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An interferometric study of the post-AGB binary 89 Herculis*

I Spatially resolving the continuum circumstellar environment at optical and near-IR wavelengths with the VLTI, NPOI, IOTA, PTI and the CHARA Array

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ABSTRACT

Context. Binary post-AGB stars are interesting laboratories to study both the evolution of binaries as well as the structure of circumstellar disks.

Aims. A multi-wavelength high angular resolution study of the prototypical object 89 Herculis is performed with the aim of identifying and locating the different emission components seen in the spectral energy distribution.

Methods. A large interferometric data set, collected over the past decade and covering optical and near-IR wavelengths, is analysed in combination with the SED and flux-calibrated optical spectra. In this first paper only simple geometric models are applied to fit the interferometric data. Combining the interferometric constraints with the photometry and the optical spectra, we re-assess the energy budget of the post-AGB star and its circumstellar environment.

Results. We report the first (direct) detection of a large (35-40%) optical circumstellar flux contribution, and spatially resolve its emission region. Given this large amount of reprocessed and/or redistributed optical light, the fitted size of the emission region is rather compact and fits with(in) the inner rim of the circumbinary dust disk. The latter dominates through thermal emission our K-band data and is also rather compact, emitting significantly already at a radius of twice the orbital separation. We interpret the circumstellar optical flux as due to a scattering process, with the scatterers located in the extremely puffed-up inner rim of the disk, and possibly also in a bipolar outflow seen pole-on. A non-LTE gaseous origin in an inner disk cannot be excluded, but is considered highly unlikely.

Conclusions. This direct detection of a significant amount of circumbinary light at optical wavelengths poses several significant questions regarding our understanding of post-AGB binaries, and of the physics in their circumbinary disks. Although the identification of the source of emission/scattering remains inconclusive without further study on this and similar objects, the implications are manifold.

Key words. Stars: AGB and post-AGB – Circumstellar matter – Binaries: general – Techniques: interferometric – ISM: jets and outflows – Scattering

1. Introduction

Waters et al. (1993) defined 89 Her as the prototype of a new class of post-AGB binaries surrounded by circumbinary dust disks. Subsequent studies (de Ruyter et al. 2006; van Winckel et al. 2009) found a link between binarity and the presence of both hot and cool circumstellar material for many high galactic latitude supergiants. **The infrared excesses are very similar to those observed for young stellar objects (YSOs) and strongly suggest a disk-like origin in all these sources (Gielen et al. 2011, and references therein).**

The orbital elements of post-AGB binaries show their companion stars to be most likely on the main-sequence and to have separations of ∼1 AU (van Winckel et al. 2009), too small to harbor an AGB star. Moreover, most post-AGB binaries are still O-rich (Gielen et al. 2011), which suggests that their evolution was short-cut during a very short-lived phase. In this phase a significant part of the primary's mass is expelled into a circumbinary orbit, while avoiding a common envelope situation (see e.g. Mastrodemos & Morris 1998; van Winckel 2003; Frankowski & Jorissen 2007). Due to the large and badly-constrained distances, luminosities are not well-known, thereby hampering progress in connecting them to other classes of the binary zoo. But disk formation is found to be a mainstream process around evolved stars, as was recently found in the LMC (van Aarle et al. 2011).

* Based on observations made with ESO Telescopes at the La Silla Paranal Observatory under programme ID 079.D-0013 and 089.D-0576.

Table 1: The stellar and binary parameters of 89 Herculis.

Parameter	Value	Error	References
Sp.T.	F2Ibe	-	-
Teff (K)	6550	100	1,2
log g	0.55	0.25	1,2
[Fe/H]	-0.5	0.2	1,2
P_{orb} (d)	288.36	0.71	3
e	0.189	0.074	3
$a_1 \sin i$ (AU)	0.080	0.007	3
f(m) ($M_\odot$)	0.00084	0.00022	3
i(°)	12	3	4
π (mas)	0.76	0.23	5
d (kpc)	1.5	$^{+1.0}_{-0.5}$	5

References. (1) Luck et al. (1990), (2) Kipper (2011); (3) Waters et al. (1993); (4) Bujarrabal et al. (2007); (5) van Leeuwen (2007)

With the coming-online of optical/near-IR interferometers, it is now possible to resolve the prevailing circumstellar geometries for stars all over the HR-diagram, from optical to mid-IR wavelengths. For YSOs this has led to the discovery of an empirical size-luminosity relation (Millan-Gabet et al. 2001; Monnier & Millan-Gabet 2002), that led to the current paradigm (Dullemond & Monnier 2010) of a passive dusty disk with the inner radius set by the dust sublimation distance, and an optically thin cavity within. The appearance and evolution of YSO and binary post-AGB disks are likely dictated by the same processes, but differences in gravity, luminosity and evolutionary timescales should lead to different disk evolution. Disks around binary post-AGB stars have been much less the subject of interferometric study. A few objects were investigated (Deroo et al. 2006, 2007) with the MIDI and AMBER instruments on VLTI, providing the final piece of evidence that the IR-excess arises from a very compact disk-like geometry. **But a detailed analysis of the compact structures remains to be performed.**

We present in this paper the first detailed multi-wavelength interferometric analysis of the prototypical object 89 Herculis. Bujarrabal et al. (2007) presented some N-band interferometric data in addition to their PdBI CO maps. The latter contained two nebular components, 1) an extended hour-glass-like structure with expansion velocities of 7 km s^{-1}, and 2) the unresolved, smaller than 0.4″, Keplerian disk with a velocity dispersion of only 5 km s^{-1}. They also derived the inclination of the system under the assumption that the symmetry axis of the resolved outflow is perpendicular to the binary orbital plane (Table 1). Attempts to spatially resolve any extended structure at optical and mid-IR wavelengths with the HST (Siódmiak et al. 2008) and VISIR/VLT (Lagadec et al. 2011) failed to detect any emission at angular scales beyond ~50 and ~300 mas respectively.

We collected a large set of observations from the VLTI, NPOI, PTI, IOTA and CHARA interferometers covering 0.5 to 2.2 μm and with baselines from 15 to 278 m. Here we describe these observations and our simple geometric analysis. With these results the SED is then redefined. In Paper II, a detailed radiative transfer modeling will be attempted to reproduce our observables.

2. Observations and data reduction

2.1. Interferometry

A log of all interferometric observations is presented in Table 2. Below we discuss the individual data sets. Figure 1 shows the obtained uv-coverage. Figs. 2, 3, 4 and 5 (some only available online) depict the near-IR calibrated visibilities and IOTA closure phases. The optical visibilities are visible in Figs. 5 and 6.

2.1.1. Near-IR

VLTI 89 Herculis was observed with the AMBER instrument (Petrov et al. 2007) on the Very Large Telescope Interferometer (VLTI) using the Auxiliary Telescopes (ATs) in 2007, 2008, and 2012, all in the low-spectral-resolution (R=30) mode covering the H and K bands with DITs of 25 and 50 ms, and without the use of fringe tracker FINITO. 89 Her is quite Northern for the Paranal site, hence observing conditions were never excellent. In ’07 the observations occurred under good atmospheric conditions, with good seeing **(**~ 0.8″**)** and coherence time **(2.5-3.0 ms)**, in ’08 conditions were a bit worse **(**~ 1.0″**,2.5 ms)**, and in ’12 they were bad **(**> 1.0″**, 2 ms, and variable)**. The data were reduced with *amdlib* v3.0.3, provided by the Jean-Marie Mariotti Center (JMMC) (Tatulli et al. 2007; Chelli et al. 2009), and calibrated with observations of HD165524 (Mérand et al. 2005).

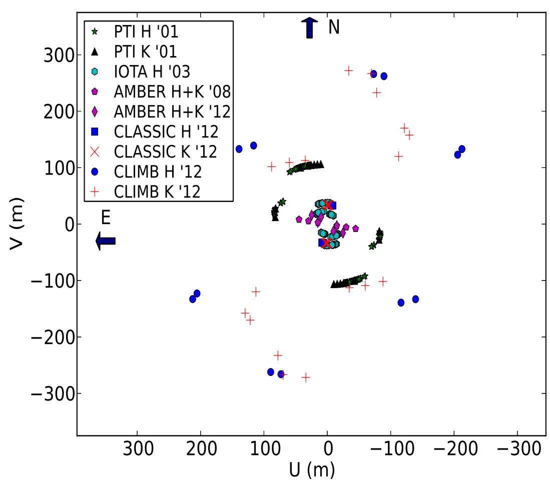
The 10% of best **signal-to-noise ratio (SNR)** frames were used for visibility amplitude estimation, while 80% of all frames were used to compute the closure phases. The exact values of these thresholds have little influence on the final numbers. A small correction to the wavelength table, in the form of a linear offset of -0.08, -0.08 and -0.07 μm for ’07, ’08 and ’12 respectively, was performed to align the H-K discontinuity correctly. Although the final calibration only used the actual calibrator, we checked the consistency of the calibration and the stability of the transfer function by repeating the calibration with each calibrator observed during that night. The generally small spread from this procedure was added to the final error budget to account for the lack of a second dedicated calibrator measurement in the ’07 and ’08 data set. Although the ’07 and ’08 data were observed at the same spatial frequencies, the visibilities are very different. The difference is larger in H-band, but also the short-wavelength end of the K-band is affected, showing that it is not just the absolute calibration in H-band. The largest effect is observed for the shortest baselines. Based on our careful analysis, and the stability of the transfer function, we can not find a reason why the visibilities are so different, and so the observed trend might be a real time-variable effect. Nevertheless, we decided not to use the ’07 data in our analysis because they are clearly discrepant from the ’08 data, which in turn are consistent with the 2003 IOTA, and ’12 VLTI and CHARA results.

CHARA Both the CLASSIC and CLIMB beam combiner on the Georgia State University (GSU) Center for High Angular Resolution Astronomy (CHARA) interferometer were used to conduct observations in the H and K bands. The CHARA Array, located on Mount Wilson, is a 6-telescope Y-shaped interferometric array and contains the longest optical/IR baselines currently in operation (ten Brummelaar et al. 2005). Its 15 baselines, ranging from 34 to 331 m, provide resolutions up to ~0.5 and ~0.2 mas at near-IR and optical wavelengths respectively. In May 2012 observations were performed with the sensitive two-beam “CLASSIC” beam combiner in both H and K band, using the S1S2 34m baseline. Also three-beam CLIMB observations, in H and K band, were obtained during three nights in July 2012 on three different station triplets with baseline lengths from 150 to 278 m. Conditions during all nights were good and stable. Data reduction and calibration was carried out with standard CHARA Array reduction software (ten Brummelaar et al.

