LETTER TO THE EDITOR

Multiplicity of Galactic Cepheids from long-baseline interferometry

II. The Companion of AX Circini revealed with VLTI/PIONIER*

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ABSTRACT

Aims. We aim at detecting and characterizing the main-sequence companion of the Cepheid AX Cir (Porb ∼ 18 yrs). The long-term objective is to estimate the mass of both components and the distance to the system.

Methods. We used the PIONIER combiner at the VLTI Interferometer to obtain the first interferometric measurements of the short-period Cepheid AX Cir and its orbiting component.

Results. The companion is resolved by PIONIER at a projected separation ρ = 29.2 ± 0.2 mas and projection angle PA = 167.6 ± 0.3°. We measured H-band flux ratios between the companion and the Cepheid of 0.90 ± 0.10% and 0.75 ± 0.17%, at pulsation phases for the Cepheid of φ = 0.24 and 0.48, respectively. The lower contrast at φ = 0.48 is due to the increased brightness of the Cepheid compared to φ = 0.24. This gives an average apparent magnitude mH(comp) = 9.06 ± 0.24 mag. The limb-darkened angular diameter of the Cepheid at the two pulsation phases was measured to be δD = 0.839 ± 0.023 mas and δD = 0.742 ± 0.020 mas, at φ = 0.24 and 0.48, respectively. A lower limit on the total mass of the system was also derived based on our measured separation, and we found Mt ≥ 9.7 ± 0.6Msun.

Key words. techniques: interferometric – techniques: high angular resolution – stars: variables: Cepheids – star: binaries: close

1. Introduction

Cepheids are powerful astrophysical laboratories that provide fundamental clues for studying the pulsation and evolution of intermediate-mass stars. However, the discrepancy between masses predicted by stellar evolutionary and pulsation models is still not understood well. The most cited scenarios to explain this discrepancy are a mass-loss process during the Cepheid’s evolution and/or a core overshooting during the main-sequence stage (Neilson et al. 2011; Keller 2008; Bono et al. 2006). Therefore, accurate masses of a few percent are needed to help constrain the two models.

In this second paper, we report the detection of the orbiting companion around the Cepheid AX Cir (HD 130701, HR 5527). This pulsating star has a spectroscopic companion, first suspected from composite spectra by Jaschek & Jaschek (1960), and later confirmed by Lloyd Evans (1982). A preliminary orbital period of about 4600 days was then estimated by Szabados (1989). Bohm-Vitense & Profitt (1985) and Evans (1994) also detected the companion from International Ultraviolet Ex.
porer (IUE) low-resolution spectra, and set its spectral type to be a B6V star. The first orbital solution was provided by Pettersson et al. (2004) from precise and homogeneous high-resolution spectroscopic measurements; however, it does not include the semi-major axis, the inclination angle, and the longitude of the ascending node, which can only be provided from astrometry. We list some parameters of the AX Ciri system in Table 1.

We present here the first spatially resolved detection of this companion from VLTI/PIONIER observations. We first describe in Sect. 2 the beam combiner, the observations, and the raw data calibration. In Sect. 3 we explain the data analysis and present our results. We then discuss our measured flux ratio and projected separation, and conclude in Sect. 5.

2. Observations and data reduction

We used the Very Large Telescope Interferometer (VLI; Haguenauer et al. 2010) with the four-telescope combiner PIONIER (Le Bouquin et al. 2011) to measure squared visibilities and closure phases of the AX Ciri binary system. PIONIER combines the light coming from four telescopes in the H band, either in a broad band mode or with a low spectral resolution, where the light is dispersed into three or seven spectral channels. The recombination provides simultaneously six visibilities and four closure phase signals per spectral channel.

The squared visibilities and closure phase signals were modeled assuming a uniform disk (UD) angular diameter for the Cepheid (the primary) plus a point source companion. The fitted parameters are the angular diameter of the Cepheid $\theta_{UD}$, the relative position of the component ($\Delta\alpha, \Delta\delta$), and the flux ratio $f = f_{com}/f_{cep}$. The coherence loss effect due to spectral smearing on the companion was also modeled using the function $\sin(x)/x$ at spectral resolution $R = 18$ and spatial frequencies $(u,v)$.

