stellar Diameters Catalogue - JSDC (Lafrasse et al. 2010)

Both plots, in particular the $V^2$, show that the error bars are clearly larger than the dispersion of the data points, indicating a correlated noise caused by the low-frequency variations (on time-scales of minutes) of the TF during the night.

3.2. Model fitting

3.2.1. Binary companion

Szabados (1990) suggested, on the basis of changes in the $\gamma$-velocity, that X Sgr might be a binary system with a period of ~507 days. The complex nature of X Sgr was further supported by Sasselov & Lester (1991) who spectrally found that line asymmetries and line-doubling were well beyond the typical Cepheids behaviour; in particular, the two absorption components showed different Doppler shifts, but they did not display secular velocity changes compared with the $\gamma$-velocity. This complex dynamical structure was also supported by other high-resolution ($R=120,000$) optical spectra by Mathias et al. (2006). They hypothesized a binary, or even triple, nature of X Sgr. The data available in the literature were analyzed by Feast et al. (2008) and by Groenewegen (2008) who also found evidence of binarity, these latter suggesting a slightly longer orbital period (~570 days).

In order to check the companion hypothesis, we performed a binary model fit to the closure phase $\phi$. We decided to use only this observable, for its low sensitivity on the unknown radius variation, for which we adopted a crude UD estimate of $r_{UD} = 0.74$ mas, provided by the $V^2$ values at the largest baselines, namely the data from nights 2011-04-24, 2011-05-03 and 2012-03-31.

We started with Run A alone assuming no temporal variation in the binary configuration within the two months, which is a plausible assumption, considering the mentioned orbital period estimates. Therefore we fit the Run A data all together in order to increase accuracy. Run B was not included here, since it was acquired 10 months later.

We adopted a grid search on a wide parameter space in $\Delta \lambda, \Delta \phi, f$ and $r_2$, where $\Delta \lambda, \Delta \phi$ are the R.A. and Dec. offsets of the companion (these are searched within a radius of 100 mas around the primary, see Absil et al. 2011), $f$ is the flux ratio of the companion to the primary, and $r_2$ is the companion UD radius.

We obtain the best fit result for a flux ratio of $f = (6 \pm 1) \times 10^{-3}$ (corresponding to a $5.6 \pm 0.2$ magnitude difference), while $r_2$ tends to zero, thus confirming the presence of a faint and un-

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1 Available at [http://www.jmmc.fr/amberdrs](http://www.jmmc.fr/amberdrs)
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Fig. 1. Left: calibrated $V^2$ versus spatial frequency $B/\lambda$ for the entire set of observations, superimposed to the average UD model (continuous line). Right: spatial frequencies ($u,v$-plane) coverage. Different colors and symbols refer to different observing nights (see legends). Note: the 2011-06-25 night is not plotted in the left panel, due to a very unstable TF for $V^2$.

Fig. 2. Calibrated $\phi$ versus $\lambda$ for the entire set of observations. Colors and symbols are the same as in Fig. 1. The yellow line shows the binary model described in Sec. 3.2 providing the best fit to the Run A observations. The dates reported above the panels refer to the observing nights.

A resolved companion, whose position is constrained by a single and well defined $\chi^2$ minimum at 7.15±0.04 S, 8.00±0.02 E mas from the primary (see Fig 3). The parameters of the companion are summarized in Table 2.

The fact that the best fit reduced $\chi^2$ is significantly smaller than one is due to the large error bars associated to the TF, already described in Sec. 3.1.

To double check our finding, we built a series of synthetic binary models with different flux ratios and the same error bars of the real data, from which we derived a sensitivity limit of $f_{lim} = 2 \cdot 10^{-3}$, i.e. 3 times lower than the measured flux ratio.

To refine this result we removed our assumption of fixed binary configuration, in order to check if we could detect possible displacements among different nights.

Therefore, we repeated the $\phi$ fitting separately for each night of Run A, to find out if the location of the $\chi^2$ minimum moves as a function of time (nights 2011-05-03/2011-05-07 and 2011-06-11/2011-06-25 were fitted as single points).