Table 2: The observing log of our interferometric observations.

Date	Mean MJD	Instrument	Stations	Nr. Obs.	$\lambda(\mu m)$	$\delta\lambda$ (μm)	Calibrators[a]
2001 May 8	52037.5	PTI	NW	8	1.65	0.05	HD166014, HD168914
2001 Jun 6	52066.4	PTI	NW	5	1.65	0.05	HD166014, HD168914
2001 Jun 23	52083.3	PTI	NS	7	2.1	0.1	HD166014, HD168914
2001 Jul 2,15	52098.5	PTI	NW	7	1.65	0.05	HD166014, HD168914
2001 Jul 28	52118.2	PTI	NW	2	2.1	0.1	HD166014, HD168914
2001 Aug 2,6,10,11,18	52132.	PTI	NS	27	1.65	0.05	HD166014, HD168914
2003 Jun 10	52800.3	PTI	NS	7	1.65	0.05	HD166014, HD168914
2003 Jun 15,16	52805.8	IOTA	N35-C10-S15	23	1.65	0.25	HD166014, HD168914
2007 Apr 13	54203.38	AMBER	E0-G0-H0	1	1.50-2.50	0.03	HD165524
2008 Mar 31	54556.39	AMBER	E0-G0-H0	1	1.50-2.50	0.03	HD165524
2011 Jun 8	55720.5	VEGA	S1-S2	1	0.672	0.015	HD168914
2011 Aug 24	55797.5	VEGA	E1-E2	1	0.672	0.015	HD168914
2011 Oct 9	55844.16	NPOI	AC0-AE0	7	0.56-0.85	0.025	HR6787
2011 Oct 9	55844.16	NPOI	AE0-AW0	7	0.56-0.85	0.025	HR6787
2012 May 1	56048.43	CLASSIC	S1-S2	4	2.13	0.3	HD162828, HD163948, HD164730
2012 May 1	56048.48	CLASSIC	S1-S2	2	1.65	0.2	HD161239, HD164730
2012 June 27	56105.15	AMBER	A1-C1-D0	1	1.50-2.50	0.03	HD165524
2012 July 3	56111.46	CLIMB	S2-E2-W2	1	2.13	0.3	HD166230
2012 July 4	56112.41	CLIMB	S1-E2-W2	2	2.13	0.3	HD166230, HD168914
2012 July 7	56115.43	CLIMB	S1-E2-W1	2	1.65	0.2	HD166230, HD168914

Notes. [(a)] Calibrator UD diameters (mas): HD166014 = 0.58±0.03, HD168914(R) = 0.45±0.03, HD168914(HK) = 0.46±0.03, HD165524 = 1.11±0.02 (Mérand et al. 2005), HR6787 = 0.34±0.02, HD162828 = 0.72±0.05, HD161239 = 0.62±0.04, HD163948 = 0.52±0.03, HD164730 = 0.75±0.05, HD166230 = 0.41±0.03



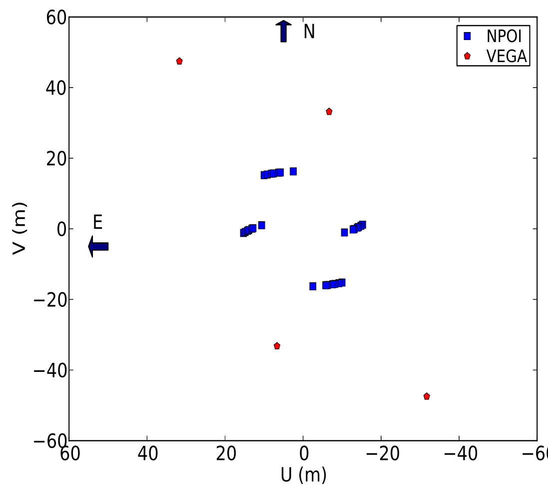


Fig. 1: Baseline coverage of our observations. Left panel: the total near-IR UV-coverage, right panel: total optical UV-coverage.

2012). Calibrators were selected with the JMMC SearchCal tool (Bonneau et al. 2006). All calibrators are less than 7.5° away from the science target, have a brightness difference of at most 1 mag at the wavelength of observation, and have visibility accuracies better than 7% at the resolution of our observations. The final calibration uncertainties include both the scatter of the data, from the repeatability of the measured calibrator visibility amplitude, and a term accounting for the calibrator diameter uncertainties. The latter contribution is negligible for the CLASSIC data but becomes important for the long CLIMB baselines.

PTI We retrieved and calibrated observations from the Palomar Testbed Interferometer (PTI) archive, which is made available by the NASA Exoplanet Science Institute (NExScI)[1]. PTI was a near-IR interferometer consisting of three 40 cm apertures at fixed separations of 85 to 110 m and that were combined pairwise (Colavita et al. 1999). Observations were performed in 4 and 5 spectral channels covering the H and K band respectively. The data reduction was performed on site (Colavita 1999), leaving only the calibration to be done with the *nbCalib* tool (provided by the NExScI, Boden et al. 1998). 89 Her was observed during 30 nights between 1999 and 2003, equally spread over the H and K bands. Only in 2001, the NW baseline was used during some nights, all other observations were taken with the NS baseline. Four of the 30 nights were discarded due to inconsistent estimates of the visibility calibration when using different calibration measurements. Since all observations at the same physical baseline give the same visibility within their (small) errors, and probe the same uv-coordinates, we select in the K-band one particularly stable night per baseline, to avoid too large a

[1] http://nexsci.caltech.edu

weight of the PTI data in the LITpro modeling (Sect. 3). In the H-band all data are retained as their number matches that of the IOTA data set. The two calibrators were originally selected using getCal, an SED-fitting routine maintained and distributed by the NExScI, but we fetched their angular diameters (well below the resolution limit of PTI) with SearchCal for HD168914 and from the catalog of van Belle et al. (2008) for HD166014. Since SearchCal quotes a significantly smaller angular diameter (~30%) for the latter calibrator, we checked and confirmed the value found by van Belle et al. (2008) by fitting Kurucz model atmospheres to archival photometry using the same tools as described in Sect. 4. The final precision of the PTI observations is ~5%, typical for PTI and an object of the given brightness.

IOTA Eight and fifteen observations of 89 Her were obtained at the IOTA interferometer (Traub et al. 2003) on 2003 June 15 and 16 respectively. IOTA was located on Mt. Hopkins (AZ) and consisted of three 0.45 m telescopes that were movable about 17 stations along two orthogonal linear arms. Our observations were done at stations N35-C10-S15. They included three simultaneous baselines using the broadband H filter. The light beams from the three telescopes were interfered using the single-mode IONIC3 combiner (Berger et al. 2003). The data reduction was the same as described in previous IOTA papers (e.g. Monnier et al. 2006). Also closure phases were procured with a precision of 1-3°. The same calibrators were used as for the PTI.

2.1.2. Optical

NPOI The Navy Precision Optical Interferometer (NPOI) was described by Armstrong et al. (1998). Observations of 89 Her were carried out in October of 2011, but only in one night were the seeing conditions good enough to allow further analysis of the data. For technical reasons, only two baselines were available, between the astrometric east (AE) and center (AC) station, and between the latter and the west station (AW). Therefore, no closure phase data were recorded. Additional “incoherent” observations away from the fringe packet were recorded for each star in order to determine the visibility bias. As a calibrator, HR 6787 was interleaved with the seven observations of 89 Her. The data reduction followed the steps outlined by Hummel et al. (2003). The calibrator diameter was estimated to be 0.34 mas based on apparent magnitudes and colors, implying that it was unresolved by the interferometer. Calibration uncertainties based on the repeatability of the calibrator visibility amplitude ranged from a few percent in the reddest channel (channel 1, 860 nm) up to about 10% in the bluest channel (channel 16, 560 nm).

CHARA Two observations were performed in June and August 2011 with the Visible spEctroGraph And Polarimeter (VEGA instrument, Mourard et al. 2009) integrated within the CHARA Array. VEGA was used to recombine two telescopes, first S1S2 (34m) and then E1E2 (62m). The spectrograph is designed to sample the visible band from 0.45 to 0.85 μm and VEGA is equipped with two photon counting detectors looking at two different spectral bands. The observations were performed with the medium resolution setting of R=6000 under average to poor seeing conditions ($r_0 \sim 4-7$cm), with HD168914 as the calibrator.

The data reduction method is fully described in Mourard et al. (2009) and we only summarize it shortly here. The spectra are extracted using a classical scheme of collapsing the 2D flux in one spectrum, wavelength calibration using a Th-Ar lamp, and normalization of the continuum by polynomial fitting. The raw squared visibilities were estimated by computing the ratio of the high frequency energy to the low frequency energy of the averaged spectral density. The same treatment was applied to the calibrators, whose angular diameter was estimated with SearchCal.

The signal was extracted from a band of 15nm centered around 672.5nm. Given the limited SNR, it was not possible to extract a useful differential signal over the Hα line.

2.2. Photometry

Photometric measurements with reliable transmission curves and zeropoints were already analyzed in de Ruyter et al. (2006) (i.e. GENEVA, IRAS, JCMT), but we also included AKARI data (Murakami et al. 2007), UV photometry from TD1 (Thompson et al. 1978) and from the ANS satellite (Wesselius et al. 1982), JOHNSON 11-band measurements (Ducati 2002) and Stromgren points from the GCPD (Mermilliod et al. 1997). Also DIRBE photometry (Smith et al. 2004) in the 3.5, 4.9 and 12 μm bands were included, as well as the WISE W4 band (Cutri & et al. 2012). Other bands in the latter systems were excluded, because of too large errors or saturation effects. Near-IR JHK photometry of 89 Her was obtained at a mean UT = 19.645 October 2012 with the Mount Abu 1.2m telescope using the 256x256 HgCdTe NICMOS3 array of the Near-Infrared Imager/Spectrometer, which has a similar spectral response as the 2MASS system. The details of the observing and data reduction techniques are given in Banerjee & Ashok (2002). Calibration was done with the standard star SAO 86043.

2.3. Spectroscopy

89 Her was observed with the SWS and LWS spectrometers onboard ISO. We downloaded from the archive the reduced and calibrated spectrum, which covers 2.5-120 μm. The features in this spectrum were already analysed by Molster et al. (2002), so we refer to this paper for more information. The absolute calibration of the spectrum agrees very well with the retrieved IRAS, AKARI, DIRBE and WISE photometry, but flux levels at near-IR wavelengths seem to be slightly overestimated.

A near-IR spectrum was retrieved from the atlas of medium-resolution K-band spectra published by Wallace & Hinkle (1997). Despite the limited resolution and SNR, the spectrum shows the CO 2-0 and higher vibrational modes in emission, pointing at the presence of a high column density of hot gas.