The choice of a UD diameter for the Cepheid instead of a limb-darkened (LD) disk for the fitting procedure is justified because the angular diameter is small compared to the angular resolution of the interferometer, and the limb darkening effects are therefore undetectable. The conversion from UD to LD angular diameter was done afterwards by using a linear-law parametrization $\theta_{LD}(u) = 1 - u_1/(1 - \mu)$, with the LD coefficient $u_1 = 0.2887$ (Claret & Bloemen 2011) for both epochs, and using the stellar parameters $T_{eff} = 5400$ K, log $g = 2.0$, [Fe/H] = 0.0, and $v_\lambda = 5$ km s$^{-1}$ (Usenko et al. 2011; Acharova et al. 2012). The conversion is then given by the approximate formula of Hanbury Brown et al. (1974):

$$\theta_{LD}(\lambda) = \theta_{UD}(\lambda) \sqrt{\frac{1 - \mu/3}{1 - 7\mu/15}}.$$

Changing $T_{eff}$ by ±400 K changes the diameter by less than 0.2%, well below our measured uncertainties.

For each epoch, the fitting procedure was done in two steps. We first proceeded to a 80x80 mas grid search in the $\chi^2$ space, with spacing of 0.2 mas, which aims at determining the approximate position of the companion and avoid local minima. Then a

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1 Available at http://www.jmmc.fr/searchcal.

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Fig. 1. $(u,v)$ plane coverage for all our observations of AX Ciri.

Fig. 2. Probability map for the companion position of July 14.
Table 1. Parameters of the Cepheid and its close companion.

|                | Primary (Cepheid) | Secondary |
|----------------|-------------------|-----------|
| \( \bar{m}_{V} \) | 5.89              | B6V       |
| \( \bar{m}_{K} \) | 3.76              | 6532      |
| \( \bar{m}_{H} \) | 3.85              | 2448      |
| Sp. Type       | F8II              | 500       |
| \( P_{\text{pul}} \) | 5.2733            | 0.19      |
| \( \bar{\theta}_{LD} \) | 0.76              | 6.05      |
| \( d' \)        | 500               | 4.03      |

Notes. \( \bar{m}_{V}, \bar{m}_{K}, \bar{m}_{H} \): mean apparent V, K and H magnitudes. Sp. Type: spectral type. \( P_{\text{pul}} \): period of pulsation. \( \bar{\theta}_{LD} \): mean angular diameter. \( d' \): distance. \( P_{\text{orb}} \): orbital period. \( T_{0} \): time passage through periastron. \( e \): eccentricity of the orbit. \( a_{1} \sin i \): projected semi-major axis of the orbit of the Cepheid about the center of mass of the system. \( \omega \): argument of periastron. \( f(M) \): spectroscopic mass function.

(a) from Klagyivik & Szabados (2009), (b) from the 2MASS catalog (Cutri et al. 2003), (c) from Samus et al. (2009), (d) from Gallenne et al. (2011, at \( \phi = 0.27 \)) (e) from the \( K \)-band P-L relation of Storm et al. (2011), (f) from Evans (2000) and Petterson et al. (2004).

Fig. 3. Closure phase signal of AX Cir for July 14, with respect to the modified Julian date. The spectral channels were averaged for clarity. The solid black line represents our best fit model.

Our model did not take a possible circumstellar envelope (CSE) emission into account, which could lead to an overestimate of the angular diameter. From the spectral energy distribution AX Cir given by Gallenne et al. (2011), the infrared excess caused by the CSE appears around 10 \( \mu \)m, while it is negligible at 1.6 \( \mu \)m (i.e., < 2 %, which would lead to visibility loss of the same amount at first order, and below our visibility accuracy).

