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Wolf-Rayet stars probed by AMBER/VLTI[*]

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ABSTRACT

Massive stars deeply influence their surroundings by their luminosity and the injection of kinetic energy. So far, they have mostly been studied with spatially *unresolved* observations, although evidence of geometrical complexity of their wind are numerous. Interferometry can provide spatially *resolved* observations of massive stars and their immediate vicinity. Specific geometries (disks, jets, latitude-dependent winds) can be probed by this technique.

The first observation of a Wolf-Rayet (WR) star (γ^2 Vel) with the AMBER/VLTI instrument yielded to a re-evaluation of its distance and an improved characterization of the stellar components, from a very limited data-set. This motivated our team to increase the number of WR targets observed with AMBER. We present here new preliminary results that encompass several spectral types, ranging from early WN to evolved dusty WC.

We present unpublished data on WR79a, a massive star probably at the boundary between the O and Wolf-Rayet type, evidencing some Wolf-Rayet broad emission lines from an optically thin wind. We also present new data obtained on γ^2 Vel that can be compared to the up-to-date interferometry-based orbital parameters from North et al. (2007). We discuss the presence of a wind-wind collision zone in the system and provide preliminary analysis suggesting the presence of such a structure in the data. Then, we present data obtained on 2 dusty Wolf-Rayet stars: WR48a-b and WR118, the latter exhibiting some clues of a pinwheel-like structure from the visibility variations.

Keywords: Techniques: interferometric - - stars: winds, outflows - stars: Wolf-Rayet stars: binaries: spectroscopic - stars: early-type

1. INTRODUCTION

According to the classical MK spectral classification system, the A, B and O stars represent the group of hot or early type stars. The most permanent luminous stellar objects are the **O stars**. They exhibit strong, fast stellar winds of relatively low opacity, driven by their strong radiation field. Luminosities are found to be up to $10^6 L_\odot$ (for O super-giants) with mass loss rates $\dot{M}$ of up to $5 \times 10^{-6} M_\odot$. Terminal wind velocities (V_∞) of up to 2000 km/s are found. Estimated surface temperatures are found to lie up to $\sim 50\,000$ K. In an evolutionary context, O stars are the probable progenitors of Wolf-Rayet stars. Intense emission lines of various ionized elements are the spectral characteristics of Wolf-Rayet stars, originating from an extended, and rapidly expanding atmosphere. Among all stable stars, WR stars reveal the strongest mass loss via (radiative) wind mechanisms. Typical mass loss rates range from $(2-10) \times 10^{-5} M_\odot \, yr^{-1}$, with wind velocities of 1000 - 2500 km/s. The Wolf-Rayet winds are mostly optically thick, so the surface is not visible. This means that the connection of spectral classification to photospheric core temperature is not possible as for normal stars via MK classification, and the WR classification is purely spectroscopic. WR stars are highly luminous, evolved, hot, massive stars, in the final state of their nuclear He burning. They create significant quantities of heavy elements and enrich the interstellar medium through mass-loss, and are also candidate as progenitor of Gamma-ray bursts.

It is of importance to probe the wind of these star, as the wind is the spectral reference for the classification and the modeling of these extreme stars. Long baseline interferometry can help constraining the spatial scale of the continuum and line forming regions, only weakly constrained for these objects by classical photometric and spectroscopic methods. AMBER (Astronomical Multi BEam Recombiner) is the VLTI (Very Large Telescope Interferometer) beam combiner operating in the near-infrared.[1] The instrument uses spatial filtering with fibers.[2] The interferometric beam passes through anamorphic optics compressing the beam perpendicularly to the fringe coding in order to be injected into the slit of a spectrograph. The instrument can operate at spectral resolutions of 35, 1500 and 10,000, and efficiently deliver spectrally dispersed visibilities, closure phases and differential phases.