89 Her is part of our spectroscopic monitoring program of evolved binaries (see e.g. Van Winckel et al. 2012; Gorlova et al. 2012) with the HERMES spectrograph (R=85000, 3770-9000 Å, Raskin et al. 2011) on the 1.2 m Mercator Telescope at the Roque de los Muchachos Observatory, La Palma. A detailed account of this large set of high-resolution spectra will be presented elsewhere, here we simply use some of them, i.e. those with good SNR and close in time to the interferometric observations and to suitable calibrator observations (Table 3), as an independent constraint on the optical continuum spectral slope. The latter can be calibrated well thanks to the high stability of the HERMES instrument, which is monitored by measuring standard stars each night. We use these standard star measurements for our a posteriori spectral shape calibration. The intrinsic calibrator spectrum was determined by fitting a reddened Kurucz model atmosphere (Kurucz 1993) to high-quality archival photometry (obtained from the same catalogs as described above, see Sect. 4 for a description of the fitting procedures). After convolution to a lower

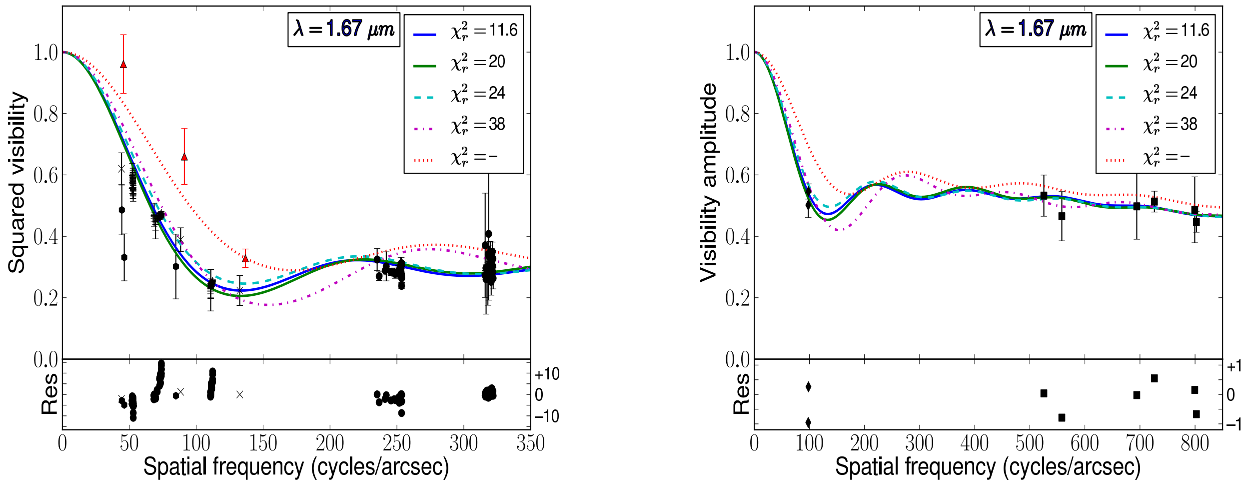


Fig. 3: Left: the AMBER (crosses: '08, pentagons: '12), PTI (circles) and IOTA (plusses) H-band squared visibilities. Right: the CHARA Array CLASSIC (diamonds) and CLIMB (squares) H-band visibility amplitudes. The red triangles are the '07 AMBER data which are treated separately. In both plots the same five geometric star+ring models are depicted. The full blue and green, dashed cyan, and dot-dashed magenta lines are models with inner diameters and widths equal to 3.0 and 4.6, 4.1 and 4.0, 1.0 and 5.5, and 5.0 and 2.5 mas respectively. The dotted red line is the best-fit model to the '07 AMBER data (see text). The legend denotes the χ_r^2 value of the corresponding model, except for the red one, which formally has too few datapoints.

Table 3: Observing log of the HERMES spectra that were used to obtain optical spectral slopes.

Date	MJD	Calibrator	V_{cal}	Sp. T.	$T_{exp,cal}$ (s)	$T_{exp,sci}$ (s)	$Airmass_{cal}$	$Airmass_{sci}$
2011 Aug 05	55779.38	HD152614	4.38	B8V	330	120	1.06	1.01
2011 Sep 21	55826.35	HD185395	4.48	F4V	360	150	1.09	1.07
2011 Oct 09	55844.32	HD184006	3.77	A5V	190	120	1.09	1.11

resolution wavelength grid, the intrinsic calibrator spectrum, and the measured counts of both science and calibrator spectrum, are normalized at 7400 $\AA$, where the HERMES throughput is maximal. The calibrated result is then the product of the intrinsic calibrator spectral shape with the measured science one, divided by the measured calibrator spectral shape. The scatter between calibrations with different calibrators and exposures is small.

3. A geometric analysis

In this section we fit and analyse the near-IR and optical interferometric data with simple geometric models, using the efficient LITpro software (Tallon-Bosc et al. 2008) provided by the JMMC, to deduce sizes and flux ratios of the different physical components. We start with the near-IR because of our experience with similar data on other disk sources, and then continue with the unexplored optical regime. Given the non-detection of large scale nebulosity at optical and mid-IR wavelengths, there is no need to take into account potential field-of-view (FOV) issues.

3.1. A ring in the near-IR

We first describe the general fitting process and then compare the results for the H and K bands. Our prime interest in this study is to constrain the broadband morphology of the object. We choose not to use the full spectral capabilities of AMBER (which are even in the LR mode significantly better than for the other instruments) and PTI, and for simplicity select the wavelength channels that are closest to the central wavelengths of the CLIMB, CLASSIC and IONIC3 broad passbands. Although a small bias might be introduced, the smooth and monotonic wavelength-dependence of the visibility validates our approach.

Monnier & Millan-Gabet (2002) argued that fitting near-IR visibilities of protoplanetary disks with a uniform ring model is well justified: in the standard model of a passive disk, the near-IR emission is dominated by the hottest dust at the sublimation radius. This simple model works well, if the inclination is small and if the region between the central star and the inner rim is optically thin. The first condition is certainly fulfilled for 89 Her (with i~10-15°) so we use such a pole-on star+ring model. In Sects. 3.2 and 3.4 we discuss the properties of the central binary and how it affects our observations in more detail, here we assume a single star at the center of the ring. Our model parameters are the angular diameter of the post-AGB star $\theta_\star$, the inner diameter of the ring $\theta_{\rm in}$, the width of the ring $\Delta(\theta_{\rm in}/2)$, and the flux ratio of the two components $f_\star = F_\star/F_{\rm tot}$ and $1-f_\star = F_{\rm ring}/F_{\rm tot}$. The visibility is computed as $V = f_\star V_\star + (1-f_\star)V_{\rm ring}$.

Table 4 lists the parameter space that was examined. The good uv-coverage allows to constrain the size and flux contribution of the uniform ring, independent of any assumptions or spectral fitting. A first estimate of the flux ratio was determined from the height of the visibility plateau at the highest spatial frequencies, where $V_{\rm ring} \sim 0$ and $V_\star \sim 1$. The K-band spatial resolution is insufficient to be sensitive to $\theta_\star$. Stellar diameters >0.6 mas only fit the H-band data when combined with large stellar flux contributions and specific ring sizes (so that its higher lobes compensate the visibility drop due to the large $\theta_\star$), and are assumed to be local minima. The H-band data are most compatible with $\theta_\star = 0.45 \pm 0.15$ mas, which is also found from SED-fitting in Sect. 4, and we fix this value in what follows. The

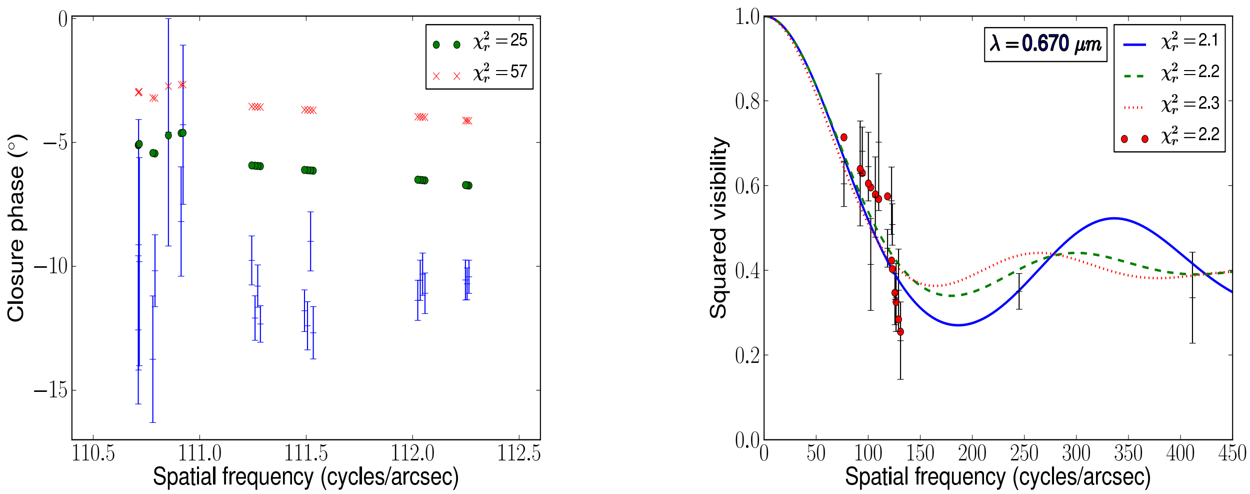


Fig. 5: Left panel: the 2003 IOTA closure phases on which the astrometric fit of Sect. 3.4 was based, together with two models, as a function of the maximal spatial frequency in the baseline triangle. The green circles are for a model including only the post-AGB star offset to a position (x,y) = (-0.4,-0.4) mas. The red crosses illustrate the effect of adding the secondary at a position (+0.4,+0.4) mas and contributing 10% of the total flux. Right panel: squared visibilities at 673 nm with some models overplotted. The blue, green and red lines correspond to star+ring models with ring diameters and widths of (5.5,1.0), (3.0,3.0) and (1.0,4.5) respectively. The red filled circles correspond to the best binary model deduced in Sect. 3.2 and online Fig. 7. The other wavelengths are shown online in Fig. 6. The legend lists the χ^2_r value which is the same for all four models.

global χ^2_r minimum was found through a Levenberg-Marquardt optimisation, starting from the best minimum found in the χ^2_r-maps of the ring parameters for a range of flux ratios.

