HAL open science

The long-period eccentric orbit of the particle accelerator HD 167971 revealed by long baseline interferometry

M. de Becker, H. Sana, O. Absil, J. -B. Le Bouquin, R. Blomme

▶ **To cite this version:**

M. de Becker, H. Sana, O. Absil, J. -B. Le Bouquin, R. Blomme. The long-period eccentric orbit of the particle accelerator HD 167971 revealed by long baseline interferometry. Monthly Notices of the Royal Astronomical Society, 2012, 423, pp.2711-2717. 10.1111/j.1365-2966.2012.21081.x . insu-03612418

HAL Id: insu-03612418

https://insu.hal.science/insu-03612418v1

Submitted on 18 Mar 2022

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

Distributed under a Creative Commons Attribution 4.0 International License

Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY

Mon. Not. R. Astron. Soc. **423,** 2711–2717 (2012) doi:10.1111/j.1365-2966.2012.21081.x

The long-period eccentric orbit of the particle accelerator HD 167971 revealed by long baseline interferometry*

M. De Becker,[1]† H. Sana,[2] O. Absil,[1]‡ J.-B. Le Bouquin[3] and R. Blomme[4]

[1]*Institut d'Astrophysique et de Géophysique, Université de Liège, 17, Allée du 6 Août, B5c B-4000 Sart Tilman, Belgium*
[2]*Astronomical Institute 'Anton Pannekoek', University of Amsterdam, Postbus 94249, 1090 GE Amsterdam, the Netherlands*
[3]*UJF-Grenoble 1/CNRS-INSU, Institut de Planétologie et d'Astrophysique de Grenoble (IPAG), UMR 5274 Grenoble, France*
[4]*Royal Observatory of Belgium, Ringlaan 3, 1180 Brussels, Belgium*

Accepted 2012 April 8. Received 2012 April 5; in original form 2012 March 19

ABSTRACT

Using optical long baseline interferometry, we resolved for the first time the two wide components of HD 167971, a candidate hierarchical triple system known to efficiently accelerate particles. Our multi-epoch Very Large Telescope Interferometer observations provide direct evidence for a gravitational link between the O8 supergiant and the close eclipsing O + O binary. The separation varies from 8 to 15 mas over the 3-year baseline of our observations, suggesting that the components evolve on a wide and very eccentric orbit (most probably $e > 0.5$). These results provide evidence that the wide orbit revealed by our study is not coplanar with the orbit of the inner eclipsing binary. From our measurements of the near-infrared luminosity ratio, we constrain the spectral classification of the components in the close binary to be O6–O7, and confirm that these stars are likely main-sequence objects. Our results are discussed in the context of the bright non-thermal radio emission already reported for this system, and we provide arguments in favour of a maximum radio emission coincident with periastron passage. HD 167971 turns out to be an efficient O-type particle accelerator that constitutes a valuable target for future high angular resolution radio imaging using Very Long Baseline Interferometry facilities.

Key words: radiation mechanisms: non-thermal – techniques: interferometric – binaries: general – stars: early-type – stars: individual: HD 167971.

1 INTRODUCTION

Massive binaries made of O-type and/or Wolf–Rayet (WR) stars are known to be the scene of stellar wind collisions whose strength is intimately dependent on wind properties. Besides the hydrodynamic aspect of such a phenomenon (e.g. Pittard 2009), colliding winds offer the opportunity to study higher level physical processes such as copious thermal X-ray emission (Stevens, Blondin & Pollock 1992; Pittard & Stevens 1997; Pittard & Parkin 2010) or even particle acceleration mechanisms (Eichler & Usov 1993; Benaglia & Romero 2003; Pittard & Dougherty 2006; De Becker 2007). The latter process considers a particle (electrons and hadrons) acceleration mechanism taking place in the presence of the strong shocks of the colliding winds. Historically, the existence of a population of relativistic electrons has been revealed by the detection of non-thermal (synchrotron) radio emission coming from several massive stars. More recently, a significant non-thermal high-energy counterpart has been confirmed in the case of WR 140 in hard X-rays (Sugawara et al. 2011), and even in γ-rays for η Car (Farnier, Walter & Leyder 2011).

So far, fewer than 40 massive stars revealed their capability to accelerate particles up to relativistic energies (De Becker 2007; Benaglia 2010). Even though it is now rather well established that most of them are confirmed binaries, uncertainties remain concerning the multiplicity status of several targets. Among these, HD 167971 deserves a particular attention. This system is known to be one of the brightest synchrotron radio emitters (Bieging, Abbott & Churchwell 1989; Blomme et al. 2007), clearly establishing its particle accelerator status. Leitherer et al. (1987) and Davidge & Forbes (1988) showed that it consists of a close O + O eclipsing binary ($P = 3.3213$ d) with a third more luminous O8I star. Considering the strong opacity of stellar winds to radio photons, the non-thermal radio emission is not expected to escape the wind–wind interaction region within the close binary (see Blomme et al. 2007 for a discussion), suggesting electrons should be accelerated in a putative interaction region involving the third star. The study of Blomme et al. also revealed a radio light curve displaying

* Based on observations collected at the European Southern Observatory, Paranal, Chile, under the programme IDs 381.D-0095, 086.D-0586 and 087.D-0264.

†E-mail: debecker@astro.ulg.ac.be
‡Postdoctoral Researcher F.R.S.-FNRS (Belgium).