The paper is organized following increasing evolutionary stage of the different Wolf-Rayet stars observed so far. In Sect. 2, we describe observations made on the star WR79a, at the boundary between O and WR types. In Sect. 3, we present new AMBER observations made on the WC-type γ^2 Velorum where we probe for the presence of a wind-wind collision zone. Then, in the last section, we present data acquired on two dusty Wolf-Rayet stars, where the observed data points are reminiscent of a "pinwheel" nebula.

2. THE "YOUNG" WOLF-RAYET STAR WR79A

HD 152408 (also known as WR79a) is probably just at the boundary between Wolf-Rayet and O spectral types. This O-type super-giant star shows typical broad Wolf-Rayet emission lines, indicating a higher wind density than usual O-type stars. Therefore, this is a very nice candidate to probe the strong changes occurring to stars from a dense but still optically thin wind of O-type stars to a fully radiatively driven optically thick and dense Wolf-Rayet wind.

This star was already partially successfully observed with AMBER in 2005. A reassessment of the data, with the latest version of the data reducing software has shown a small, but significant, signal in the Brγ line. This star do not show a significant polarization in the continuum, but may present a polarization enhancement in Hα line, that may be linked to a latitude-dependent stellar wind.[3] It is therefore important to use the Brγ line, as a probe of radial structure of the wind (density and velocity), and to test whether it departs significantly from a spherical symmetry.

AMBER observations of HD152408 were carried out during the AMBER Science Demonstration Time in 2005 but at this time and for such 'faint' target ($m_K = 4.9$), both the observing procedure and data reduction software were not ready to perform successful observations in the medium resolution mode required for isolating the signal from the Brγ line. In the frame of recent AMBER data reduction developments (AMBER DRS 2.0 Beta and detector fringes removal[4]), we have investigated again the data obtained at this time and managed to compute relative visibilities (see Fig. 1). However, due to the data noise and lack of a suitable calibration star, no absolute visibility nor relevant differential or closure phase could be computed.

The relative visibilities observed at this time show a clear variation in the blended Brγ-HeI line, indicating a larger wind envelope in this complex emission line than in the continuum, as expected by radiative transfer modelling. However we currently cannot extract relevant information on this envelope given the very partial information we get from this data.

3. THE COLLIDING-WINDS BINARY γ^2 VELORUM

γ^2 Velorum (WR 11, HD 68273) is the closest known Wolf-Rayet (WR) star, with an Hipparcos-determined distance of 258^{+41}_{-31} pc,[5,6] whereas other WR objects lie at $\sim$1 kpc or beyond. It is also a well-studied SB2 spectroscopic binary WR+O system (WC8+O7.5III, P = 78.53 d[7,8]) offering access to fundamental parameters of the WR star, usually obtained indirectly through the study of its dense and fast wind.

This object was observed by the Narrabri intensity interferometer operating around 0.45 μm as early as 1968.[9] By observing such a star with a long baseline interferometer, one may constrain various parameters, such as the binary orbit, the brightness ratio of the two components, the angular size associated with both the continuum and the lines emitted by the WR star.
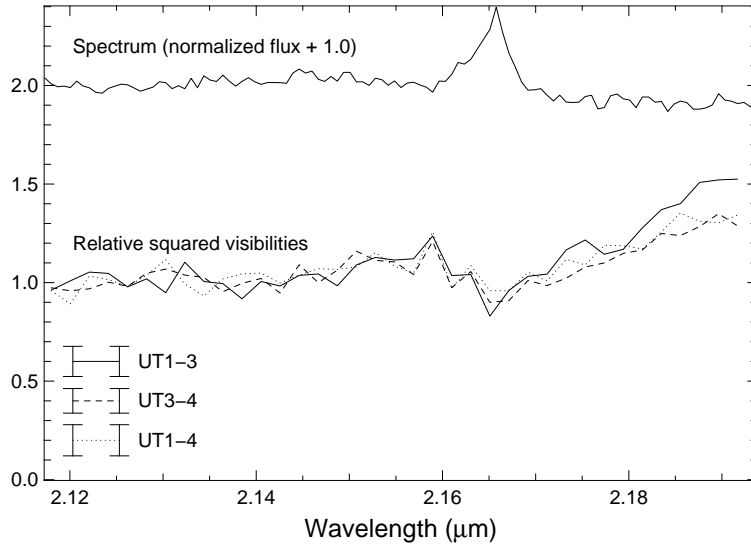
Figure 1. The relative visibilities recorded on WR79a for 3 baselines in 2005. **A drop of visibility in the Brγ line is seen for ALL baselines, related to the probably much larger spatial extent of the line forming region than the continuum one.**