The best-fit values are listed in Table 4. The χ^2_r-maps for the best-fit flux ratios are shown in Fig. 8, and the best-fit model visibility curves in Fig. 3 and 4 (available online). Their left panels also contain the AMBER '07 data in red, to which a fit was made in the H-band, by fixing $\theta_{\rm in}$ to 1 mas and leaving the flux ratio and ring width free. This gives a slightly increased stellar flux contribution of 60% (vs. 55% in the general best-fit model) and a ring width of 4 mas, similar as in the optical (see Sect. 3.3).

The simple model fits the observations well, as is evidenced by the low χ^2_r-values. The best-fit ring is similar in the H and K bands. Particularly in H, but also in K band, a small degeneracy still exists between the ring's inner diameter and its width, with a slight preference for smaller diameters in combination with larger widths. This means there is flux coming from radii close to the binary orbit, which is in contrast to our original assumption that the emission is coming from dust in a well-localised inner rim. A wide uniform ring works well, but is not perfect.

3.2. The central binary in the optical?

As shown in Fig. 5, our measured optical continuum visibilities are lower than expected for a uniform disk (UD) of $\theta_\star$ = 0.45 mas, and don't have the spatial frequency dependence of such a simple geometry. It is unlikely that we resolve the binary as the companion is probably still on the main-sequence and hence too faint. However, accretion disks, already inferred from spectral monitoring by several authors for similar objects (see e.g. Witt et al. 2009; Gorlova et al. 2012), are typically hot and can contribute significantly at optical wavelengths, yielding a binary-like signature in the observations. Because the VEGA and NPOI data were obtained at different orbital phases of the binary system, we analyzed the most extensive snapshot, i.e. the NPOI data, first. Already from this analysis, the binary model can be ruled out, as detailed below.

Since the flux ratio can be wavelength dependent, we selected a subset of three wavelengths that cover the full spectral range, i.e at 562, 673 and 859 nm. Given the lowest squared visibility of ~0.2 (Fig. 5), the flux ratio $F_\star/F_{\rm sec}$ should be well within the range $\{0.2, 5.0\}$. Starting from equal fluxes, and assuming diameters of 0.45 and 0.5 mas for the post-AGB star and the accretion disk respectively, we search for the best relative position of both components. Then, the flux ratios and position are iteratively adjusted to find the global minimum. The data do not constrain the flux ratios well, but the exact values do not influence the minimal separation needed to fit the data. Thanks to the good baseline position angle coverage, the positional minimum is rather well defined, except for the 180° ambiguity that can only be resolved with closure phases. The minimal separation is 2 mas (for flux ratios of 5.0, 2.2 and 1.4 at 562, 673 and 859 nm respectively), and this value does not depend on the exact post-AGB and accretion disk diameters. The squared visibilities of the best-fit binary model are displayed in Figs. 5, and 6, and the χ^2_r-map of the secondary's relative position is shown in Fig. 7.

At a distance of 1.5±0.5 kpc, the required angular separation converts into a minimal physical separation of $\rho = 2$ AU at the NPOI epoch. The smallest semi-major axis that can accomodate such a projected separation, is for an orbit in which the time of the NPOI measurement would correspond to apastron passage, and with $\omega = 0°$. In that limiting case, also assuming the maximal eccentricity of 0.25 (see Table 1), $a = \rho/(1+e) = 1.6$ AU. For 89 Her's period of 288 days this implies a minimal total system mass of 6.6 $M_\odot$. If the primary is a post-AGB star of ~0.6 $M_\odot$, the inclination is 3.2°, as derived from the spectroscopic mass function.

Such a high total mass can not be reconciled with a post-AGB status for the primary, because it would require an extremely efficient mass transfer, and an original primary mass

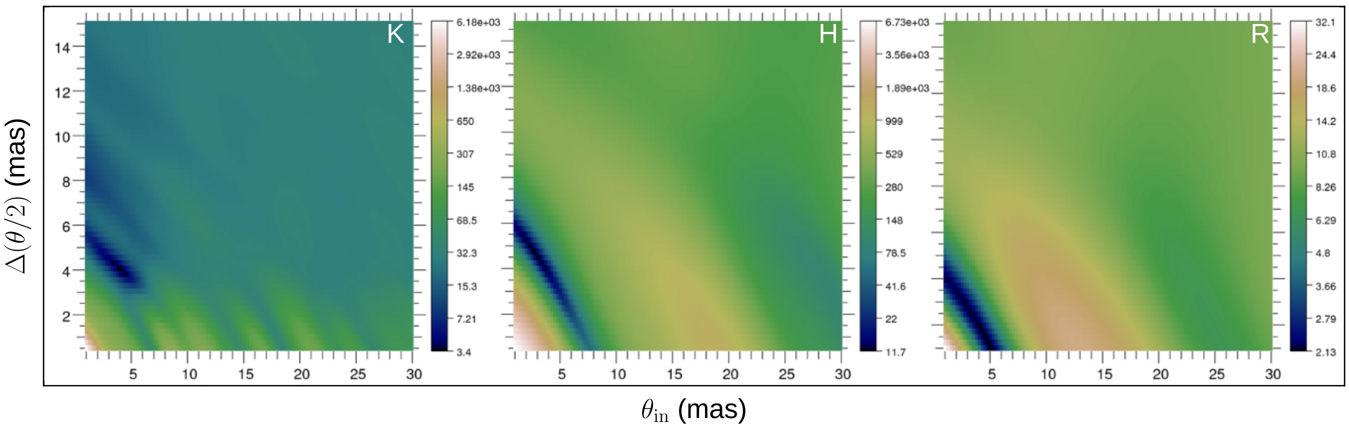


Fig. 8: χ_r^2 maps of the ring's geometric parameters for the star+ring model that was fitted to the three different visibility data sets. From left to right: K, H and R-band.

Table 4: The parameter space for a star+ring model searched with LITpro, and the final best-fit values.

Parameter	Range	Best H	Best K	Best optical
$F_\star/F_{tot}$	(0.0,1.0)	0.56 ± 0.05	0.28 ± 0.05	0.65 ± 0.07
F_{ring}/F_{tot}	(0.0,1.0)	0.44 ± 0.05	0.72 ± 0.05	0.35 ± 0.07
$\theta_\star{}^a$ (mas)	(0.2,0.7)	0.45±0.15	0.435^b	0.435^b
$\theta_{in}{}^{a,c}$	(1.0,30.0)	2.5 ± 1.0	4.1 ± 0.4	3 ± 2
$\Delta(\theta/2)^{a,c}$	(1.0,15.0)	4.5 ± 1.0	4.0 ± 0.2	3 ± 2
$\chi_r^2 \pm \sigma^d$	-	11.8 ± 0.1	3.8 ± 0.3	2.1 ± 0.1

Notes. $^{(a)}$ θ denotes diameter (mas), so $\Delta(\theta/2)$ is the width of the ring as the difference between its outer and inner radius. $^{(b)}$ Data impose no constraint, so value fixed from SED fit. $^{(c)}$ A strong correlation exists between these parameters, so the given errors reflect the range of good χ_r^2. We refer to the χ_r^2-maps for a better estimate of the confidence interval. $^{(d)}$ This is the final χ_r^2 obtained by fitting all parameters, as opposed to the χ_r^2-maps where only the shown parameters are left free. So the number of degrees of freedom is slightly different in both cases.

which is incompatible with the system's high Galactic latitude and the absence of a detected ejection velocity.

Second, there is no signature of the companion's velocity in the optical spectra (Waters et al. 1993; Climenhaga et al. 1987), which is incompatible with the required (from the flux ratio) high luminosity for this putative high-mass companion, or its accretion disk. At the minimal distance of 1 kpc the secondary's luminosity would need to be ~2100 $L_\odot$ (see Sect. 4). For a 6 $M_\odot$ main sequence star of radius 3 $R_\odot$, this implies an accretion luminosity of ~1350 $L_\odot$, and hence an accretion rate of $LR/GM = 2\times10^{-5}$ $M_\odot$ yr^{-1}, too high to be compatible with the mass loss rate derived from the P Cygni type Hα profile of ~10^{-8} $M_\odot$ yr^{-1}.

Third, although the inclination of Bujarrabal et al. (2007) is probably not precise to a few degrees, a value of 3° is hard to reconcile with the asymmetry observed in their CO-maps. And finally, the near-IR visibilities do not allow for the presence of a low-contrast 2nd stellar-like component (see Sect. 3.4), and no star (or accretion disk at a realistic temperature) is blue enough to be optically bright while being indetectable in the near-IR.

We conclude that the spatial scale and flux ratio of the central binary do not agree with what is needed to fit our optical interferometry data.

3.3. A ring in the optical

The small inner diameter of the best-fit near-IR ring, and the **similar scale found with the binary model**, motivated us to try a ring model to explain our optical data as well. The geometric star+ring model of Sect. 3.1 was fit to all the VEGA and NPOI data. Ring diameters and widths up to 50 mas were tried to allow for a strong scattered light contribution from the outer disk.

The longer-baseline VEGA observations are essential to resolve some of the degeneracies between the model parameters, especially to fix the flux ratio more precisely. The fitting strategy was the same as in Sect. 3.1. We adopted a single flux ratio at all wavelengths (see Sect. 4.1). This resulted in a good χ_r^2, while a wavelength-dependent flux ratio does not improve the fit.

Three model visibility curves, and the χ_r^2-map of the ring diameter versus its width, are depicted in Figs. 5 and 8 respectively. A uniform ring fits the optical observations very well. The size of the emitting area is rather small with an outer radius of only 3.5 to 5.5 mas. This agrees well with the fit to the AMBER '07 data. The inner diameter is not constrained. By changing the flux ratio slightly, the same χ_r^2 can be obtained for an infinitely thin ring at the outer edge (a circle) as for a ring starting at the binary orbit (a disc), and part of the emission may even originate from within it. Independent of the inner diameter, the outer radius of the ring is smaller than in the near-IR.

3.4. Improving the near-IR fit

A circumcompanion accretion disk is not causing the low optical visibilities, but could still affect our near-IR data, providing it has a low luminosity and temperature. Although we have good χ_r^2 values, the best-fit is still not perfect, and results in a rather small inner diameter. A closer look at the near-IR data offer a few arguments against a signature of the secondary in it.