The probability map for the observations of July 14 is shown in Fig. 2, and the fitted parameters for both epochs are reported in Table 3. The companion is clearly detected at the two epochs at coordinates \( \rho = 29.2 \pm 0.2 \) mas and \( PA = 167.6 \pm 0.3^\circ \). The model for the observations of July 14 is represented graphically in Fig 3. We estimated limb-darkened angular diameters \( \theta_{LD} = 0.742 \pm 0.020 \) mas and \( 0.839 \pm 0.023 \) mas, for July 11 and 14, respectively (at pulsation phases \( \phi = 0.48 \) and 0.24, respectively), in agreement with the angular diameter, 0.76 \pm 0.03 as estimated by Gallenne et al. (2011) at phase \( \phi = 0.27 \). It is also consistent with the average value of 0.84 mas estimated from the surface brightness relation of Kervella et al. (2004, using magnitudes from Table 1). However, no IR photometric measurements were available at the time of our interferometric observations, and we cannot compare our measured diameters to those derived from surface brightness relationships. Uncertainties were estimated using the subsample bootstrap technique with replacement and 10 000 subsamples. The medians of the probability distribution of the parameters match the best-fit values very well, and we used the maximum value between the 16 % and 84 % percentiles as uncertainty estimates (although the distributions were roughly symmetrical about the median values).

Table 3. Final best-fit parameters.

|            | 2013-07-11 | 2013-07-14 |
|------------|------------|------------|
| Single star model |            |            |
| \( \theta_{LD} \) (mas) | 0.770 \pm 0.016 | 0.931 \pm 0.019 |
| \( \theta_{UD} \) (mas) | 0.787 \pm 0.016 | 0.952 \pm 0.020 |
| \( \chi^2 \) | 1.45 | 1.09 |
| Binary model |            |            |
| \( \theta_{UD} \) (mas) | 0.726 \pm 0.020 | 0.821 \pm 0.022 |
| \( \theta_{LD} \) (mas) | 0.742 \pm 0.020 | 0.839 \pm 0.023 |
| \( f \) (%) | 0.75 \pm 0.17 | 0.90 \pm 0.10 |
| \( \Delta \alpha \) (mas) | 6.421 \pm 0.198 | 6.153 \pm 0.155 |
| \( \Delta \phi \) (mas) | -28.366 \pm 0.366 | -28.584 \pm 0.229 |
| \( \chi^2 \) | 1.17 | 0.72 |

Notes. \( \theta_{UD}, \theta_{LD} \): uniform and limb-darkened disk angular diameter, respectively. \( f, \Delta \alpha, \Delta \phi \): flux ratio and position of the companion. \( \chi^2 \): reduced \( \chi^2 \) of the corresponding best-fit model.
4. Discussion

The measured flux ratios are slightly different between the two epochs, although within the uncertainties. This is because the Cepheid is slightly brighter at phase $\phi = 0.48$ (July 11) than in $\phi = 0.24$, which makes the contrast a bit lower. Since we do not have $H$-band light curves to extract the Cepheid magnitude at a given phase, we took an average to estimate a mean contrast $f = 0.83 \pm 0.14 \%$. This gives a difference in apparent magnitude of $\Delta m_H = 5.20 \pm 0.18$ mag. This converts to apparent magnitudes for each component by using the 2MASS magnitude as a measure of the combined flux and the following equations:

$$m_1 = m_{12} + 2.5 \log(1 + f) \quad (1)$$

$$m_2 = m_{12} + 2.5 \log(1 + 1/f) \quad (2)$$

where $m_{12}$ is the 2MASS measurements, and $m_1$ and $m_2$ the apparent magnitude of the Cepheid and the component, respectively. We obtain $H_{\text{comp}} = 9.06 \pm 0.24$ mag and $H_{\text{cep}} = 3.86 \pm 0.24$ mag. The quoted errors are due to the uncertainties in 2MASS. We determined the reddened magnitude, $H_{\text{comp}} = 9.06 \pm 0.24$ mag and $H_{\text{cep}} = 3.72 \pm 0.24$ mag, by adopting the reddening law from Fouqué et al. (2007) with a total-to-selective absorption in the $V$ band of $R_V = 3.23$ (Sandage et al. 2004) and a color excess $E(B-V) = 0.262$ from Tammann et al. (2003). From the distance $d = 500 \pm 10$ pc given by the $K$-band period–luminosity relation (Storm et al. 2011, the quoted error is statistical), we obtain an absolute magnitude for the companion $M_V = 0.45 \pm 0.24$ mag. Combining the known spectral type B6V with a color–spectral type relation (Ducati et al. 2001), we obtain $M_V = -0.12 \pm 0.24$ mag.

