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LETTER TO THE EDITOR

δ Cen: a new binary Be star detected by VLTI/AMBER spectro-interferometry [★]

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ABSTRACT

Aims. We studied the Be star δ Cen circumstellar disk using long-baseline interferometry which is the only observing technique able to resolve simultaneously, spatially and spectroscopically objects smaller than 5 mas in the H and K band.

Methods. We used the VLTI/AMBER instrument on January 6, 8, and 9, 2008, in the H and K bands combining Low (35) and Medium (1500) spectral resolution observations.

Results. We detected an oscillation in the visibility curve as a function of the spatial frequency which is a clear signature for a companion around δ Cen. Our best fit leads us to a binary separation of 68.7 mas, a companion flux contribution in the K band of about 7% of the total flux, a PA of 117.5° and an envelope flux around the Be primary contributing to about 50% of the total flux, in agreement with our Spectral Energy Distribution (SED) fit. The envelope size is estimated to be 1.6 mas in K but no departure from the spherical symmetry was detected.

Key words. Techniques: high angular resolution – Techniques: interferometric – Stars: emission-line, Be – Stars: winds, outflows – Stars: individual (δ Cen) – Stars: circumstellar matter Stars: binary

1. Introduction

We have started an observational campaign which aims to determine the global parameters of Be stars as well as the origin of the so-called "Be-phenomenon" with the VLTI interferometer which combines, for the first time, a milli-arcsecond spatial resolution with a good spectral resolution up to 12000 in the near-IR K band. We are thus able to study the geometry and kinematics within the circumstellar environment. Up to now, three Be stars were observed with the VLTI instruments and the global physical properties of these stars varies strongly from one star to another.

Achernar was the first Be star observed with the VLTI using the VINCI beam recombiner. These observations exhibit a strongly flattened star due to a nearly critical rotation (Domiciano de Souza & Kervella 2003) and an extended polar wind contributing to nearly 4% of the total flux in the H band (Kervella & Domiciano de Souza 2007), but no detectable equatorial disk. Nevertheless its circumstellar environment is known to be highly variable with a quasi-cyclic formation an dissipation timescale of about 13 years as shown by Vinicius et al (2007). Kanaan et al. (2008) successfully model these variations as a possible outburst of circumstellar matter, ejected and propagating within the stellar environment with an expansion velocity of 0.2km s⁻¹.

The second Be star observed was α Arae, both with MIDI and AMBER instruments in medium spectral resolution (MR)

mode for the last one. Results were published by Chesneau et al. (2005) and Meilland et al. (2007a). The data interpretation was done with the SIMECA code developed by Stee et al. (1994) which is able to simulate the gaseous circumstellar environment of active hot stars. The results clearly exhibit the presence of two distinct regions in the circumstellar environment of α Arae: a thin Keplerian rotating equatorial disk and a fast expanding enhanced polar wind. As for Achernar, the stellar rotational velocity, determined thanks to the flatness of the projected envelope onto the sky plane, was found to be nearly critical. By combining MIDI and AMBER data, they found that the disk size was not varying as a function of the observing wavelength, which was a strong clue for a possible disk truncation, as confirmed by more "classical" spectroscopic measurements.

Finally, the third Be star studied using the VLTI instruments, was κ CMa, observed with AMBER in MR mode and published in Meilland et al. (2007b). For this star, a non-Keplerian rotating disk was detected. Moreover, the star was found to rotate far below its critical velocity, which seems to indicate that critical rotation may not be a requirement for the "Be phenomenon". On the other hand, since it has an early spectral type of B2V, the radiation pressure might be sufficient to initiate a mass loss and a possible disk formation. This hypothesis is in agreement with the Cranmer (2005) statistical study. Finally the spectro-differential interferometric measurements were able to detect the presence of an inhomogeneity in the circumstellar envelope of this star which can be explained within the "one-armed" viscous disk framework Okazaki (1997).