A strong constraint on the secondary's near-IR flux contribution comes from the lack of visibility variations over the orbital cycle on the two PTI baselines. As the binary moves in its orbit, the projected separation onto the fixed baseline changes, thereby modulating the visibility. The visibility scatter then gives a lower limit on the contrast of the binary. **The strongest constraint is derived in the H-band, because the circumbinary disk dominates the K-band. With a continuous phase coverage over a third of the orbital cycle in 2001, we estimate a contrast >5 in H-band.**

The strongest contribution to the residuals of the best-fit star+ring model comes from the shortest and longest AMBER baseline in K, and from the two shortest IOTA baselines in H-band. A simple way to improve the general fit would be to add a small (~5%) flux component that is fully resolved already at our shortest spatial frequencies. This relaxes the visibility slope in the first lobe, and fits with the interpretation of the AMBER '07 data to be erroneous even in K-band. Note that a proper radiative transfer model, that takes scattering into account fully, typically has such a feature (Pinte et al. 2008). This is because material at radii beyond the inner rim scatters part of the inner rim thermal emission into the line-of-sight. Note that although part of this flux might fall outside the coherent FOV ($=\lambda^2/(B\Delta\lambda)$ ~20 mas) at the longest CLIMB baselines, this does not influence any of our results as the dust disk is already fully resolved at these baselines. Our estimation of the flux ratio is thus robust.

Second, we checked the compatibility of the closure phases with the expected post-AGB offset from the phase reference provided by the ring. No constraints could be derived from the AMBER and CLIMB closures due to their large errors, so we present our analysis of the more numerous and precise IOTA data. The expected range of displacements from the center-of-mass is 0.2-0.5 mas, depending on the distance, spectroscopic orbit and inclination. Fig. 10 (available online) shows the χ_r^2-map of the IOTA closure phases as a function of the post-AGB star's position with respect to the best-fit H-band ring. Even at the maximal allowed offset, there is a significant difference between the measurements and the model ($\chi_r^2 = 12.6$). The measurements are depicted in the left panel of Fig. 5, along with two models. The green circles correspond to a model in which the post-AGB star is positioned at (-0.4,-0.4) mas, which is more realistic than the boundary values preferred by the fit. For the red crosses the secondary is added at the opposite position as well, and contributes 10% of the total flux (corresponding to a flux ratio of ~5). The red model shows that if the secondary would be present at the limiting flux contribution determined above, even at a modest separation, the discrepancy between the model and measured closure phases becomes significantly worse.

There are several possibilities to explain the remaining discrepancy. First, the expected displacement could be underestimated, which could imply an overestimated distance. Second, at the given spatial frequencies, the measured closure phases will be strongly influenced by the exact geometry of the circumbinary disk, and any deviation from point symmetry in it. Here we approximate the disk with a uniform ring, whose size and width influence the closure phases directly through the cross-terms in the triple product. Given the small inclination, the skewness of the disk is insufficient to induce a strong closure phase signal if it is inherently point-symmetric. An intrinsic asymmetric illumination of the disk might be required to explain the measured closure phases. This would not be hard to imagine, given the close proximity of the best-fit ring to the central object. To properly take these effects into account at the precision level of the IOTA measurements, a detailed radiative transfer model is needed, so we did not try to improve the χ_r^2 within the current modeling framework.

3.5. Summarizing remarks

We summarize our interferometric analysis as follows:

1. Our H, K and optical visibilities, collected with different instruments and spanning a decade in time, are fully consistent with a simple geometric star+ring model.
2. The central post-AGB source only contributes 28±5%, 56±5% and 65±7% of the total received flux at 2.2, 1.65 and 0.67 μm respectively.
3. Our near-IR data exclude a geometrically thin ring. Part of the emission might stem from close to the central binary.
4. The optical ring can be either geometrically thin or extended, but its outer diameter is smaller than the near-IR one.
5. A low-contrast binary model can equally well fit the optical visibilities, but results in an unrealistic binary configuration.
6. Our largest spatial frequencies in H and K, the time series of PTI H visibilities, and the IOTA closure phases rule out the presence of a companion with a contrast ≤5.
7. It is unclear whether our closure phase discrepancy is caused by an inconsistency in the standard orbital parameters, the radial intensity distribution of our uniform ring model or an azimuthally asymmetric illumination of the inner disk rim.
8. The 2007 AMBER data deviate from all the rest, especially in H and at the shortest baselines. The latter makes an astrophysical interpretation problematic.

4. The stellar SED

In our search for the origin of the resolved optical flux, we first re-evaluated the stellar parameters. "Stellar fluxes" are obtained by combining the interferometric flux ratio (Table 4) with the total photometric fluxes. Four photometric bands (V, R, H and K) were used to refit the SED. This is insufficient to independently constrain all model parameters, i.e. the effective temperature $T_{\rm eff}$, surface gravity log g, metallicity z, interstellar reddening E(B-V) and angular diameter $\theta_\star$. So we restricted some parameters by taking spectroscopic constraints into account, as listed in Table 1. We fix the metallicity to the subsolar value of [Fe/H] = −0.5, and bound log g to {0.3,0.8} dex, $T_{\rm eff}$ to {6000,7000} K, and E(B-V)<0.25 mag.

Since the optical interferometric data correspond to the JOHNSON R-band, while the absolute magnitude is better determined in V, we chose to include both. We thus make two assumptions: 1) the stellar flux fraction is the same over the 450 to 850 nm wavelength range, and 2) the archival JOHNSON V-R color of 0.32 mag is not variable. Deviations from these assumptions are expected to be small, as a single flux fraction fits the 550-850 nm range well and because the flux-variability is dominated by low-amplitude pulsations which do not affect the V-R color too much. The error is dominated by the absolute uncertainty on the interferometric flux ratios, so our final confidence intervals should be robust. The fitted fluxes are listed in Table 1.

We fit the SED with the Kurucz (1993) model atmospheres. We use the grid-based method of Degroote et al. (2011), which allows to identify correlations between parameters and to take them into account in determining parameter uncertainties. It uses a χ^2-statistic with five degrees of freedom to determine the goodness-of-fit and confidence intervals (CI) for the five parameters. In practice, a model SED is corrected for interstellar reddening with the reddening law of Fitzpatrick (2004), then integrated over the required photometric passbands and finally scaled to the measurements by optimizing the angular diameter.

$T_{\rm eff}$ and E(B-V) are, as expected, correlated, since reddening and effective temperature similarly affect the V-K color. In the literature, different values for both parameters are quoted: based on photometry Luck et al. (1990) adopt E(B-V)=0.1 and find $T_{\rm eff}$=6400 K, while Waters et al. (1993) find the best fit for E(B-V)=0.0 and $T_{\rm eff}$=6500 K. Kipper (2011) suggests an E(B-V)>0.1 based on the equivalent width of the interstellar component of the Na I line. Spectroscopic effective temperatures are

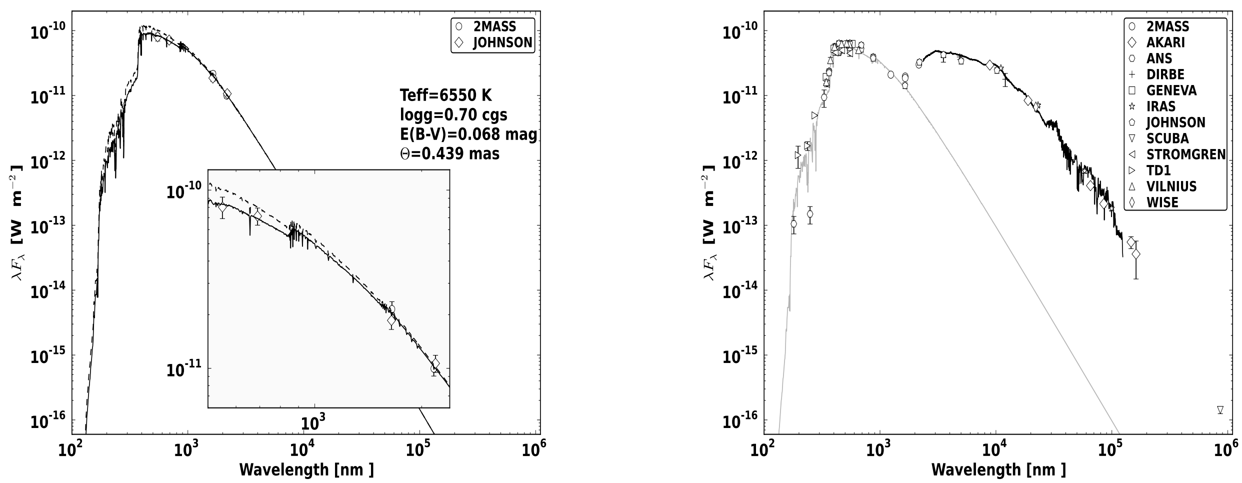


Fig. 12: Left: the observed (i.e. reddened, in full) and original (i.e. dereddened, in dashed) stellar SED model, plotted over the “stellar fluxes”. The inset shows a zoom-in on the actual measurements. Right: the circumstellar SED (not corrected for reddening), obtained after subtracting the measured total fluxes with the reddened stellar Kurucz model, overplotted with the same reddened Kurucz model (in grey) but with the angular diameter arbitrarily scaled to these “circumstellar fluxes”. Both panels have the same scales on the x and y axes to illustrate the large amount of circumstellar flux.

consistently in the range 6500-6600 K (Luck et al. 1990; Kipper 2011), except for the value of 7177 K found by Takeda et al. (2007). The latter study also found a larger gravity (log g=1.66) and turbulent velocity (v_t=8 km/s). Finally, the Galactic extinction maps of Arenou et al. (1992), Schlegel et al. (1998) and Drimmel & Spergel (2001) all give E(B-V)~0.1 for a distance larger than 1 kpc in the direction of 89 Herculis. We adopt the spectroscopic temperature of 6550 K, and E(B-V)=0.07±0.04, both fully in agreement with our new SED. The derived CI are shown online in Figure 11.

$T_{\rm eff}$ and $\theta_\star$, are not correlated strongly: the near-IR fluxes mainly delimit $\theta_\star$, since they are in the Rayleigh-Jeans regime. Our final angular diameter, at $T_{\rm eff}$=6550 K, is $\theta_\star$=0.435±0.008 mas, which is perfectly within the range determined in Sect. 3.1 based on the H-band interferometric data. The final stellar SED models are shown in the left panel of Fig. 12.

We made a stellar luminosity histogram by sampling the model parameter space according to our derived probabilities. Model bolometric fluxes are converted into luminosities by assuming a distance of 1.5 kpc. Following the measured parallax, this is the distance with the highest probability. Due to Lutz-Kelker bias and the rather large error on the parallax, it is likely an underestimate of the true distance, and hence of the derived luminosity. In general, our results are unaffected by this large uncertainty, since the same distance is consistently used to convert the interferometric angular quantities into physical scales. By imposing the spectroscopic constraint on $T_{\rm eff}$, we adopt a final luminosity of 8350 $L_\odot$, the median value of the subset of the histogram shown in Fig. 13. As a comparison we also show the histograms that would be obtained without our flux ratio correction (selecting only photometry up to J band). The median luminosity is then 13 400 $L_\odot$.