The WR component of the γ^2 Velorum system is of a WC8 spectral type. While 50% of such WR stars (and 90% of the WC9 type) show heated ($T_d \sim 1300K$) circumstellar amorphous carbon dust, ISO observations of γ^2 Velorum revealed no such dust signatures.[5] Keck observations resolved, although only barely, the system in the K band and confirmed the absence of any dust emission from this system,[10] suggesting that if dust is created near the wind-wind collision zone, it is in small amounts.

Our team observed γ^2 Velorum in December 2004 using the AMBER/VLTI instrument with the telescopes UT2, UT3, and UT4 on baselines ranging from 46 m to 85 m. It delivered spectrally dispersed visibilities, as well as differential and closure phases, with a resolution $R = 1500$ in the spectral band 1.95-2.17 μm. We interpreted these data in the context of a binary system with unresolved components, neglecting in a first approximation the wind-wind collision zone flux contribution (Millour et al. 2007, A&A,[11] hereafter paper I).

Based on the accurate spectroscopic orbit and the Hipparcos distance, the expected absolute separation and position angle at the time of observations were 5.1±0.9mas and 66±15°, respectively. However, using theoretical estimates for the spatial extent of both continuum and line emission from each component, we inferred a separation of $3.62^{+0.11}_{-0.30}$ mas and a position angle of 73^{+9}_{-11}°. Our analysis thus implied that the binary system lies at a distance of 368^{+38}_{-13} pc, in agreement with recent spectro-photometric estimates, but significantly larger than the Hipparcos value of 258^{+41}_{-31} pc. A parallel observation with SUSI by North et al.[12] confirmed our astrometric point and refined the direct distance estimate of γ^2 Velorum to be 336^{+8}_{-7} pc.

We present new AMBER data acquired with different spectral resolutions and spectral coverage, from H to K bands. As a near-infrared signature of a wind-wind collision zone was discussed in the paper I, we investigate in further details the presence or not of a third light source in the system, using the full available data set acquired at five different orbital points, in order to account for, as best as possible, the binary signature of the system.

3.1 Previous AMBER observations and new data

γ^2 Velorum was observed during a follow-up campaign in 2006 and 2007 after the 2004 AMBER first scientific light, with the initial goal to characterize the orbit of the system. During this campaign, K-band medium spectral resolution observations were repeated, as well as H-K low spectral resolution. We also take the opportunity of this paper to present archival data of the very first light of AMBER in H-band medium spectral resolution that was made on γ^2 Velorum. The corresponding observing log is presented in Table 2 and the orbit coverage, is shown in Figure 2.

Table 1. Log of the observations and atmospheric conditions for γ^2 Velorum. The data-set is mainly divided in 5 epochs corresponding to different dates, telescopes configurations and spectral resolutions.