© 2012 The Authors
Monthly Notices of the Royal Astronomical Society © 2012 RAS

Downloaded from https://academic.oup.com/mnras/article/423/3/2711/2460794 by guest on 18 March 2022

Table 1. Observing log for HD 167971 and its calibrators.

Epoch	Date	MJD	Star	Type	No. of files	Instrument	Baseline
1	2008 May 17	54603.258	HD 167971	SCI	11	AMBER	U1–U3–U4
1	2008 May 17	54603.275	HD 179688	CAL	9	AMBER	U1–U3–U4
1	2008 May 17	54603.339	HD 167971	SCI	9	AMBER	U1–U3–U4
1	2008 May 17	54603.356	HD 179688	CAL	9	AMBER	U1–U3–U4
2	2008 July 16	54663.153	HD 167971	SCI	8	AMBER	U1–U3–U4
2	2008 July 16	54663.170	HD 179688	CAL	6	AMBER	U1–U3–U4
2	2008 July 17	54664.105	HD 154088	CAL	5	AMBER	U1–U3–U4
2	2008 July 17	54664.120	HD 167971	SCI	5	AMBER	U1–U3–U4
2	2008 July 17	54664.161	HD 179688	CAL	8	AMBER	U1–U3–U4
3	2011 March 29	55549.389	HD 167971	SCI	5	AMBER	A0–G1–I1
3	2011 March 29	55549.401	HD 166521	CAL	5	AMBER	A0–G1–I1
3	2011 March 29	55549.417	HD 167971	SCI	5	AMBER	A0–G1–I1
4	2011 August 9	55782.141	HD 166521	CAL	5	PIONIER	A1–G1–I1–K0
4	2011 August 9	55782.151	HD 167971	SCI	5	PIONIER	A1–G1–I1–K0
4	2011 August 9	55782.161	HD 166191	CAL	5	PIONIER	A1–G1–I1–K0

long-term variations, compatible with a period of ∼20 years or more. HD 167971 appears to be the brightest X-ray source in the NGC 6604 open cluster, with a rather hard thermal emission spectrum compatible with pre-shock velocities too large to be attributed to the close binary colliding winds (De Becker et al. 2005). With a period of about 3.3 d, the separation in the eclipsing binary is too short to allow stellar winds to reach their terminal velocities before collision, leading therefore to low post-shock temperatures unable to produce a significantly hard X-ray spectrum. The latter point suggests again an interaction between the winds of the close binary with that of the distant O8 supergiant, although its gravitational link with the close binary has yet to be demonstrated.

In this paper, we report on the results of long baseline interferometric observations of HD 167971 performed with the Very Large Telescope Interferometer (VLTI) at the European Southern Observatory (ESO), Chile. The observations and data processing are briefly described in Section 2. The results are discussed in detail in Section 3 and we conclude in Section 4.

2 OBSERVATIONS AND DATA PROCESSING

2.1 VLTI observations

HD 167971 was a target of the VLTI on 2008 May 17 and July 16, using three unit telescopes (UTs; UT1–UT3–UT4) and the Astronomical Multi-BEam combineR (AMBER) instrument (Petrov et al. 2007). Our target was also observed on 2011 March 29 with AMBER and three auxiliary telescopes (ATs) in the A0–G1–K0 configuration, translating into baselines ranging between about 50 and 120 m. The AMBER instrument was operated in the low-resolution *HK* mode, which provides a spectral resolution of $R \simeq 35$ across the *H* and *K* bands. Calibrated visibility and closure phase values were computed using the latest public version of the AMBER data reduction package (AMDLIB version 3.1; Tatulli et al. 2007; Chelli, Utrera & Duvert 2009) and the YORICK interface provided by the Jean-Marie Mariotti Center.[1] The data were processed following the same procedure as described by Sana et al. (2011). The accuracy of the absolute calibration was typically of 20 per cent for the visibilities and 5° for the closure phases.

[1] JMMC software: http://www.jmmc.fr.

On 2011 August 9, HD 167971 was observed with the visitor instrument Precision Integrated-Optics Near-infrared Imaging Experiment (PIONIER) (Le Bouquin et al. 2011) fed by all four ATs of VLTI in the A1–G1–I1–K0 configuration. PIONIER was operated with a low spectral resolution $R \approx 15$, that is, three spectral channels across the *H* band. Calibrated visibility and closure phase values were computed using the latest version of the PIONIER data reduction package (PNDRS version 2.3; Le Bouquin et al. 2011). The accuracy was typically of 5 per cent for the visibilities and 1° for the closure phases. Table 1 summarizes all observations obtained for the four observing runs, including the observations of calibrator stars used to estimate the instrumental visibility and closure phase.

Special care was taken to retrieve the absolute sign of the closure phases for both instruments, which were previously calibrated with observations of known binaries.

2.2 Binary modelling

The angular separation between the two stars in the close eclipsing binary is expected to be of the order of 0.1 mas (assuming a circular orbit with a period of 3.3 d), and is therefore seen as an unresolved point source by our interferometer. The O8I outer star is also seen as a point-like source, with an estimated angular diameter of 0.05 mas based on the work of Martins, Schaerer & Hillier (2005). We therefore a priori expected to separate two point-like objects in our observations: the close binary and the O8 supergiant. For all four epochs, large closure phases and strong visibility variations with respect to wavelength, baselines and time are observed. This is illustrated in Fig. 1 for the closure phases at epoch 3. This suggests indeed a binary system with a flux ratio close to unity. We therefore decided to model the system by two unresolved stars with a constant flux ratio over the *H* and *K* bands, a valid assumption for O + O binaries.