From Kepler’s law and assuming our measured projected separation $\rho$ as a lower limit for the angular semi-major axis, that is $a \geq \rho$, a minimal total mass for the system can be derived:

$$M_T = M_1 + M_2 = \rho^3 \frac{d^3}{P^2},$$

with $\rho$ in arcsecond, $d$ in parsec, and $P$ in year. We therefore derived $M_T = 9.7 \pm 0.6 M_\odot$. This is compatible with the $5.1 M_\odot$ for the Cepheid, predicted from the pulsation mass (Caputo et al. 2005), and with the $5 M_\odot$ for the companion, inferred from its spectral type.

5. Conclusion

We used the high angular resolution provided by the four-telescope combiner PIONIER to detect the orbiting companion of the short-period cepheid AX Cnr. We employed a binary model with a primary represented by a uniform disk and the secondary as an unresolved source. We derived a limb-darkened angular diameter for the Cepheid at two pulsation phases, $\theta_{1D} = 0.839 \pm 0.023$ mas (at $\phi = 0.24$) and $\theta_{2D} = 0.742 \pm 0.020$ mas (at $\phi = 0.48$). We also measured an averaged $H$-band flux ratio between the companion and the Cepheid, $f = 0.83 \pm 0.14 \%$, and the astrometric position of the secondary relative to the primary, $\rho = 29.2 \pm 0.2$ mas and $PA = 167.8 \pm 0.3^\circ$. We also set a lower limit on the total mass of the system based on our measured projected separation. Finally, we point out the need of accurate infrared light curves to enable a more precise flux estimate of the companion from the contrast measured from interferometry.

This second detection (after that of V1334 Cyg, Paper I) demonstrates the capabilities of long-baseline interferometers for studying the close-orbit companions of Cepheids. Further interferometric observations will be obtained in the future to cover the orbit, and then combined with radial velocity measurements to derive all orbital elements. For now, only single-line spectroscopic measurements are available, we are also involved in a long-term spectroscopic program to detect the radial velocity of the companion. This will provide an orbital parallax and model-free masses.