Time	Telescopes	Resolution	$\Delta\lambda$	Seeing	Coherence Time	Air Mass	Phase
Data set 1							
26/12/2004 3h48	UT2-3-4	1500	2.04 - 2.08 μm	0.53"	5.9 ms	1.293	0.36
26/12/2004 4h18	UT2-3-4	1500	1.95 - 2.03 μm	0.72"	4.5 ms	1.213	0.36
26/12/2004 4h35	UT2-3-4	1500	2.02 - 2.10 μm	0.60"	5.3 ms	1.180	0.36
26/12/2004 4h49	UT2-3-4	1500	2.09 - 2.17 μm	0.73 "	4.4 ms	1.158	0.36
Data set 2							
08/02/2006 3h42	UT1-2-3	1500	1.64 - 1.79 μm	1.06 "	4.5 ms	1.084	0.49
Data set 3							
30/12/2006 6h39	UT1-3-4	35	1.64 - 1.79 μm	0.82 "	8.8 ms	1.087	0.62
30/12/2006 6h39	UT1-3-4	35	1.88 - 2.51 μm	0.82 "	8.8 ms	1.087	0.62
Data set 4							
07/03/2007 3h07	UT1-3-4	35	1.48 - 1.78 μm	0.66 "	6.4 ms	1.123	0.51
07/03/2007 3h07	UT1-3-4	35	1.88 - 2.38 μm	0.66 "	6.4 ms	1.123	0.51
Data set 5							
31/03/2007 1h39	UT1-2-4	1500	2.02 - 2.10 μm	0.90 "	2.5 ms	1.129	0.77
31/03/2007 1h57	UT1-2-4	1500	2.09 - 2.17 μm	0.77 "	2.9 ms	1.154	0.77

For all the observations, the Unit Telescopes were used. As explained in Malbet et al.[13] and recalled in paper I, the optical trains of the UT telescopes were affected by non-stationary high-amplitude vibrations at the time of the observations. Therefore the same data processing strategy as in paper I was used for reducing the medium spectral resolution data (R=1500), i.e. rejecting 80% of the available data based on a SNR estimate on the interferometric fringes.

For the low spectral resolution data, we used the new calibration features developed in Millour et al. 2008[14] to get the most out of the new data. However, we did not use for this study the coherence length and jitter corrections developed also in Millour et al. 2008[14] since they were not yet properly tested. Therefore, we find that the low spectral resolution visibility data are much less accurate than the medium spectral resolution ones. At the other hand, the closure phase measurement in LR, has a typical error of 0.3° i.e. 5×10^{-3} rad, which is highly sufficient for this study. The old 2004 data-set was also reduced using this new calibration strategy and we find very similar results as in the paper I. A part of the data-set is shown in Fig. 3.

3.2 Orbital solution refinement

The reference orbital solution used in this paper is the one computed by North et al.[12] We compared the previous orbital solutions to the one we can find from a fit to the AMBER interferometric data taking into account the synthetic spectra of the two components, as explained in paper I. We find, using this new data, a very good agreement with the published North et al.[12] orbital elements. Our previous orbital elements match this new purely interferometric estimate marginally. This could be explained by the larger error coming from the uncertainty of the spectropolarimetric measurements combined with the sole astrometric point derived by AMBER in paper I.

The resulting model can be seen in Fig. 3 as a thin black line, to compare to the measurements plotted with error bars. The fit is personally good but not formally good (reduced χ^2 of about 2). Therefore one need to add, such as for the first AMBER paper, an additional component to explain the discrepancy seen in the data.

Table 2. Orbital parameters from paper I, from North et al.[12] and from this work. Our AMBER data agrees very well to the published North et al.[12] ephemeris, but only marginally to our previous astrometric measurement.