We used the calibrated closure phases to derive the flux ratio and astrometry of the binary system, following the procedure presented in Absil et al. (2011). In short, we constructed binary models with various flux ratios and positions within the interferometric field of view (∼40 mas on the UTs and ∼200 mas on the ATs at the *H* band), and computed the reduced χ^2 goodness of fit for all models to populate a χ^2 cube. The global minimum, its significance and its uniqueness were then determined by inspecting the cube. For all epochs, a unique binary solution was found. The best fit

Downloaded from https://academic.oup.com/mnras/article/423/3/2711/2460794 by guest on 18 March 2022

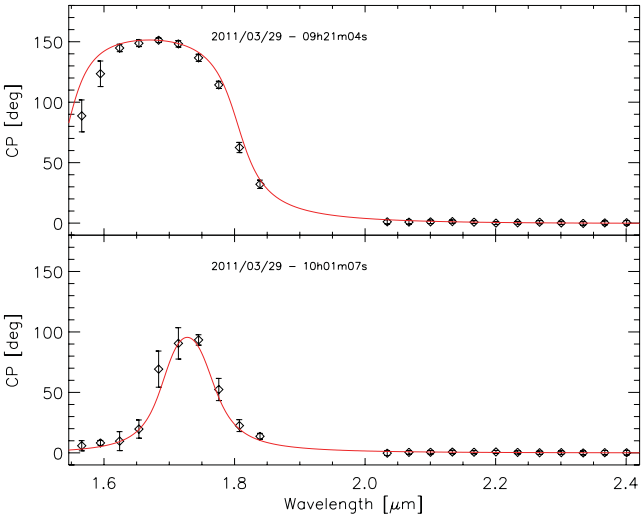

Figure 1. Illustration of the closure phases obtained during the epoch 3 observing run on AMBER (diamonds with error bars) and of the best-fitting binary model (solid line). The χ^2 value associated with this fit is about 0.8.

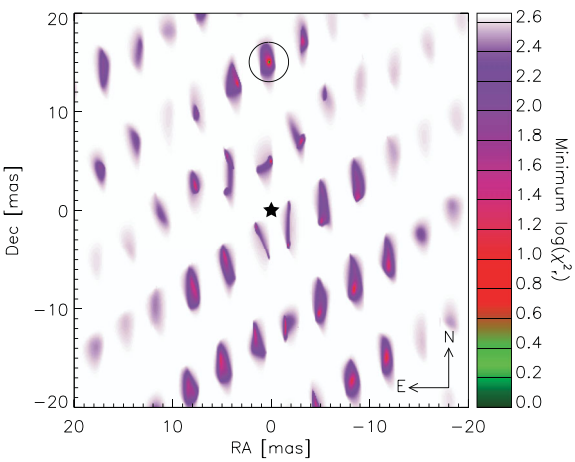

Figure 2. Reduced χ^2 map resulting from the fit of a binary model to the closure phases of the epoch 3 AMBER data set. The circle indicates the position of the sharply peaked minimum χ^2 value. The figure appears in colour in the electronic version of the paper.

to the data for epoch 3 and the resulting χ^2 map are shown in Figs 1 and 2, respectively. It is clear that the measurement of the binary separation is unambiguous: all locations are associated with $\chi^2 \geq 5$ except the one identified with a circle in Fig. 2, which has $\chi^2 \sim 0.8$.

The uncertainties on the best-fitting parameters were derived by inspecting the behaviour of the reduced χ^2 cube around the absolute minima (see Absil et al. 2011 for details). The final error bars on the astrometry also take into account the estimated uncertainty on the spectral calibration of the two instruments (i.e. central wavelength of the spectral channels). It was conservatively set to 3.2 per cent in AMBER (twice the width of a spectral channel) and to 2 per cent in PIONIER (Le Bouquin et al. 2011). Finally, we checked that a similar analysis, performed on the calibrated squared visibilities instead of the closure phases, gives consistent results, although generally with larger error bars as discussed in Absil et al. (2011). The parameters of the best-fitting models for the four epochs are summarized in Table 2.

3 RESULTS AND DISCUSSION

3.1 First evidence for a wide orbit

The main result of our investigation is the separation of HD 167971 into two components, respectively, referred to as A and B. The brightest one, component A, should a priori be associated with the O8 supergiant (see Section 3.2 for a detailed discussion). The best-fitting relative positions of the two resolved components in HD 167971 are given in Table 2 and plotted in Fig. 3. The second important result is the clear demonstration that the relative positions of components A and B changed significantly from one epoch to the other. In particular, it is noticeable that we detect a weak (but significant) change between observations 1 and 2, separated by only about two months. These facts provide for the first time compelling evidence that the third star is gravitationally bound to the close binary, definitely confirming the triple status of HD 167971. Considering the lower limit on the orbital period suggested by radio light curves ($P \sim 20$ yr; Blomme et al. 2007), this strongly suggests a very large eccentricity for the orbit with a periastron passage rather close to the epochs 1 and 2.