To improve our sample of Be stars observed with the VLTI in order to start a statistical study of the geometry and kinematics of their surroundings and a possible dependence of the

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[★] Based on observations made with ESO telescopes at La Silla Paranal Observatory under GTO programme IDs 080.D-0131(A) and 080.C-0099(B)

“Be phenomenon” with the spectral type of the central star, we have asked for new AMBER observations of 6 close and bright enough Be stars with spectral types ranging from B1 to B8 and δ Cen was one of those stars.

This letter is organized as follows: in Section 2 we briefly introduce the Be star δ Cen and its fundamental parameters, in Section 3 we present our VLTI/AMBER observations and the data reduction, and in the last section our results are summarized and conclusions are presented.

Name	L (m)	P.A. ($^\circ$)
B ₁	85	-158
B ₂	85.9	-75
B ₃	127.9	-116
B ₄	31.9	-111
B ₅	16	-111
B ₆	47.8	-111

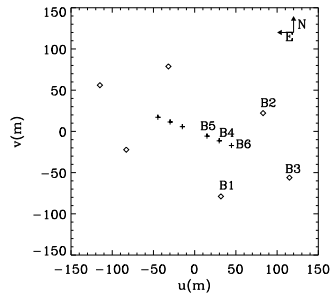


Fig. 1. Left : Names, lengths, and P.A. for each baseline of the two triplets of observation. Note that the two measurements from January 8 with A0-K0-G1 are merged into B₁, B₂, and B₃ baselines, as the projected baseline length and P.A. does not vary significantly between them. B₄, B₅, and B₆ baselines correspond to the E0-G0-H0 triplets. Right: (u,v) plane coverage obtained during the δ Cen observing run. Fortunately, the largest projected baseline is aligned with the shorter ones.

2. δ Cen

δ Cen (HR 4621, HD 105435, HIP 59196) is usually presented as a B2IVne star, although Levenhagen & Leister (2006), following a spectroscopic analysis made without taking into account the effects of gravity darkening, proposed a B2Vne classification. It is a variable star with a brightness variation from magnitude 2.65 to 2.51. δ Cen shares the same proper motion with the nearby stars HD 105382 (which is also a Be star) and HD 105383 and thus may be member of a triple visual star system. A precise radial velocity (RV) measurements campaign of B stars in the Scorpius-Centaurus association by Jilinski et al. (2006) found a RV for δ Cen of 3.8 km s^{-1} but with an error on the same order, i.e., $\pm 2.8 \text{ km s}^{-1}$. Moreover, the RV determined from various authors from the SIMBAD database exhibits a large dispersion which might already be a good indication of possible binarity, as we will see in the following. On the other side, Mason et al. (1996), and Mason (2008), using UNSO and CHARA speckles cameras did not detect any binarity for this star.

Based on autocorrelation analysis of Hipparcos photometry Percy et al. (2002) present a self-correlation diagram with strong minima at 0.55 and 1.1 days whereas Balona (1990) report a tentative period of 1.923 days, making δ Cen a possible short-period variable Be star. Rivinius et al. (2003), studying line profile variation from 1999 HEROS spectroscopic data, confirm both values at 0.532d and 1.139d but with a formally somewhat higher significance of the longer period which was adopted in their paper. They conclude that δ Cen line profile variability is successfully modeled as a non-radial pulsator with $l = m = +2$, as for the Be star ω CMa, but with a strongly asymmetric power distribution of the line profile variability with a unidentified cause. The star’s distance estimated by Hipparcos is $121 \pm 11 \text{ pc}$ and its K and V magnitude is respectively 2.7 and 2.56. Lenorzer et al. (2002) have identified δ Cen as a B star with emission lines observed in the ISO Short Wavelength Spectrometer Post-Helium