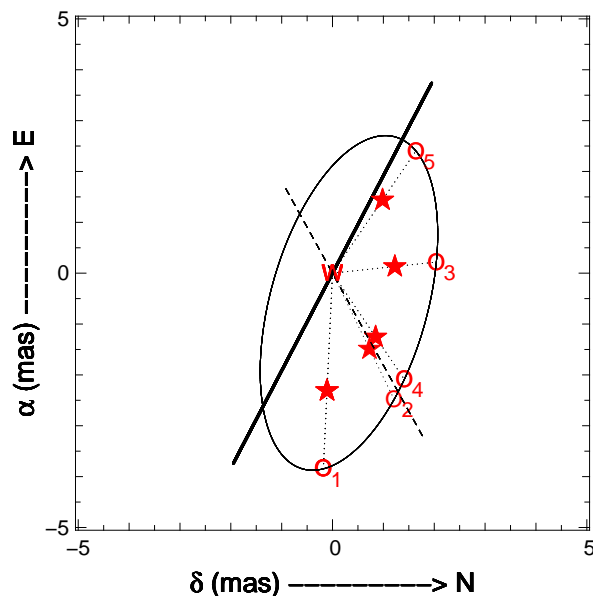| Reference	T_0 (days, fixed)	e	Ω (°)	ω (°)	i (°)	P (days, fixed)	a (mas)
Millour et al. A&A 2007[11]	50120.0	0.326	232.7	68.0	65.0	78.53	4.8
North et al. MNRAS 2007[12]	50120.4	0.334	247.7	67.4	65.5	78.53	3.57
This work	50120.4	0.334	253	67	64	78.53	3.56

Figure 2. Sketch of the orbit of γ^2 Velorum. The thick black line is the line of node, whereas the dashed line is the periastron-apoastron line. Over-plotted are the positions of the O star relative to the WR one at the different epochs of observation. The star symbol represent the approximate location of an additional light-source in the system, accounting for 5-10% of the overall flux, that might be linked to the wind-wind collision zone.

3.3 A third light source in the system

To investigate the presence of an additional contribution of the wind-wind collision to the overall near-IR continuum flux of the system, we added a third component to our 2-stars model, which is spatially unresolved and whose position is restricted within the line joining the two stars. We also restricted the spectrum of this additional component to be a fraction of the total spectrum (i.e. with a pseudo-achromatic contribution). Therefore, the corresponding model can be easily described as a 3-body model, the binary star being fixed by the previous study and the 3rd component being described by only 2 parameters: R, the flux fraction of this additional component, and r, the relative coordinate of the source between the WR star and the O star. In this way, R and r are therefore 2 numbers between 0 and 1.

Given this simple model, one can vary R and r and compute a χ^2 map. The striking fact is that the minimum of χ^2 does not match to a flux R for the third component of 0, but to a fraction of light of 5-10%, where the χ^2 goes from 2 in the previous study to 1.6 here. This fact is probably confirming the speculation on paper I of an additional light source contributing to about 5% of the overall flux. Moreover, we are able to constrain the position of this additional source, which is roughly centered at 2/3 in-between the WR and O stars.

4. DUSTY WOLF-RAYET STARS

A challenging problem is to understand how dust can form in the hostile environment of hot Wolf-Rayet stars. We successfully observed so far with AMBER 2 dusty Wolf-Rayet stars, which illustrate the potential of interferometry to contribute to answer to the fascinating question of binarity of these targets.