The relation between periastron (d_p) and apastron (d_a) stellar separations, and eccentricity (e), is the following:

$$\frac{d_p}{d_a} = \frac{1-e}{1+e}. \quad (1)$$

On the basis of the values of the relative separation at epochs 1 and 4, i.e. two extreme separations in our sampling, we derive an upper limit for the periastron over apastron separation ratio of about 0.6, translating into a lower limit on the eccentricity of about 0.25. It should be emphasized that this value is very conservative as the separation at epochs 3 and 4 strongly underestimates the expected separation at apastron. The configurations at four epochs illustrated in Fig. 3 suggest an actual separation at apastron at least twice as large as at epoch 4, converting into an eccentricity of at least 0.5. Even though our analysis led to valuable constraints on the

Table 2. Relative position of component B with respect to component A, and near-infrared luminosity ratios for the three observations (average over H and K bands for AMBER, and over the H band for PIONIER). The angular separation (S) and the position angle (θ) are also given.

Epoch	Date	δRA (mas)	δDec. (mas)	S (mas)	θ (°)	$L_{B,HK}/L_{A,HK}$
1	2008 May 17	8.28 ± 0.27	−2.53 ± 0.09	8.66 ± 0.28	107.0 ± 1.1	0.76 ± 0.01
2	2008 July 16–17	8.78 ± 0.28	−1.03 ± 0.05	8.84 ± 0.28	96.7 ± 0.6	0.81 ± 0.04
3	2011 March 29	0.28 ± 0.03	15.03 ± 0.48	15.03 ± 0.48	1.1 ± 0.2	0.83 ± 0.01
4	2011 August 9	−1.53 ± 0.03	15.03 ± 0.30	15.11 ± 0.30	354.2 ± 0.2	0.75 ± 0.01

Downloaded from https://academic.oup.com/mnras/article/423/3/2711/2460794 by guest on 18 March 2022

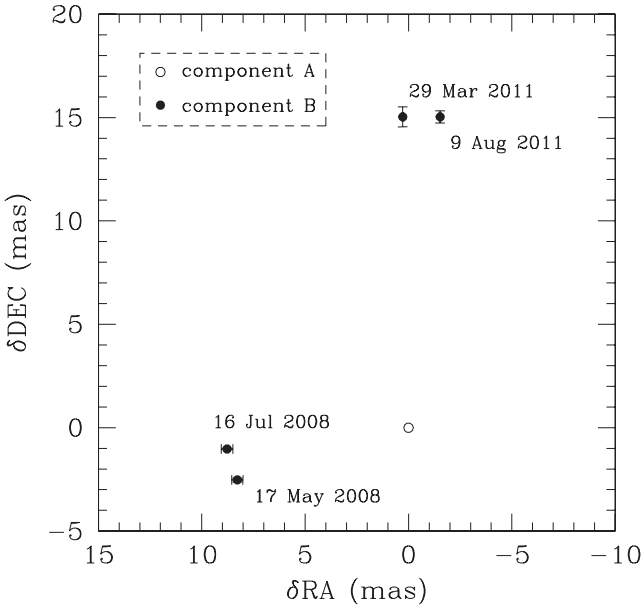

Figure 3. Relative positions of components A and B in HD 167971 at the four observation epochs. Component A, the brightest object, is arbitrarily located at coordinates (0, 0).

properties of the wide orbit in HD 167971, we note that the undetermined inclination, the incomplete orbital coverage and the lack of information from spectroscopic monitoring (especially close to periastron passage) inhibit our capability to derive the orbital parameters of the system. For this reason, we will refrain from speculating further on the orbital parameters of the wide orbit and will come back to this issue as soon as the adequate observational information (interferometric and spectroscopic) will be made available.

It is also interesting to note that our astrometric results for the wide orbit suggest a not so high inclination (defined as the angle between the line of sight and the normal to the orbital plane), although the eclipse measured for the close binary leads to an inclination angle for the short orbit of at least about 70° (Davidge & Forbes 1988). These results provide evidence for a significant inclination between the short and wide orbits in HD 167971, i.e. the orbits are not coplanar. This fact is important for the issue of star formation scenarios depending on initial cluster conditions (see e.g. Sterzik & Tokovinin 2002).

3.2 The components in HD 167971

Our interferometric measurements alone could not lift the ambiguity in the association of components A and B to the close binary and to the distant supergiant. However, Leitherer et al. (1987) reported that the O supergiant is the most luminous and dominates the optical and ultraviolet (UV) spectra. Even though our measurements were performed in the near-infrared domain, the rather similar effective temperatures of the three stars in the system strongly suggest that the luminosity ratio should go in the same direction in the infrared as in optical and UV domains. We will therefore consider that the supergiant is component A and that the close binary is component B.