Obs. time	Target	Triplet	Mode	Seeing
06/01/08 08:59	δ Cen	A0-K0-G1	MR	1.02''
06/01/08 09:11	HD109538	A0-K0-G1	MR	1.13''
06/01/08 09:26	δ Cen	A0-K0-G1	MR	1.19''
08/01/08 08:48	HD90798	E0-G0-H0	LR	0.50''
08/01/08 09:11	δ Cen	E0-G0-H0	LR	0.94''
09/01/08 08:07	HD47536	E0-G0-H0	MR	0.68''
09/01/08 08:31	δ Cen	E0-G0-H0	MR	0.74''
09/01/08 08:50	HD109538	E0-G0-H0	MR	0.87''
09/01/08 09:08	δ Cen	E0-G0-H0	MR	1.22''
09/01/08 09:28	HD109538	E0-G0-H0	MR	0.71''

Table 1. Observations log of δ Cen and its calibrators during the January 2008 Be AMBER GTO run.

program of the Infrared Space observatory (ISO). The more recent fundamental parameters determined for fast rotating B-type stars by Frémat et al. (2005), taking into account the gravitational darkening is $T_{eff} = 22384 \pm 446 \text{ K}$, $\log g = 3.942 \pm 0.053$ and $V \sin i = 263 \pm 14 \text{ km s}^{-1}$. Its linear critical equatorial rotation velocity is $V_c = 527 \pm 29 \text{ km s}^{-1}$ and its inclination angle is estimated to be $i = 41.6 \pm 2.3^\circ$. Levenhagen & Leister (2004) estimate its age to be $\log \text{Age} = 7.20 \pm 0.15 \text{ yr}$, a luminosity of $\log L/L_\odot = 3.70 \pm 0.10$ and a mass of $8.6 \pm 0.3 M_\odot$.

3. Observations and data reduction

δ Cen was observed with AMBER in low as well as medium spectral resolution modes (spectral resolving powers of $R=35$ and $R=1500$ respectively) during the observing runs 080.C-0099 and 080.D-0131, held in January 2008. Five measurements were obtained with the Auxilliary Telescopes (1.8m diameter) on the A0-K0-G1 and E0-G0-H0 baseline triplets. HD 109593 (apparent diameter of $1.638 \pm 0.021 \text{ mas}$ in the CHARM2 catalog from Richichi et al. 2005), HD 47536 (apparent diameter of $1.69 \pm 0.03 \text{ mas}$, also in CHARM2) and HD 90798 (apparent diameter $1.70 \pm 0.51 \text{ mas}$ using the getCal¹ tool) were also observed to calibrate the δ Cen visibilities. The log of these observations (including calibrators) are presented Table 1.

The data were reduced using the AMBER data reduction software developed by the JMMC: `amdlib`, version 2.1. It computes a fringe fitting of the AMBER data, after correcting for detector bias and flat-field (Millour et al., 2004 and Tatulli et al., 2007). After that step, we used two different approaches to calibrate the data:

- The “standard” approach which keeps 20% of the total number of frames according to the fringe SNR. This allows us to limit the fringe smearing effect (also called “jitter” effect) and the coherence length visibility loss due to the atmospheric OPD (described in Millour et al. 2007). The following steps (transfer function estimation, calibration) were done using a new set of custom scripts described in Millour et al. (2008²).
- An approach using bootstrapping, roughly explained in Tatulli et al., (2007) and described in more detail in Cruzalèbes et al. (2007). A frame selection scheme rejecting frames with a negative flux, a high OPD variation from frame to frame, and a SNR less than 1, is also applied. The calibration procedure is then done the same way as for the previous method.

¹ available at <http://mscweb.ipac.caltech.edu/gcWeb>

² The scripts are available to the community at the following web-page: <http://www.mpi-fr-bonn.mpg.de/staff/fmillour>

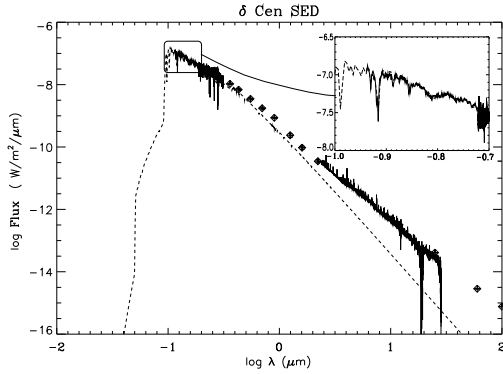


Fig. 2. δ Cen Spectral Energy Distribution (SED) reconstructed from various sources in the literature : Morel (1978), 2MASS, and IRAS magnitude and flux measurements (diamonds), IUE spectra (solid line in the UV), and ISO spectra (solid line in the IR). The dashed line is a Kurucz model for $T_{eff} = 21000\text{K}$, $R_{\star} = 5.9R_{\odot}$, $\log g = 4$, and $d = 121\text{pc}$.