4.1. The circumstellar SED

The circumstellar SED, obtained by subtracting the stellar SED from the total fluxes, is shown in the right panel of Fig. 12, together with the stellar (but rescaled) Kurucz model. Fig. 14 contains the calibrated Hermes spectral shapes. Overplotted are three similarly convolved and scaled stellar Kurucz models with E(B-V)=0.02, 0.07 and 0.12 for the upper dashed, full, and lower dashed line respectively. The observations follow the best-fit stellar model with E(B-V)=0.07 in both figures, although a careful inspection of the Hermes spectral slopes shows that the measurements are slightly bluer in the 500-700 nm range, which could be due to (the more abundant) small emission lines or to a residual in the calibration. The Hermes spectrum is the sum of the stellar and circumstellar contribution. So the absence of a color difference between the measured spectral shape and that of the star alone, independently confirms that the process responsible for the circumstellar flux is essentially grey over the whole optical wavelength range.

A basic quantity, often used to estimate the scaleheight of a passive dusty disk (see e.g. Dominik et al. 2003), is the ratio of the infrared excess over the stellar bolometric flux $F_{\rm IR}/F_\star$. The reasoning is that it equals the fraction of the stellar luminosity that is reprocessed/redirected by the disk. This translates into geometrical terms as the fractional solid angle subtended by the disk. The latter, $F_{\rm RP}/F_\star \times 4\pi R^2$, should be equal to the disk surface area, which is that of a cylinder in a fully optically thick approximation, $2\pi R \times 2H$. We changed $F_{\rm IR}$ to $F_{\rm RP}$ since it is the total amount of reprocessed light that matters, which is not necessarily equal to the infrared excess. This leads to the relation:

$$\tan\alpha = \frac{H}{R} = \frac{F_{\rm RP}}{F_\star}, \tag{1}$$

and half-opening angles of α = 32° and α = 52°, obtained by integrating our revised stellar and circumstellar SEDs ($F_{\rm IR}/F_\star$ = 0.62 and $F_{\rm RP}/F_\star$ = 1.29). Note that we do not yet know whether all circumstellar flux is coming from the disk (see Sect. 5).

Finally, we emphasize that our finding of an essentially grey circumstellar flux is not fully independent from our previous assumptions. A wavelength-dependent flux ratio between 0.56 and 0.85 μm is possible, since our observations are not very sensitive to this. Although our CI were determined conservatively as they are dominated by the error on the optical flux ratio, a signif-

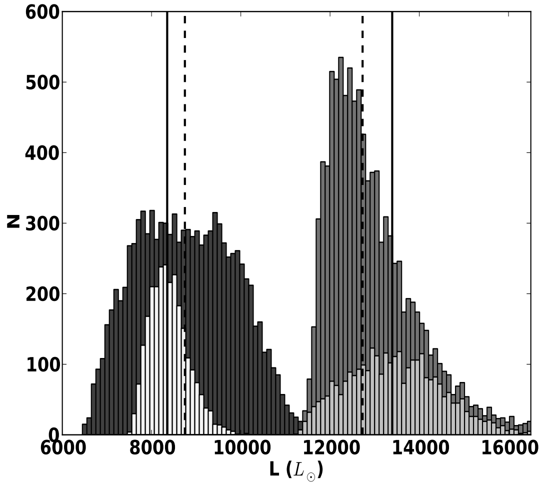


Fig. 13: The luminosity histogram of the stellar SED fit. The left and right histograms show the results of the fit to the flux-ratio-corrected and total photometry respectively. The full histogram (10000 points), is shown in dark grey, while the light grey sub-samples were obtained thanks to the spectroscopic temperature constraint. The full and dashed lines are the median values of the light and dark histograms respectively, and have values of 8350 and 8750 $L_\odot$ for our revised "stellar photometry". The histograms were made assuming a distance of 1.5 kpc.

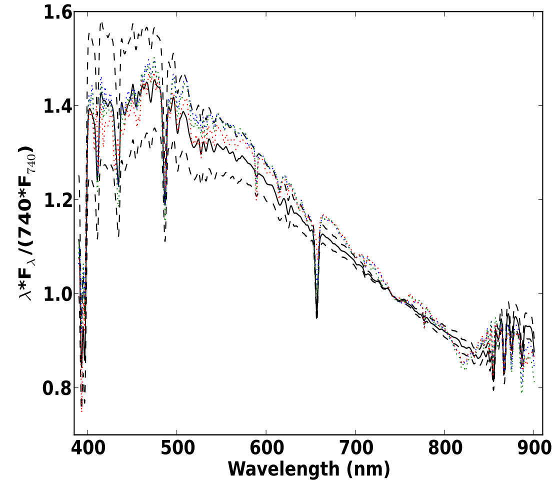


Fig. 14: The Hermes spectral shapes (dotted lines, colors denote the observation epoch) compared to spectral shapes from different atmosphere models convolved to the same resolution. The full black line is the model shown in Fig. 12. The dashed lines have the same parameters except for the reddening, which is E(B-V)=0.12 and 0.02 for the lower and upper line respectively.

icant wavelength-dependence could result in an underestimated E(B-V) upper limit. The angular diameter is not affected since our near-IR flux ratios are more robust. Our $F_\star$ follows directly from $\theta_\star$ and the spectroscopic $T_{\rm eff}$, and is independent of the reddening, while $F_{\rm RP}$ depends on it twice. First, the circumstellar fluxes in the blue part of the SED are an extrapolation: they are obtained by subtracting the *reddening-dependent* stellar Kurucz model from the measured (and still reddened) fluxes. Second, these reddened circumstellar fluxes need to be dereddened to obtain $F_{\rm RP}$. So our derived $F_{\rm RP}/F_\star$ can still be underestimated, and the circumstellar flux would then be blue instead of grey.

5. Discussion

In this study we presented the first multi-wavelength long-baseline interferometric data of a post-AGB binary with circumbinary disk that covers wavelengths from 0.55 to 2.5 μm. Our most intriguing result is the discovery of a strong resolved optical flux component. We considered two geometric models to explain our observations: a binary or a star+ring, which both technically fit our optical data equally good based on their χ^2_r. Nevertheless, we argued that the binary model is hard to understand in terms of our near-IR data, as well as from a physical point-of-view. A star+ring model offers a more natural explanation for all our optical visibilities, and is compatible in size with our near-IR findings. The optical ring can be anything between thin with a diameter of 5.5±1.0 mas (a circle), to extended with an outer diameter of 10±2 mas (a UD). Our analysis of the SED and the Hermes spectral slopes showed that the spectrum of the extended emission is very similar to that of the post-AGB star, which strongly suggests a scattering process as its origin.

In the following we discuss three ways to explain our observations **(see Fig. 15)**. Given the similarities between post-AGB and protoplanetary disks, we relate our results to both of them.

5.1. Simply the circumbinary disk

In the simplest case all optical flux is light scattered off the inner rim of the dust disk. The question is whether a passive disk can reach the necessary scaleheight ($\alpha = 52°$) and redirect the required fraction of optical light into our direction, while simultaneously avoiding to emit too much near-IR flux. The small inclination does not help, as the light will be favorably directed into the disk (see e.g. Mulders et al. 2013). Moreover, it remains to be seen whether a circumbinary disk alone fits the near-IR visibilities, as it might result in a too thin, circle-like, emission geometry. Detailed radiative transfer modeling is required to answer these questions. Here we restrict ourselves to a qualitative discussion.

Protoplanetary disks have been well studied in scattered-light images, especially with the HST (see e.g. Grady et al. 2013; Cox et al. 2013; Mulders et al. 2013, and references therein), but also with Subaru 8.2m near-IR coronagraphic imaging (Fukagawa et al. 2004, 2006) and sparse aperture masking experiments or adaptive optics imaging on the VLT (Cieza et al. 2013) or Keck (McCabe et al. 2011; Tuthill et al. 2001). These and other studies find integrated scattered light flux ratios of up to a few percent, while we find 35-40% of the total optical flux is resolved. All above methods have a limiting resolution of ~30-50 mas, which corresponds to 5-10 AU for the nearest star-forming regions at 200 pc. For all but the brightest Herbig Be sources, these scales probe the bulk of the disk and not the inner rim. Near-IR interferometers do have the required resolution, and many inner rim regions have been resolved in this way (see further), but at these wavelengths and with their typically sparse uv-coverage it is impossible to make a distinction between thermal and scattered light, contrary to the current study. To our knowledge, the only optical study of a protoplanetary disk and at a similar angular, but ten times higher spatial, resolution are the results on AB Aur with CHARA/VEGA (Rousselet-Perraut et al. 2010). They resolved the Hα line forming region at sub-AU scales, but found the continuum to be unresolved. Bonneau et al. (2011) did find a 15%, fully resolved, optical continuum flux from a circumbinary dust reservoir in the interacting binary system ν Sgr, but with rather large error bars.

No published radiative transfer disk model, at viewing angles close to pole-on, has yet predicted such a large optical scattered flux as is found here. This implies that if we probe scattered light off the inner rim, either the models are lacking an important ingredient, or post-AGB disks are different from protoplanetary ones, or even 89 Her is special in some way. In any case, evolved star disks are likely to be more puffed-up than protoplanetary ones, given their high luminosities and small central masses.

5.2. The circumbinary disk + an inner gas disk

Our results show a preference for an extended emission region, starting close to the central object. Since dust only survives beyond the sublimation radius, some of this flux may be gaseous emission from within the inner rim, not unlikely given the detection of CO emission (at 2.3 μm, needing temperatures >2000 K).

Such gaseous emission was often suggested in the literature as the missing component to explain near-IR interferometric data of protoplanetary disks. Monnier & Millan-Gabet (2002) found that certain high-luminosity sources are seriously undersized with respect to their size-luminosity relation. This was later confirmed (Monnier et al. 2005; Eisner et al. 2004) and attributed to the presence of a (geometrically thin, but optically thick?) gaseous disk within the dust sublimation radius. More evidence was claimed in the studies of Akeson et al. (2005) for some T Tauri stars, and Kraus et al. (2008) and Tannirkulam et al. (2008) for some Herbig Ae/Be sources. Only the latter study had a sufficient spatial resolution to resolve the K-band continuum emission from within the expected inner rim. They attempted to empirically derive the sources of opacity responsible for the emission from the spectral shape of the flux-deficit between 1.25 and 10 μm. A slight preference for free-free and bound-free opacity of H^- (5000 K) or neutral hydrogen (8000 K), was found over a mixture dominated by molecular opacity (2000-2500 K), due to the lack of strong molecular features between 4 and 10 μm. The former overshoots their observations at wavelengths $\leq$2 μm and produces a significant optical flux. However, they did not investigate whether such extreme conditions are physically realistic.