4.1 WR48a(-b)

WR48a is a carbon-rich Wolf-Rayet stars (WC) producing dust in the form of large or mini eruptions, that suggest the presence of a companion. It is found to be within ∼1' of the two heavily reddened, optically visible clusters Danks 1 and 2 which are themselves separated by only ∼2'.[15] WR 48a is present and visible as the bright object in the cleared centre of the field of the Mid-Course experiment observations (MSX6C G305.3614+00.0561) and a close object that seems to be also a dusty WR star (MSX6C G305.4013+00.0170) was found close to it, that
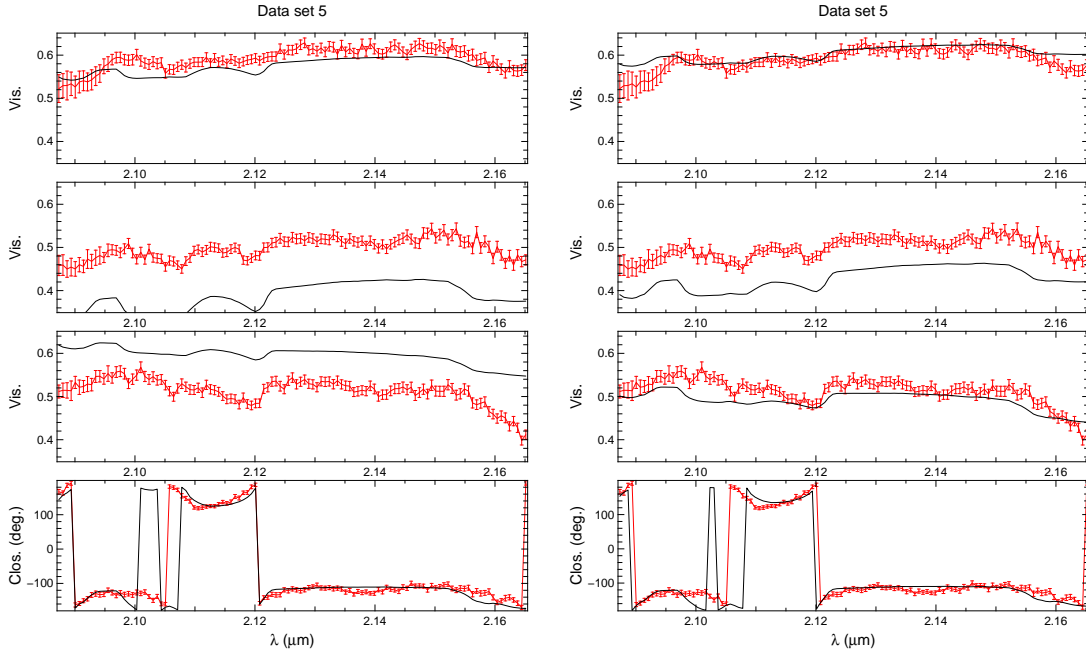
Figure 3. A sub-sample of the data acquired on γ^2 Velorum in 2006. The left panel shows the data together with a fit of the previously determined binary model. The right panel shows the same data with a fit including a 3rd component.

we hereafter denote as WR48a-b. No optical counterpart is reported in the literature and the JHK photometry for this source from the 2MASS survey show an emission falloff indicative of an object with high extinction (AV≥10 mag). With fluxes of 53.2, 54.7 and 42.0 Jy for bands A, C, D respectively (corresponding to N band), WR48a-b is almost as bright as WR48a in the mid-IR. The discovery of a WR is always an important event since these objects are very rare (no more than 500-1000 in our galaxy) and it turns out that most of the dusty WR may harbor pinwheel nebulae as shown recently by the observations of Tuthill et al.[16] WR48a was successfully observed in P78 (078.D-0503D) by the AMBER/VLTI instrument. The size measured is quite large and these two objects are probably two good candidates to harbor 'pinwheel' nebulae. WR48a-b was also successfully observed by AMBER with a 43, 59 and 89m baselines in the low resolution mode: the visibilities are quite low, between 0.2 and 0.5 (see Fig. 4), implying that the object has an angular diameter of about 4-6mas in K band, and that mid-IR sizes might be of the order of 10-15mas. Definitely these two targets are interesting, because they produce dust and hence are likely binary candidate, and also because they belong to a young star forming region whose distance is more accurately known that usual.