The corresponding $\chi^2$ maps (Fig. 3 panel A) show several local minima within the 99% confidence interval, all of them having the same probability to be the true position of the companion. This shows us that a single baseline configuration is not sufficient to unambiguously locate such a faint object.

However, each $\chi^2$ map shows a particular local minimum in the same position found using the entire data set, and even more importantly the little displacements of these minima are in the correct temporal sequence, as disclosed by Fig. 3 panel B.

This empirical evidence further confirms our detection of the postulated companion of X Sgr, and although current data do not allow us to constrain the orbit, we have a hint on the direction of its motion.

The binary fit for the single night of Run B also show the same kind of multiple minima $\chi^2$ map (not displayed), but with no minima close to the quoted position, as expected after a time interval of ten months.

3.3. Angular diameter

To determine the mean Cepheid diameter, and possibly its variation, we fit the $V^2$ separately for each night by fixing the binary parameters (Table 2) and varying only the primary radius $r_1$. Following Kervella et al. (2004), we adopted the Limb Darkening (LD) intensity profile by Claret (2000).

The radius $r_1$ only depends on the mean value of each visibility spectrum ($< V^2(\lambda) >$), whose error bar we computed as the
quadratic sum of the weighted average error plus the correlated component due to the TF variation.

For the diameter determination we only took into account the nights 2011-04-24, 2011-05-03 and 2012-03-31, which have sufficiently long baselines and good quality. The night of 2011-05-03 plays a key role in this context, since it shows a pure random error with a negligible correlated component.

Therefore we only computed a mean physical radius of $53 \pm 3 \, R_\odot$ by adopting the trigonometric parallax of $3.0 \pm 0.18$ mas from the HST (Benedict et al. 2007). In Table 3 we compared it with recent estimates from both optical interferometry (Kervella et al. 2004) and Infra Red Surface Brightness (IRSB, Groenewegen et al. 2011), having used the same distance for all of these measurements. Finally, we also report the radius obtained by neglecting the binary companion, which has a $\sim 3\%$ impact on the mean radius.

### 4. Conclusions

We found evidence of the binary nature of the Cepheid X Sgr by analysing new interferometric data collected with AMBER at VLTI. The main conclusions of our work can be summarized as follows:

i) Our analysis of the closure phase indicates that both the flux and the position of the companion can be constrained by our data sets. We find that the angular separation is $10.7 \, \text{mas}$ and that the companion is $5.6 \, \text{mag}$ fainter than the primary in the $K$-band.

ii) The data allow us to directly measure an average Limb-Darkening diameter of $1.48 \pm 0.08 \, \text{mas}$ (i.e. a physical radius of $53 \pm 3 \, R_\odot$) which agrees, at $1\sigma$ level, with similar interferometric and IRSB mean radii for X Sgr available in the literature.

iii) We find that MR AMBER closure phases obtained from 3 baseline configurations have the sensitivity needed to detect companions around nearby classical Cepheids. This evidence thus only computed a mean physical radius of $53 \pm 3 \, R_\odot$ by adopting the trigonometric parallax of $3.0 \pm 0.18$ mas from the HST (Benedict et al. 2007). In Table 3 we compared it with recent estimates from both optical interferometry (Kervella et al. 2004) and Infra Red Surface Brightness (IRSB, Groenewegen et al. 2011), having used the same distance for all of these measurements. Finally, we also report the radius obtained by neglecting the binary companion, which has a $\sim 3\%$ impact on the mean radius.

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becomes even more compelling if we take into account that current data were collected in medium quality seeing conditions.

iv) The average visibilities of the 2001-05-03 night show that a non systematic error as small as 1% can be obtained with AMBER in MR mode in stable TF conditions. This would be sufficient to clearly trace the differential diameter pulsation in future measurements, provided that the same calibrator star is used for all the observations.

v) We find that, in the case of a binary Cepheid, the effect introduced by the companion on the primary radius measurement (\(\sim 3\%\)) is comparable with the expected radius variation (\(\sim 5 \div 10\%\)).

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