The two methods give the same results within the error bars, therefore we choose to use the calibrated data from the first method in the latter parts of the paper. In this very first step, we focus only on visibilities, and not on phase closure nor differential phase. Moreover since the aim of the letter is to determine the newly detected binary parameters we exclude the January 9 MR data whose projected baselines are similar to the January 8 LR ones and whose data quality is significantly lower. Finally, we merged the two January 5 MR measurements obtained with almost the same projected baseline, and we obtained wavelength-dependent visibilities for the six baselines presented Fig. 1. The corresponding (u,v) plane coverage on the science target is also plotted Fig 1.

4. Results

For a single Be star, assuming that the visibility we measure, V , is only due to the central star and its circumstellar disk we can write:

$$V = \frac{V_{env}F_{env} + V_{\star}F_{\star}}{F_{tot}} \quad (1)$$

where V_{env} and F_{env} are respectively the envelope visibility and flux in the continuum, V_{\star} and F_{\star} the star visibility and flux in the continuum and $F_{tot} = F_{env} + F_{\star}$. Thus, in order to measure accurately the extension of a circumstellar envelope from an interferometric measurement, we need to determine both F_{\star} and F_{env} at the observing wavelength. This can be done directly by interferometry if, at least, two baselines fully resolved the envelope but not the star (i.e., $V_{env}=0$ and $V_{\star} \sim 1$). But in the case of our δ Cen AMBER data, even the longest baseline (i.e., $B_3=127.9\text{m}$) is too small to fully resolve the circumstellar envelope.

Consequently, in order to determine with the best possible accuracy F_{\star} and F_{env} in H and K bands, we started our modeling by constructing the δ Cen Spectral Energy Distribution (SED) using various sources in the literature (see Fig. 2). A Kurucz model, fitted from UV and visible measurements, where the circumstellar contribution is negligible, is used to determine the stellar contribution to the flux for wavelength ranging from UV to Far-IR. The values of the best Kurucz model parameters, which are consistent with those found in the literature and introduced Section 1, are presented Table 3. This method allows us to characterize

precisely the circumstellar IR-excess. Taking into account the uncertainty on δ Cen's spectral class and its small variability in the near IR, we obtain $F_{env} = 0.52 \pm 0.06 F_{tot}$ in the K band and $0.38 \pm 0.08 F_{tot}$ in the H band.

K and H band calibrated visibilities obtained with the small aligned triplet in LR mode (i.e., B_4 , B_5 , and B_6) are plotted as a function of the spatial frequency Fig. 3. These data clearly exhibit a sinusoidal modulation with a period of $T_{4,5,6} = 22$ cycles/arcsec and an amplitude of $A_{4,5,6} = 0.15 \pm 0.02$. This variation cannot be explained with a simple star + circumstellar envelope model whatever the geometry of this second component is (uniform or Gaussian disk, ring,...), and is usually produced by a companion. The separation between the two components along the direction of the projected baselines (i.e., -111°) is given by $S_{4,5,6} = 1/T_0 = 44.8 \pm 0.5$ mas, and its flux by $F_c = A_{4,5,6}/2 = 0.075 \pm 0.01 F_{tot}$. We note that this value may be biased towards a dimmer flux ratio since the stars separation is $\sim 25\%$ of the telescopes PSF ($\sim 240\text{mas}$ with the ATs at $2.1\mu\text{m}$) and the AMBER instrument uses monomode fibers (Tatulli et al. 2004). However, it is beyond the scope of this paper to correct for this effect.