4.2 WR118

WR 118 is a highly evolved, carbon-rich Wolf-Rayet star of spectral type WC10. It is the third brightest Wolf-Rayet star in the K band ($K = 3.65^{\mathrm{m}}$), and the large IR-excess is usually attributed to an envelope composed of carbonaceous dust. Since no remarkable changes in the dust emission have been observed in the past two decades, WR 118 is classified as permanent dust maker. The extended dust envelope of WR 118 was successfully resolved, for the first time, by Yudin et al.[17] using bispectrum speckle interferometry with the BTA 6 m telescope. They found that up to the cutoff-frequency the K-band visibility is spherically symmetric and drops to 0.66. From their 1D-radiative transfer modeling of the K-band visibility and spectral energy distribution Yudin et al. concluded that the apparent diameter of WR 118's inner dust shell boundary is 17 ± 1 mas. Furthermore, they found that the SED and K-band visibility can either be reproduced with a two-component grain model containing large (grain size $a = 0.38\,\mu$m) as well as small grains ($a = 0.05\,\mu$m), or with a model where the grain sizes follow a $n(a) \sim a^{-3}$ size distribution. At the inner edge of the dust shell, the dust temperature and density of the best-fitting model are 1750 ± 100 K and $(1.0 \pm 0.2) \cdot 10^{19}\,\mathrm{g/cm}^3$.
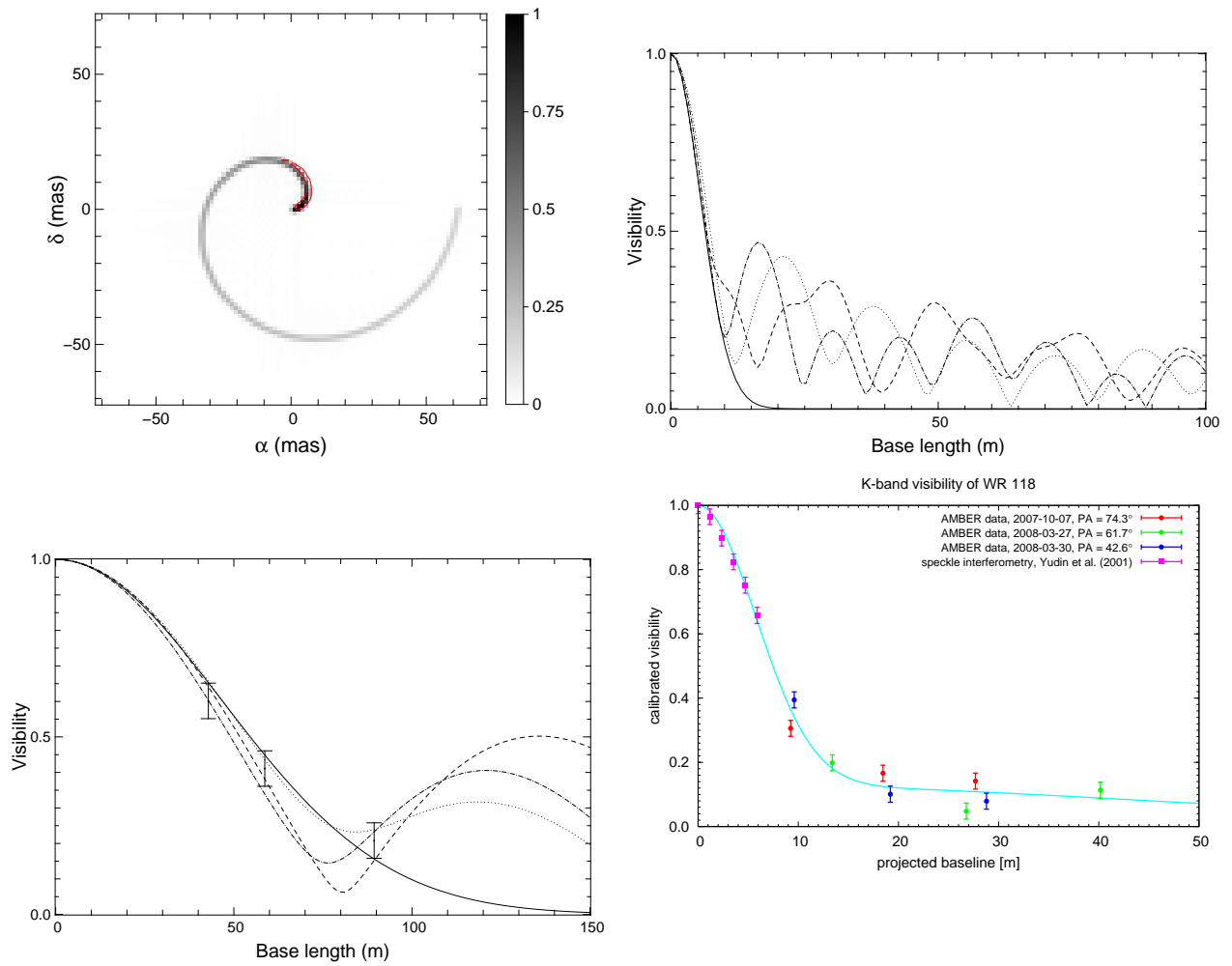
Figure 4. *Top-left*: A phenomenological model for a *pinwheel* dusty nebula. The tail is 10 times fainter than the core of the nebula. *Top-right*: Visibility cuts at 3 different hour angles (dashed lines) for the previous model, compared to a Gaussian model with the same typical size (full line). *Bottom-left*: The WR48a data compared to 2 different models: a Gaussian source (full line) and a pinwheel at three different position angles (dashed lines). The visibilities marginally fit to a Gaussian model, and could be better explained by the presence of a pinwheel nebula. *Bottom-right*: K-band visibility of the carbon-rich Wolf-Rayet star WR 118 obtained with bispectrum speckle interferometry (magenta bullets; Yudin et al. 2001) and with VLTI/AMBER (three measurements; red/green/blue bullets). In addition to the extended dust envelope, the VLTI/AMBER measurements reveal a compact component contributing $\sim 15\%$ to the total K-band flux. To guide the eye and to give a rough idea of the spatial scales involved, the light blue curve shows the fit of a double-Gaussian intensity profile, revealing components of ~ 30 and ~ 3 mas. A comparison with the top-right figure shows that the visibility signature of WR 118 found from the speckle + AMBER observations could be qualitatively explained by a spiral-like dust distribution. This would support the idea that WR 118 is a close binary system where the dust production takes place in a wind-wind collision zone, similar to the well-known examples WR 98a and WR 104.