A more extensive data set on HD163296, one of the targets in Tannirkulam et al. (2008), was presented by Benisty et al. (2010) and compared to simple gaseous disk models in a bit more detail. The optically thick models of Muzerolle et al. (2004) were similarly rejected because of the absence of strong molecular emission features in the SED. Additionally, they presented SEDs of non-LTE gaseous components with varying densities and temperatures and showed its spectral dependence to be incompatible with the observations. It might be tempting to interpret our resolved optical flux in terms of these hot gas models, but the latter argument also holds for 89 Her. H^- is the foremost source of continuum opacity below 8000 K, while bound-free processes dominate above it. In both cases the spectral dependence is incompatible with our smooth circumstellar SED. H^- opacity reaches a maximum value at 850 nm and drops steeply shortwards.

Moreover, the source function needs a temperature >4500 K (assuming optically thick radiation) over the full emitting surface area to reproduce our visibilities and fluxes. Close to the illuminating source the combination of such a temperature with a reasonable density (hence optical depth) *might* be attainable. But due to flux dilution the temperature drops quickly with radius as a power law with exponents of 1/2 and 3/4 for a flaring or flat reprocessing disk respectively (Kenyon & Hartmann 1987). Given the large size of the post-AGB star and our observations that do not support a bright companion, accretion energy cannot contribute significantly. Since also the density drops with radius, the disk becomes very quickly too optically thin at large radii. By decoupling the gas from the dust temperature, Woitke et al. (2009) found in their detailed thermo-chemical protoplanetary disk models a hot surface layer that bends around the inner rim with temperatures in excess of 4000 K. However, the density in this small region is too low to produce a significant continuum optical depth and flux. Muzerolle et al. (2004) on the other hand found typical temperatures of only ~1100 K (assuming LTE opacities), even close to the central star. All these models are very crude and as Benisty et al. (2010) remarked, more realistic models, treating the transition from optically thin to optically thick gas layers in a dust-free environment, are needed to definitely rule inner gas disks out as a dominant effect.

Alternatively, they proposed an inner dusty disk consisting of highly refractory grains that manage to survive the low-pressure, high-temperature environment within the inner rim of the “silicate-disk”. This model reproduced their near-IR interferometric data perfectly, but required high temperatures of ~2200 K at the inner radius. Kama et al. (2009) also found solutions with a large optically thin region, covering up to 70% of the surface inside the inner rim, using a more sophisticated treatment of dust sublimation and condensation physics within a Monte Carlo radiative transfer code. It is unclear what this optically thin region holds in terms of scattered flux at pole-on viewing angles.

This geometry offers advantages as it allows for the existence of a large surface within the actual rim with possibly a distinct grain population. But several questions come up as well. First, AB Aur was found by Tannirkulam et al. (2008) to have such a smooth inner emission region in the near-IR while Rousselet-Perraut et al. (2010) did not resolve it in the optical continuum. Second, the light scattered away by this inner region cannot reach the inner rim of the optically thick part of the disk, reducing its scaleheight and therefore compensating the whole effect.

5.3. The circumbinary disk + a (bipolar) outflow

The emission morphology might be more complex. The rather large errors on the NPOI visibilities prevent a firm conclusion on any position angle dependence of the visibility, but the good fit of the binary model shows that it cannot be excluded either. A bipolar outflow seen pole-on, originating as a stellar wind or jet, might naturally give rise to the presence of small scale structure, including arc or knot-like features. There are several arguments in favor of this model. First, there is the large-scale hour-glass-like nebula discovered by Bujarrabal et al. (2007), which must have an origin in the central object. Second, bipolar outflows are commonly inferred to explain high-resolution spectroscopic time series of many classes of evolved binaries, and in particular post-AGB ones like the Red Rectangle (Witt et al. 2009; Thomas et al. 2011, 2013) or BD+46°442 (Gorlova et al. 2012). The weak, neutral or low excitation level, emission lines of metals (e.g. Fe I near 805 nm) were already interpreted by Waters et al. (1993) in terms of a collisionally excited interaction between a modest stellar wind and the circumbinary disk. The same lines, which are variable in strength but not in velocity, are seen in emission in QY Sge (Kameswara Rao et al. 2002) and BD+46°442 (Gorlova et al. 2012), but with a different width which the latter authors suggest to be an inclination effect. Also the weak and variable Hα P Cygni profile is a clear indication for a small mass loss rate of ~10^{-8} $M_\odot$ yr^{-1} (Sargent &

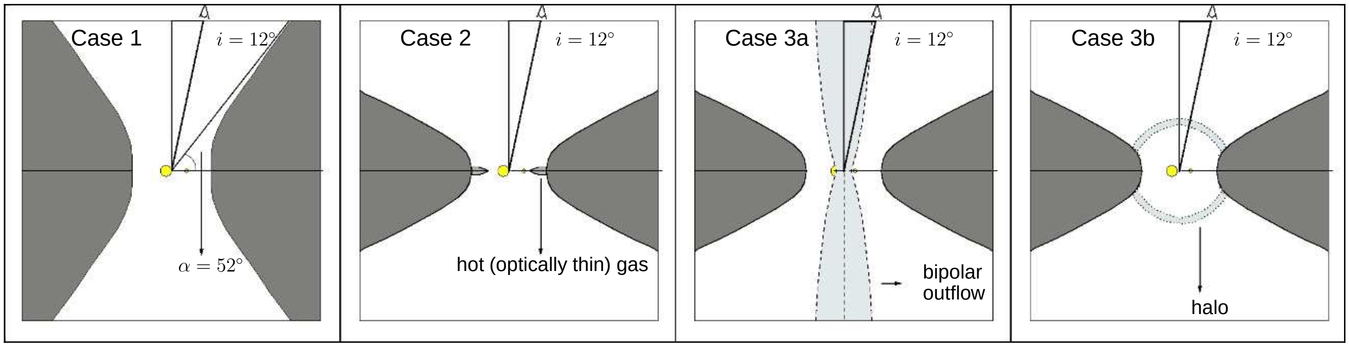


Fig. 15: Pictographic representations of the different geometries that are discussed in Sect 5.

Osmer 1969). The main question in this outflow scheme is why the scattered light is so well confined to the size of the disk inner rim (compare the panels in Fig. 8).

Jets or bipolar outflows are often detected around YSOs for a wide range of central masses, and their presence is strongly linked to accretion phenomena (Königl 1999). These jets are detected over the full electromagnetic spectrum, most notably through maser, free-free and synchrotron emission at radio wavelengths, IR molecular tracers, and in shock-excited near-IR/optical/UV spectral lines (Bally 2007). For highly obscured objects, significant bipolar reflection nebulae are seen and interpreted as scattering by dusty material within or on the walls of the outflow cavities produced by the jet (Padgett et al. 1999).

A similar explanation (but with a different origin for the dust) has been given for the HST images of bipolar planetary (PNe) and proto-planetary nebulae (PPNe) in scattered light (Kwok et al. 1998, 2000; Ueta et al. 2000; Bujarrabal et al. 2002; Cohen et al. 2004; Siódmiak et al. 2008). **Post-AGB binaries are classified as "stellar" in these HST surveys, which is corroborated by the small scale of the here found optical circumstellar flux.**

Based on optical and UV spectropolarimetry, Joshi et al. (1987) claim the presence of two geometrically distinct dust populations around HR4049, consisting of differently sized particles. Later, Johnson et al. (1999) confirm this result and associate the component with the smallest particles ($\leq 0.05\mu$m), seen mainly at wavelengths <2000 Å, to a bipolar structure. Joshi et al. (1987) found for 89 Her an even larger degree of polarization than for HR4049, but without the latter's PA dependence.

The main advantage of an outflow is that it allows to have material at a high altitude above the disk midplane that can scatter part of the light into our line of sight that would otherwise freely escape. **Although contested, optically thin haloes are an alternative way to do this and are often inferred to explain (near-IR resolved) data of protoplanetary disks (Chen et al. 2012; Verhoeff et al. 2011; Mulders et al. 2010). Explanations for halo formation go from collisions between planetesimals with highly inclined orbits (Krijt & Dominik 2011), to dust entrainment in upper disk layers where dust and gas are not thermally coupled (Woitke et al. 2009), so that the gas has a higher vertical extension (Verhoeff et al. 2011).** In any case, "haloes" are likely too optically thin if dynamically stable. In the model of Verhoeff et al. (2011), the halo contributes at most 10% of the stellar optical flux.

6. Conclusions

Our optical interferometric data show that one should be careful not to overlook a possible scattering component when establishing the energy budget in systems with significant circumstellar material as derived from the IR excess. By separating the direct stellar light from the reprocessed, circumstellar light between 0.5 and 2.2 μm, we re-assessed the stellar and circumstellar spectral energy distributio and revised the stellar luminosity of 89 Her from 13 400 to 8350 $L_\odot$, assuming a distance of 1.5 kpc. This lower luminosity corresponds to a decrease in angular (and thus also physical) diameter from the previously assumed ~0.65 to the directly measured 0.435±0.008 mas.

The circumstellar luminosity is then likewise increased, resulting in a ratio of $L_{RP}/L_\star = 1.29$, which leads to a circumbinary disk half-opening angle of 52° *if* all the observed circumstellar flux is reprocessed/redirected light by the disk. In paper II we will use a radiative transfer code to test whether a passive circumbinary disk can be created that reproduces our observations.

Alternatively, adding geometric components could ease the requirements on the scaleheight of the disk, and we discussed several possibilities. A bipolar outflow is an interesting option from an evolutionary perspective, but requires explanation in terms of projected size. A vertical extension of the disk into a kind of halo is also possible, but might be too optically thin. An inner gas disk is deemed unlikely, but definite exclusion of it requires more realistic models in non-LTE conditions.

Our redefined SEDs show that the circumstellar energy budget is in H-band already dominated by scattered light. Compared to the K-band, we find a slight preference for a smaller (projected) emission region in H-band and a clear preference in the optical, which could be a hint for the presence of material above the orbital plane that only contributes through scattering.

An important consequence of our findings is that determining luminosities of post-AGB binaries from SED fitting is even more complex than previously assumed. On top of the difficulties related to inclination, reddening and distance (still the dominant source of uncertainty), one now also has to take into account a possibly dominant scattered light contribution. Its exact origin decides whether 89 Her is an extreme or average case, and what will be the spread in scattered light fractions for other objects. If resolved observations are the only way to detect this extended optical emission, a detailed comparison of post-AGB objects with evolutionary tracks might become problematic, as distances to galactic sources will remain uncertain at least until the Gaia satellite comes online, while LMC sources cannot be resolved spatially.