The luminosity ratio derived at every epoch can be discussed in order to derive additional constraints on the spectral classification of the stars in HD 167971. Even though it is quite well established that the third star should be an O8 supergiant, the spectral types of the components in the close binary are not fully determined. On the basis of the fundamental parameter values given by Martins et al. (2005), we derived rough estimates of the expected luminosity ratios assuming various spectral type combinations, and assuming the two components in the close binary to have the same spectral classification. According to the study of Leitherer et al. (1987), the members of the close binary should be main-sequence stars, with spectral types ranging between O5 and O8. The expected bolometric luminosities and luminosity ratios, assuming an O8I third star (with $L_{\rm BOL} = 4 \times 10^5\,{\rm L}_\odot$; Martins et al. 2005), are quoted in Table 3. The values given in Table 2 for the measured luminosity ratio seem to significantly change from one epoch to the other. It should be emphasized that the eclipsing nature of the close binary (component B) may be responsible for a significant change of its brightness as a function of time, mostly considering the depth and duration of the eclipses reported for instance by Davidge & Forbes (1988). However, the propagation of the uncertainties on the ephemeris of the eclipsing binary over more than 2000 cycles (between the photometric and interferometric observations) prevents us from determining the orbital phase of the close binary at the epoch of our interferometric observations. In addition, a slight difference may also appear between the three AMBER observations and the PIONIER measurement, as these instruments operate in different wavebands (HK and *H*, respectively). Assuming that luminosity ratios should be similar for both bolometric and *K*-band luminosities, our $L_{\rm B,HK}/L_{\rm A,HK} \sim 0.8$ measurements suggest spectral types for the stars in the close binary between O6 and O7 (typically O6.5 with an uncertainty of half a spectral type) for main-sequence stars, as illustrated in Fig. 4.[2] For a giant luminosity class, the close binary components should not be earlier than O8, assuming that the third star is at least as luminous as the close binary. On the basis of these estimates we favour the main-sequence luminosity classes as suggested by Leitherer et al. (1987), and we consider that the giant or even supergiant luminosity classes as claimed by Davidge & Forbes (1988) are unlikely. This result is also in agreement with the idea that the typical radius of evolved stars may be too large to fit within the small orbit of the eclipsing binary. Considering typical radii and masses for O6.5 stars given by Martins et al. (2005), and applying Kepler's law for a 3.3-d circular orbit, we estimate that supergiants would be too large and that about 80 per cent of the stellar separation would be occupied by the stars if they were giants. If main-sequence stars are assumed, we estimate that only about 50 per cent of the stellar separation is filled by the stars.

Assuming an (O6.5V + O6.5V) + O8I spectral classification for the stars in HD 167971, we estimate the total visual absolute magnitude $M_{\rm V} = 6.73$ (for typical visual magnitudes as given by Martins et al. 2005). For a *V* apparent magnitude of about 7.35 as reported by Leitherer et al. (1987) between the eclipses, and a colour excess $E(B-V)$ of 0.9, we derive a distance modulus of 11.29, translating into a distance of about 1.8 kpc. Considering the uncertainties, such a distance is in agreement with the distance of 1.7 kpc reported by Reipurth (2008) for the NGC 6604 open cluster, lending further support to the adopted spectral classification.

We note that the additional information given here on the spectral classification of the components in HD 167971, with respect to previously published results, should be considered with caution:

[2] The uncertainty of 0.2 dex taken into account in this figure could seem overestimated considering the error bars given in Table 2 for the luminosity ratios, but we selected a comfortable confidence range in order to be sure to include the a priori unknown uncertainty on the theoretical luminosity ratio values, and therefore get rid of any overinterpretation of the results.

Downloaded from https://academic.oup.com/mnras/article/423/3/2711/2460794 by guest on 18 March 2022

Table 3. Potential stellar parameters for the stars in HD 167971, assuming main-sequence (upper part) and giant (lower part) luminosity classes for the components in the close binary. We assumed the close binary to be made of two identical stars.

Sp. type	O5V	O5.5V	O6V	O6.5V	O7V	O7.5V	O8V
L_{BOL} ($L_\odot$)	3.2×10^5	2.6×10^5	2.0×10^5	1.6×10^5	1.3×10^5	1.0×10^5	0.8×10^5
L_B/L_A	1.60	1.30	1.00	0.80	0.65	0.50	0.40
Sp. type	O5III	O5.5III	O6III	O6.5III	O7III	O7.5III	O8III
L_{BOL} ($L_\odot$)	5.0×10^5	4.3×10^5	3.6×10^5	3.1×10^5	2.7×10^5	2.3×10^5	2.0×10^5
L_B/L_A	2.5	2.15	1.80	1.55	1.35	1.15	1.0

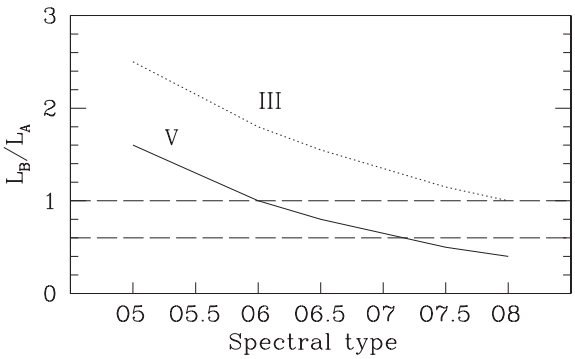

Figure 4. Expected luminosity ratios assuming various spectral types, along with main-sequence (V) and giant (III) luminosity classes for the close binary components. The long-dashed horizontal lines encompass the ratio values compatible with our interferometric measurements, if one tolerates a 0.2 dex uncertainty.

stellar classification based on luminosities is indeed generally less accurate than classification approaches based on spectroscopic criteria. This issue would therefore strongly benefit from a long-term spectroscopic monitoring with application of state-of-the-art disentangling techniques to accurately classify individual components in the system, such as in the case of the hierarchical triple system HD 150136 (Mahy et al. 2012), provided the inclination of the wide orbit allows the measurement of significant radial velocity shifts of spectral lines of the three components.