To fit the small slope of the visibility as a function of the spatial frequency, we also need to introduce a small circumstellar envelope (i.e., $D = 2 \pm 0.5\text{mas}$) around one of the two components. Note that the data also show some small differences in term of modulation amplitude between the H and K bands data. The characterization of these differences, probably due to the variation of the binary flux ratio between these spectral bands is far above the aim of this letter and will not be detailed here.

B_1 , B_2 , and B_3 data are also plotted Fig 3. These measurements put additional constraints on the binary and the circumstellar envelope. B_2 and B_3 data show a sinusoidal modulation with periods corresponding respectively to a separation between the binary components in the projected baseline directions of $S_2 = 62 \pm 5\text{mas}$ and $S_3 = 52 \pm 6\text{mas}$. The amplitude of the modulation is $A_2 = A_3 = 0.15 \pm 0.05$ which is in agreement with the January 8 LR data (i.e., $A_0 = 0.15 \pm 0.02$). The separation measured by B_3 is compatible with the one made with the LR triplet which is a good indication that our measurements are not biased by some instrumental effects since B_3 is almost aligned with the LR triplet (i.e., P.A. $= -116^\circ$ for B_3 and P.A. $= -111^\circ$ for B_4, B_5 , and B_6). The difference between the two measurements can be due either to a bad spectral calibration of AMBER LR data (up to $0.1\mu\text{m}$) or to a small change of the projected separation due to the 5° of variation in P.A. between the two data sets. Finally, there is no evidence of a sinusoidal modulation in the B_1 data. Taking into account that the modulation may not be evidenced if its period is at least 3 times the observation range in spatial frequency (i.e., $T \geq 50$ cycles/arcsec), the binary separation along this projected angle, S_1 , is less than 20 mas. Moreover, the average visibility for each triplet baseline (i.e., $\bar{V}_1 = 0.82$, $\bar{V}_2 = 0.86$, and $\bar{V}_3 = 0.81$) clearly indicates the presence of an extended component, probably a circumstellar envelope, with an extension is about $2 \pm 0.5\text{mas}$.

By measuring the projected separation in at least two different directions in the sky, we can determine the modulus and the orientation of the binary separation on the sky plane. Our best binary star + circumstellar envelope model is obtained for a set of value given Table 2. The modeled visibility obtained in K band for each of the six baselines are overplotted with the observed ones in Fig. 3. Note that, to verify that the binary signal was not coming from the calibrators we checked that the modulation was visible on the science object raw visibilities and not on the calibrator ones.

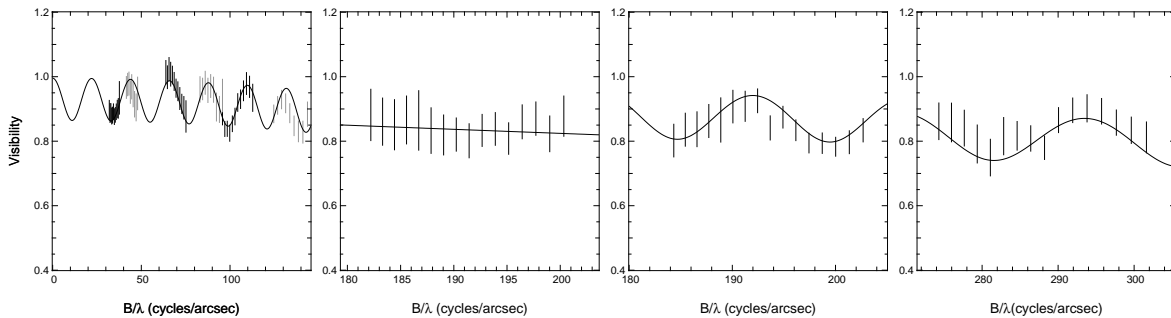


Fig. 3. Left: LR K (dark) and H (gray) bands visibilities for the January, 8 2008 baselines (B_4 , B_5 , and B_6) as a function of the spatial frequency. Second picture from the left to the right: MR visibilities for the January, 5 2008 baselines (B_1 , B_2 , and B_3) as a function of the spatial frequency. For all figures, measurements are given by the error bars whereas the solid line corresponds to our best binary + uniform disk circumstellar envelope modeled using parameters from Table 2.