Recently, the first K-band measurements of WR 118 have been obtained with VLTI/AMBER in low-spectral resolution mode. For all three observations,a linear baseline configuration was used, with projected baselines ranging from ~ 10 to ~ 40 m. Fig. 4 presents the AMBER visibilities at $2.2\,\mu$m together with the azimuthally averaged K-band visibility from the speckle-interferometric measurements of Yudin et al.[17] The figure illustrates that the AMBER measurements nicely supplement the previous speckle observations. Moreover, these data show some interesting results:

- At first glance, the AMBER visibilities suggest that there is an unresolved component contributing approximately 15% to the total K-band flux.

- Taking a closer look at the AMBER data, one can see that the K-band visibility is not spherically symmetric within the error bars (see, for instance, the red and blue data points) and the visibility at position angle $61.7°$ is not monotonically decreasing.

- On the other hand, the comparison of the AMBER and speckle measurements with the model visibility in Fig. 4 illustrates that the overall shape of the measured visibility of WR 118, i.e. the noticeable, basically spherically-symmetric drop at short baselines plus the plateau-like, non-spherically-symmetric trend at baselines larger than 10 m, is in qualitative agreement with the visibility signature expected from a spiral-like dust distribution.

All these clues might imply that WR 118 harbours a binary system where circumstellar dust is produced in the co-rotating wind-wind collision zone where the physical conditions are favourable for dust production. Currently, the interpretation of the recently obtained AMBER data is subject to a more detailed analysis.

5. CONCLUSION

We presented here a collection of AMBER observations on several Wolf-Rayet stars, and the different phenomena that can be characterized using the VLTI today:

- the wavelength-dependent spatial extent of the optically thick wind of single Wolf-Rayet stars (WR79a),

- the presence of wind-collision zones by means of the free-free emission of the compressed gas,

- the detection of "pinwheel" nebulae in dusty Wolf-Rayet stars which are too far to be resolved by single-dish telescopes.

The corresponding data processing and interpretations are still under progress, but they all show the great potential of AMBER to resolve the many different geometric features that evolved stars such as Wolf-Rayet can show to us.

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