3.3 The radio emission in HD 167971

The radio light curve presented by Blomme et al. (2007) shows a bright non-thermal radio emission whose strong variability is worth discussing in relation with the long-period eccentric orbit. The demonstration of a gravitational connection between the O8 supergiant and the eclipsing binary provides a straightforward interpretation scheme for the radio variability: the non-thermal radio photons should arise from an emission region coincident with the wind–wind interaction region in the wide binary, where relativistic electrons (and particles in general) are expected to be accelerated. The light curve presented by Blomme et al. (2007) at 6 cm is the one that benefits from the best time coverage. Its maximum occurred close to 1988–1989, and its minimum between 1995 and 1999. Assuming a period of about 20 years, the next maximum is expected to have occurred in 2008–2009, i.e. close to the time of our observations 1 and 2. In this context, it is tentative to attribute the maximum radio flux density to orbital phases close to periastron passage, i.e. when the separation is shorter.

The non-thermal radio emission is indeed expected to be variable mainly for two reasons, respectively, related to emission and absorption. First, the intrinsic synchrotron mechanism responsible for the non-thermal radio emission is more efficient when the stellar separation is shorter (typically, close to periastron passage). Synchrotron emission is indeed dependent on the local magnetic field strength (B), where relativistic electrons are accelerated: $L_{synch} \propto B^2$. Considering the magnetic field strength dependence on the distance to the stars described for instance by Usov & Melrose (1992), B is expected to decrease significantly as the stellar separation increases, leading to a maximum synchrotron emission at periastron. In addition, one should keep in mind that the kinetic power injected in the wind–wind interaction region, and consequently the power available for particle acceleration, is expected to decrease as the separation increases (see discussion in Section 3.4). Secondly, radio emission from the colliding-winds region is also expected to vary significantly because of the phase-dependent free–free absorption due to the stellar winds material along the line of sight. In very eccentric orbits, the absorption is expected to be stronger close to periastron, when the synchrotron emission region is more likely to be located within the $\tau \sim 1$ radiosphere. The combination of these two effects is especially striking in the case of the long-period WR + O-type binary WR 140 (White & Becker 1995), where the radio maximum occurs slightly before periastron, just before the strong increase of the free–free absorption.[3] In the case of HD 167971, however, the impact of free–free absorption is a priori expected to be less spectacular: (i) the winds of the O-type stars in our target are not so efficient at absorbing radio photons as the WR wind in WR 140; (ii) HD 167971 is not so asymmetric as WR 140 and the stagnation point in the wide orbit is more likely to be located close to mid-separation. As a result, we consider that the variability of the radio light curve in HD 167971 should be dominated by the variation in the synchrotron emission, with a maximum rather close to periastron passage.

Finally, considering the rather wide orbit of the system whose wind–wind interaction is responsible for the non-thermal radio emission, along with the large brightness of the synchrotron source in the system, we claim that HD 167971 would deserve high angular resolution radio imaging observations using Very Long Baseline Interferometry facilities such as the Very Long Baseline Array, as already done in the case of a few systems such as WR 140 (Dougherty et al. 2005), WR 146 (O'Connor et al. 2005), WR 147 (Williams et al. 1997), HD 93129A (Benaglia et al. 2010) and Cyg OB2 #5 (Ortiz-León et al. 2011). This would allow us to spatially disentangle the thermal and non-thermal contributions in HD 167971, and therefore more accurately quantify the synchrotron luminosity without contamination by the free–free (thermal) emission arising in individual stellar winds.

[3] We note that the situation may be somewhat more complex notably due to the Razin–Tsytovich effect, as illustrated in the case of the massive binary Cyg OB2 #8A (Blomme et al. 2010), but the simple orbital phase dependence discussed here is correct to first order.

Downloaded from https://academic.oup.com/mnras/article/423/3/2711/2460794 by guest on 18 March 2022

3.4 Energy budget in HD 167971

The results detailed in previous sections allow us to give a few words on energetic considerations related to the physics of massive binaries, and in particular to particle acceleration and non-thermal processes in general. The available energy for physical processes related to the wind–wind interaction comes from the kinetic power of the colliding stellar winds. For a stellar wind with mass-loss rate $\dot{M}$ and terminal velocity V_∞, the kinetic power is $P_{\rm kin} = 0.5\dot{M}V_\infty^2$. For a long-period orbit as the one revealed by our interferometric measurements, the stellar winds are expected to have reached their terminal velocity before colliding. Considering the spectral types and luminosity classes discussed in Section 3.2, and assuming terminal velocities of 3000 km s^{-1}, we used the predicted mass-loss rates given by Muijres et al. (2012) based on stellar parameters from Martins et al. (2005) to compute kinetic powers of about 1.9×10^{36} and 0.7×10^{36} erg s^{-1}, respectively, for components A and B. In order to evaluate the energy injected in the colliding-wind region, one has to consider the fractional solid angle of the wind–wind interaction region as seen from each star surface. Typically, one could consider that it amounts up to a few per cent. If a fraction of about 5 per cent is assumed, the total energy per unit time injected in the wind–wind interaction by both stars is about 10^{35} erg s^{-1}. The efficiency of the conversion of collision mechanical energy to particle acceleration is expected to be of the order of 1 per cent, shared between electrons and hadrons (mostly protons), i.e. about 10^{33} erg s^{-1}. The assumed value for the electron-to-hadron acceleration efficiency is still uncertain for colliding-wind binaries. Considering that this quantity is similar for environments accelerating cosmic rays in general, it should be of the order of 1 per cent (Longair 1992; Pittard & Dougherty 2006). However, we should not reject the possibility that this efficiency ratio may be somewhat different, and possibly larger (1–10 per cent). Consequently, at the level of approximation of this discussion, we will consider that 10^{31}–10^{32} erg s^{-1} is potentially available for non-thermal emission processes involving relativistic electrons (i.e. so-called leptonic processes).