Moreover, since AMBER works simultaneously with three telescopes, we are able to measure the closure phase for each triplet. Such measurements put additional constraints on our models. Fig. 4 shows a reasonable agreement between observed and modeled closure phase using parameters from Table 2.

Finally, using $R_\star = 5.9R_\odot$ and $d = 121\text{pc}$, the 68.7mas separation between δ Cen and its companion corresponds to $300 \pm 50R_\star$. Assuming a circular orbit, this gives a lower limit to its semi-major axis. The companion spectral class can be inferred using both δ Cen spectral class and K band flux ratio determined from the amplitude of the modulation in the interferometric data. The companion spectral class should range between B4V and A0III, and its mass between 4 and $7M_\odot$. Using Kepler third law of planetary motion, $P = \sqrt{a^3/M_{tot}}$, where P is the period in years, a the semi-major axis in AU, and M_{tot} the binary system total mass in M_\odot , we can determine a lower limit of its period, i.e., 4.6 years, with $M_{tot} = 15.2M_\odot$ and $a = 250R_\star = 6.9\text{AU}$.

Additional interferometric observations including a long-term monitoring are needed to solve the issue concerning the discrepancy between these results and Mason (1997 ; 2008) speckles observations, and to fully determine the projected orbit of δ Cen companion. Moreover, spectroscopic follow-up should also be carried out even if the Doppler shifts due to the binarity can be difficult to detect knowing that the star is a fast rotator (i.e., $V \sin i = 263\text{km s}^{-1}$), and that the profiles are also affected by non radial pulsations. The circumstellar environment geometry and kinematics will be studied in a forthcoming paper which will include all January 2008 VLTI/AMBER Medium resolution differential visibilities as well as VLTI/MIDI data.

Distance	$121 \pm 11 \text{ pc}$
T_{eff}	$21000 \pm 1000 \text{ K}$
Stellar Radius	$5.9 \pm 0.5 R_\odot$
$\log g$	3.75 ± 0.25
Companion flux (K band)	$0.07 \pm 0.01 F_{tot}$
Separation	$68.7 \pm 0.5 \text{ mas}$
Position Angle (PA)	$117.5 \pm 0.5^\circ$
Envelope flux (K band)	$0.52 \pm 0.06 F_{tot}$
Envelope diameter (K band)	$1.6 \pm 0.4 \text{ mas}$

Table 2. Parameters and results for the binary system + uniform disk circumstellar envelope obtained for δ Cen. Note that there is a 180° ambiguity in the position angle since AMBER closure phase data reduction process is not fully validated.

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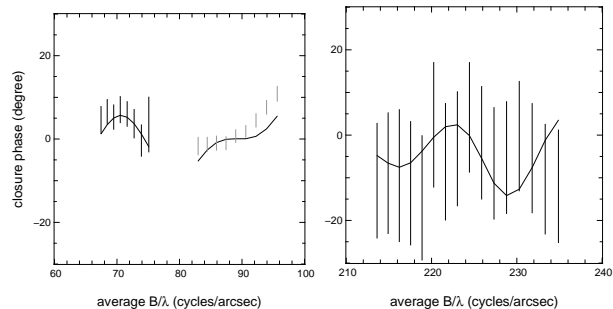


Fig. 4. Observed and modeled closure phase for the $B_4B_5B_6$ (left) and $B_1B_2B_3$ (right) triplets plotted as a function of the average spatial frequency. For all figures the measurements are given by the error bars whereas the solid line corresponds to our best binary + uniform disk circumstellar envelope modeled using parameters from Table 2.

success and more particularly J-B Lebouquin and F. Rantakyro. This research has made use of SIMBAD database, operated at CDS, Strasbourg, France.

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