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References

Acharova, I. A., Mishurov, Y. N., & Kotvukh, Y. V. 2012, MNRAS, 420, 1590
Böhm-Vitense, E. & Profitt, C. 1985, ApJ, 296, 175
Bonneau, D., Clauss, J.-M., Delfosse, X., et al. 2006, A&A, 456, 789
Bonatto, D., Delfosse, X., Mourard, D., et al. 2011, A&A, 535, A53
Bono, G., Caputo, F. & Castellani, V. 2006, Mem. Soc. Astron. Italia. 27, 207
Caputo, F., Bono, G., Fiorentino, G., Marconi, M., & Musella, I. 2005, ApJ, 629, 1021
Claret, A. & Bloemen, S. 2011, A&A, 529, A75
Cutri, R. M., Skrutskie, M. F., van Dyk, S., et al. 2003, VizieR Online Data Catalog, 2246, 0
Ducati, J. R., Bevilacqua, C. M., Rembold, S. B., & Ribeiro, D. 2001, ApJ, 558, 309
Evans, N. R. 1994, ApJ, 436, 273
Evans, N. R. 2000, AJ, 119, 3050
Evans, N. R., Schaefer, G. H., Bond, H. E., et al. 2008, AJ, 136, 1137
Fouqué, P., Arriagada, P., Storm, J., et al. 2007, A&A, 476, 73
Gallenne, A., Kervella, P., & Mérand, A. 2011, A&A, 538, A24
Gallenne, A., Monnier, J. D., Mérand, A., et al. 2013, A&A, 552, A21
Haguenauer, P., Alonso, J., Bourget, P., et al. 2010, in Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series, Vol. 7734, Society for Photo-Optical Instrumentation Engineers (SPIE) Conference Series
Hanbury Brown, R., Davis, J., Lake, R. J. W., & Thompson, R. J. 1974, MNRAS, 167, 475
Jaschek, M. & Jaschek, C. 1960, PASP, 72, 500
Keller, S. C. 2008, ApJ, 483
Kervella, P., Bersier, D., Mourard, D., et al. 2004, A&A, 428, 587
Klagyivik, P. & Szabados, L. 2009, A&A, 504, 959
Le Bouquin, J.-B., Berger, J.-P., Lazareff, B., et al. 2011, A&A, 535, 667
Lloyd Evans, T. 1982, MNRAS, 199, 925
Neill, H. R., Cantiello, M., & Langer, N. 2011, A&A, 529, L9
Peterson, O. K. L., Cottrell, P. L., & Albrecht, M. D. 2004, MNRAS, 350, 95
Petitjean-Pitt, G., Thompson, I. B., Gieren, W., et al. 2010, Nature, 468, 542
Petitjean, P., Thompson, I. B., Graczyk, D., et al. 2011, ApJ, 742, L20
Prada Moroni, P. G., Gemmaro, M., Bono, G., et al. 2012, ApJ, 749, 108
Samus, N. N., Durtovich, O. V., & et al. 2009, VizieR Online Data Catalog: B/gcvs. Originally published in: Institute of Astronomy of Russian Academy of Sciences and Sternberg State Astronomical Institute of the Moscow State University, 1, 2025
Sandage, A., Tammann, G. A., & Reindl, B. 2004, A&A, 424, 43
Storm, J., Gieren, W., Fouqué, P., et al. 2011, A&A, 534, A94
Szabados, L. 1989, Communications of the Konkoly Observatory Hungary, 91, 1
Tammann, G. A., Sandage, A., & Reindl, B. 2003, A&A, 404, 423
Uzenko, I. A., Kniazev, A. Y., Berdnikov, L. N., & Korneev, V. V. 2011, Astronom Letters, 37, 499
Table 2. Journal of the observations.

| UT               | Star      | Configuration |
|------------------|-----------|---------------|
| 2013 July 11     |           |               |
| 0:14             | AX Cir    | K0-A1-G1-J3   |
| 0:27             | HD 129462 | K0-A1-G1-J3   |
| 0:36             | AX Cir    | K0-A1-G1-J3   |
| 0:46             | HD 129462 | K0-A1-G1-J3   |
| 0:58             | AX Cir    | K0-A1-G1-J3   |
| 1:18             | HD 133869 | K0-A1-G1-J3   |
| 1:27             | AX Cir    | K0-A1-G1-J3   |
| 1:39             | HD 133869 | K0-A1-G1-J3   |
| 1:51             | AX Cir    | K0-A1-G1-J3   |
| 2:01             | HD 133869 | K0-A1-G1-J3   |
| 2013 July 14     |           |               |
| 23:07            | HD 133869 | D0-G1-H0-I1   |
| 23:21            | AX Cir    | D0-G1-H0-I1   |
| 23:32            | HD 129462 | D0-G1-H0-I1   |
| 23:45            | AX Cir    | D0-G1-H0-I1   |
| 23:55            | HD 133869 | D0-G1-H0-I1   |
| 2013 July 15     |           |               |
| 00:08            | AX Cir    | D0-G1-H0-I1   |
| 00:24            | HD 129462 | D0-G1-H0-I1   |
| 00:47            | AX Cir    | D0-G1-H0-I1   |
| 00:58            | HD 133869 | D0-G1-H0-I1   |
| 01:07            | AX Cir    | D0-G1-H0-I1   |
| 01:17            | HD 129462 | D0-G1-H0-I1   |
| 01:24            | AX Cir    | D0-G1-H0-I1   |
| 01:35            | HD 129462 | D0-G1-H0-I1   |