In massive star environments, the most efficient non-thermal leptonic process is expected to be inverse Compton (IC) scattering (i.e. energy transfer from relativistic electrons to UV and visible photons that are upscattered in the high-energy domain). Considering the ratio between magnetic and radiation energy densities close to massive stars, IC scattering will be the dominant energy loss process for relativistic electrons (Pittard & Dougherty 2006; De Becker 2007). Typically, one could expect that at most 1 per cent of the energy transferred to relativistic electrons is converted into synchrotron radiation in the radio domain. As a result, the synchrotron radio luminosity should be of the order of 10^{29}–10^{30} erg s^{-1}.

This number is worth comparing to observational quantities as reported in the study by Blomme et al. (2007). To do so, we need radio flux density measurements at the same epoch in order to derive a spectral index. We selected in the data published by Blomme et al. measurements obtained in 1985 February,[4] with measurements, respectively, of 7.4 ± 0.4 mJy at 2 cm and 14.7 ± 0.3 mJy at 6 cm. From these quantities, we determine a spectral index $\alpha \approx -0.6$, which is a comfortable non-thermal value.[5] We can therefore consider that the radio emission at the selected date is clearly dominated by synchrotron radiation, and that thermal contributions from the individual stellar winds contribute only a small fraction of the measured flux density at a given wavelength. Using equation (26) in De Becker (2007) and assuming a distance of 1.7 kpc for the NGC 6604 open cluster harbouring HD 167971 (Reipurth 2008), we converted the flux density into an integrated radio luminosity of about 10^{30} erg s^{-1}. The latter value is close to the maximum expected on the basis of the above discussion. This suggests that the electron-to-hadron particle acceleration efficiency is rather high in HD 167971, or that the energy injection in the particle acceleration mechanism is especially efficient. These considerations lend further support to the idea that HD 167971 is an especially valuable target for the investigations of non-thermal processes in O-type multiple systems.

These estimates suggest finally that the remaining energy injected in the relativistic electron population (i.e. about 10^{31}–10^{32} erg s^{-1}) should be available for IC scattering, likely responsible for a weak hard X-ray emission (and potentially soft γ-rays). Considering the sensitivity of current high-energy facilities, the detection of such an IC scattering emission is unlikely, and next-generation hard X-ray facilities such as *ASTRO-H* (Japan Aerospace Exploration Agency mission to be launched in 2014; Miyata, Tamura & Kunieda 2011) are required to detect and quantify this emission process, and therefore derive valuable constraints on the non-thermal and electron-to-hadron efficiency.

4 CONCLUSIONS

Our analysis provided for the first time evidence that HD 167971 is a gravitationally bound hierarchical triple system, with a very eccentric wide outer orbit. Using long baseline interferometry (with AMBER and PIONIER instruments at the VLTI), we resolved the system into two components: (i) the close eclipsing O-type binary and (ii) the additional O-type supergiant. The small fraction of the orbit covered by our observations suggests that the orbit between the two resolved components is wide, in agreement with the previously published lower limit on the orbital period of about 20 years, on the basis of the radio light curve. Our results suggest an eccentricity of at least 0.25 (and most probably $e > 0.5$), even though additional interferometric observations are required to ascertain its value.

Our measurements of the luminosity ratio allowed us to derive some constraints on the spectral classification of the members of the triple system. Considering that the brightest component is the O8I star identified by previous studies, our results favour an O6–O7 main-sequence classification for the two stars in the close binary (assuming these two stars are very similar, in agreement with previously published photometric results).

On the basis of these results, we can comfortably argue that the strong non-thermal radio emission associated with HD 167971 should come from the wind–wind interaction region between the close binary and the additional supergiant. The rather wide orbit allows the bulk of the synchrotron radio emission to escape the stellar winds without undergoing strong free–free absorption. The

[4] That date was selected as it corresponds to the epoch closest to the maximum radio emission for which reliable flux density measurements exist at two wavelengths in order to determine a spectral index. At the maximum (1988–1989), flux density measurements exist only at 6 cm.

[5] A thermal radio emission component from a spherically symmetric and homogeneous stellar wind is expected to be characterized by a spectral index close to 0.6, as demonstrated by Wright & Barlow (1975) and Panagia & Felli (1975). A negative value for the spectral index is considered as a valuable tracer for non-thermal radio emission.

Downloaded from https://academic.oup.com/mnras/article/423/3/2711/2460794 by guest on 18 March 2022

large (though undetermined) eccentricity of the orbit provides a straightforward explanation for the strong variability of the non-thermal radio emission in HD 167971. Assuming an orbital period of about 20 years, as suggested by previously published radio light curves, our results provide hints for the maximum radio emission occurring close to periastron passage. A more complete interferometric monitoring of HD 167971 is however needed to establish that coincidence with more accuracy. We emphasize that our results lend additional support to the so-called 'standard scenario' for non-thermal processes in massive star environments that considers efficient particle acceleration in the colliding-winds region. Finally, we note that the wide orbit and the brightness of the synchrotron source in HD 167971 designate it as a potential good target for future high-resolution radio imaging observations of colliding-wind massive binaries.