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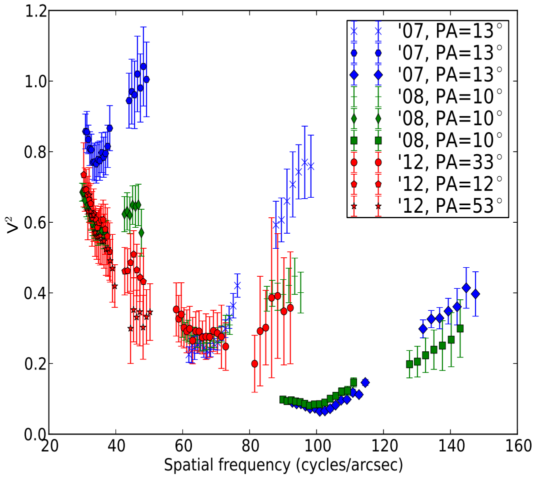

Fig. 2: The AMBER (LR-HK) squared visibilities as a function of the spatial frequency. The legend denotes the epoch and the position angle (PA) of the baseline of the observation. All '07 and '08 data have a similar PA because the same co-linear baseline configuration was used. Per baseline, the H and K band are separated by the HK-discontinuity, but still show a smooth transition between the two.

Table 1: The fluxes used in the "stellar SED" fit. For each filter, both the total flux and the stellar flux, i.e. the total flux corrected with the stellar flux fractions of Table 4, are listed.

Photometric filter	Total	Stellar	Error
JOHNSON.V	5.45[a]	6.00	0.15
JOHNSON.R	5.13	5.68	0.12
2MASS.H[b]	4.21	4.86	0.11
2MASS.Ks[b]	3.41	4.92	0.1
JOHNSON.H	4.39	5.04	0.12
JOHNSON.K	3.35	4.85	0.12

Notes. [(a)] Average of AAVSO light curve over 2011-2012,[(b)] Mt. Abu measurements.

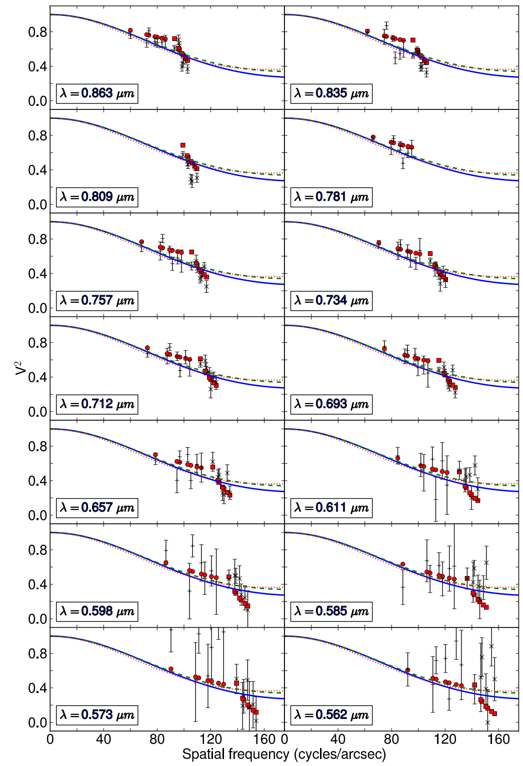

Fig. 6: All NPOI visibilities, except the 673 nm channel which is shown in Fig. 5. A different wavelength is shown in each panel, as indicated. The symbols correspond to different physical baselines, plusses for AC0-AE0 and crosses for AE0-AW0. The blue, green and red lines are the same star+ring models as in Fig. 5, and have ring diameters and widths of (5.5,1.0), (3.0,3.0) and (1.0,4.5) respectively. The red filled circles correspond to the best binary model deduced in Sect. 3.2 and online Fig. 7.

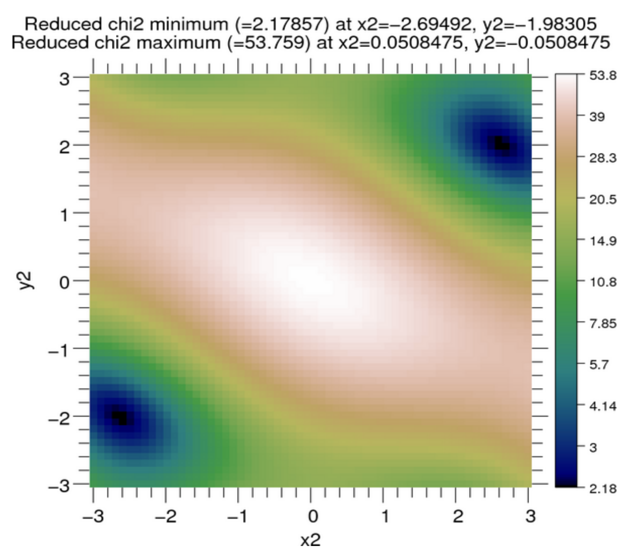

Fig. 7: The χ_r^2-map of the relative position of the secondary component with respect to the primary at the center, if a binary model is applied to fit the optical NPOI visibilities.

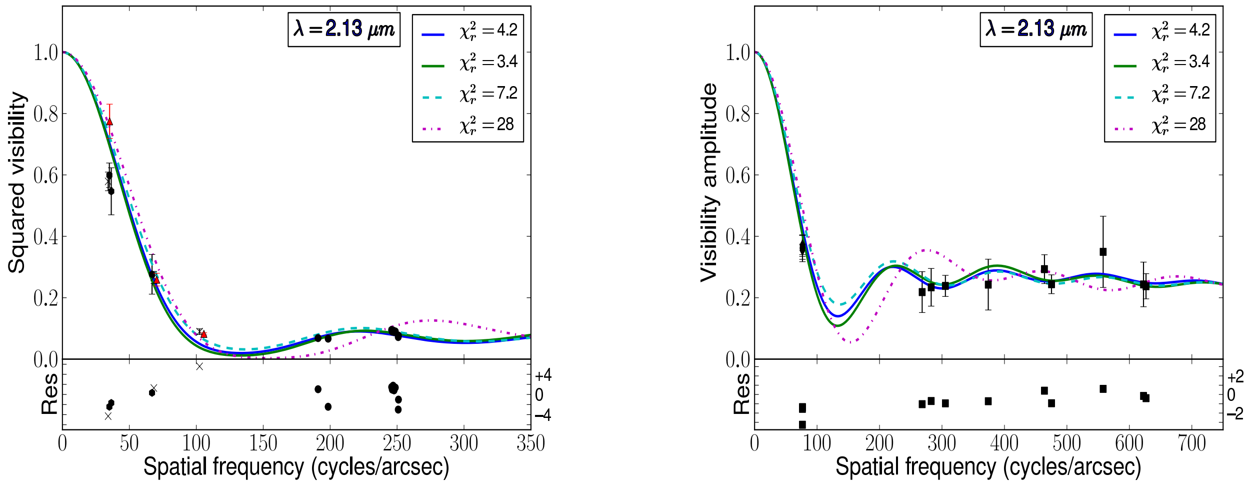

Fig. 4: The same as Fig. 3 but for K-band (for which there are no IOTA data). The red model is not relevant in K and is not shown.

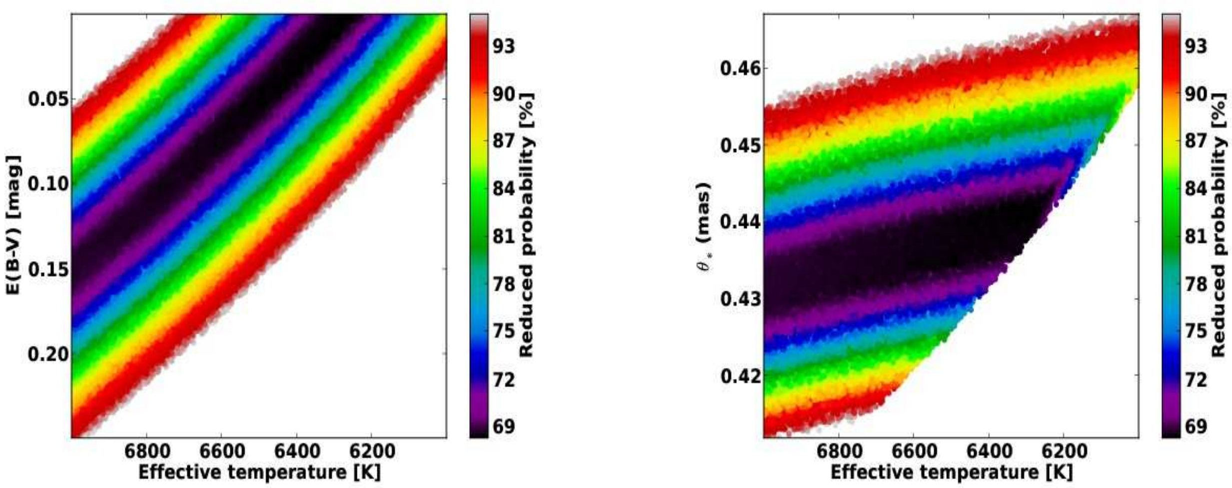

Fig. 11: Left: CI of T_{eff} versus E(B-V), right: CI of T_{eff} versus angular diameter $\theta_\star$ (mas), for the stellar SED fit.

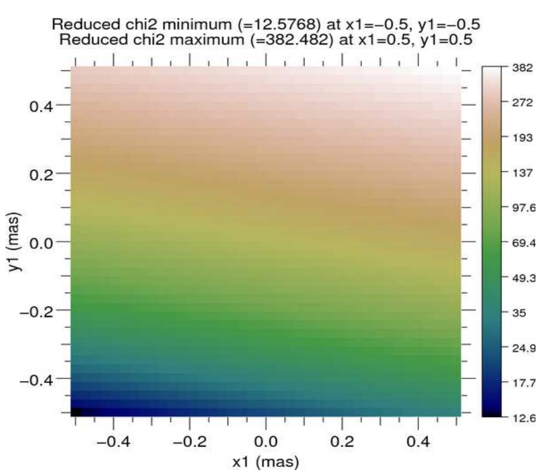

Fig. 10: The χ^2_r-map of the position x versus y of the post-AGB star with respect to the phase reference defined by the ring (inner diameter 3 mas and width 4.6 mas, see Sect. 3.4).