ACKNOWLEDGMENTS

PIONIER is funded by the Université Joseph Fourier (UJF, Grenoble) through its Poles TUNES and SMING and the vice-president of research, the Institut de Planétologie et d'Astrophysique de Grenoble, the 'Agence Nationale pour la Recherche' with the programme ANR EXOZODI, and the Institut National des Science de l'Univers (INSU) with the programmes 'Programme National de Physique Stellaire' and 'Programme National de Planétologie'. The integrated optics beam combiner is the result of a collaboration between IPAG and CEA-LETI based on CNES R&T funding. The authors want to warmly thank all the people involved in the VLTI project. MDB thanks Dr Gregor Rauw for a reading of a preliminary version of the manuscript, and Dr Eric Gosset for fruitful and stimulating discussions on these results. Finally, it is a pleasure to thank the referee, Dr Olivier Chesneau, for his positive and constructive comments that improved the manuscript. The SIMBAD data base has been consulted for the bibliography.

REFERENCES

Absil O. et al., 2011, A&A, 535, A68
Benaglia P., 2010, in Martí J., Luque-Escamilla P. L., Combi J. A., eds, ASP Conf. Ser. Vol. 422, High Energy Phenomena in Massive Stars. Astron. Soc. Pac., San Francisco, p. 111
Benaglia P., Romero G. E., 2003, A&A, 399, 1121
Benaglia P., Dougherty S. M., Phillips C., Koribalski B., Tzioumis T., 2010, Rev. Mex. Astron. Astrofis. Conf. Ser., 38, 41
Bieging J. H., Abbott D. C., Churchwell E. B., 1989, ApJ, 340, 518
Blomme R., De Becker M., Runacres M. C., van Loo S., Setia Gunawan D. Y. A., 2007, A&A, 464, 701
Blomme R., De Becker M., Volpi D., Rauw G., 2010, A&A, 519, A111
Chelli A., Utrera O. H., Duvert G., 2009, A&A, 502, 705
Davidge T. J., Forbes D., 1988, MNRAS, 235, 797
De Becker M., 2007, A&AR, 14, 171
De Becker M., Rauw G., Blomme R., Pittard J. M., Stevens I. R., Runacres M. C., 2005, A&A, 437, 1029
Dougherty S. M., Beasley A. J., Claussen M. J., Zauderer B. A., Bolingbroke N. J., 2005, ApJ, 623, 447
Eichler D., Usov V., 1993, ApJ, 402, 271
Farnier C., Walter R., Leyder J.-C., 2011, A&A, 526, A57
Le Bouquin J.-B. et al., 2011, A&A, 535, A67
Leitherer C. et al., 1987, A&A, 185, 121
Longair M. S., 1992, High Energy Astrophysics, 2nd edn. Cambridge Univ. Press, Cambridge
Mahy L., Gosset E., Sana H., Damerdji Y., De Becker M., Rauw G., Nitschelm C., 2012, A&A, 540, A97
Martins F., Schaerer D., Hillier D. J., 2005, A&A, 436, 1049
Miyata Y., Tamura K., Kunieda H., 2011, Proc. SPIE, 8147, 81470V
Muijres L. E., Vink J. S., de Koter A., Müller P. E., Langer N., 2012, A&A, 537, A37
O'Connor E., Dougherty S., Pittard J., Williams P., 2005, J. R. Astron. Soc. Canada, 99, 142
Ortiz-León G. N., Loinard L., Rodríguez L. F., Mioduszewski A. J., Dzib S. A., 2011, ApJ, 737, 30
Panagia N., Felli M., 1975, A&A, 39, 1
Petrov R. G. et al., 2007, A&A, 464, 1
Pittard J. M., 2009, MNRAS, 396, 1743
Pittard J. M., Dougherty S. M., 2006, MNRAS, 372, 801
Pittard J. M., Parkin E. R., 2010, MNRAS, 403, 1657
Pittard J. M., Stevens I. R., 1997, MNRAS, 292, 298
Reipurth B., 2008, in Reipurth B., ed., Handbook of Star Forming Regions, Vol. 2, The Southern Sky. Astron. Soc. Pac., San Francisco, p. 590
Sana H., Le Bouquin J.-B., De Becker M., Berger J.-P., de Koter A., Mérand A., 2011, ApJ, 740, L43
Sterzik M. F., Tokovinin A. A., 2002, A&A, 384, 1030
Stevens I. R., Blondin J. M., Pollock A. M. T., 1992, ApJ, 386, 265
Sugawara Y. et al., 2011, Bull. Soc. R. Sci. Liege, 80, 724
Tatulli E. et al., 2007, A&A, 464, 29
Usov V. V., Melrose D. B., 1992, ApJ, 395, 575
White R. L., Becker R. H., 1995, ApJ, 451, 352
Williams P. M., Dougherty S. M., Davis R. J., van der Hucht K. A., Bode M. F., Setia Gunawan D. Y. A., 1997, MNRAS, 289, 10
Wright A. E., Barlow M. J., 1975, MNRAS, 170, 41

This paper has been typeset from a TEX/LATEX file prepared by the author.

Downloaded from https://academic.oup.com/mnras/article/423/3/2711/2460794 by guest on 18 March 2022