Near-infrared VLT adaptive optics imaging of evolved stars

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Summary. The high angular resolution and dynamic range achieved by the NACO adaptive optics system on the VLT is an excellent tool to study the morphology of Planetary Nebulae (PNe). We observed four stars in different evolutionary stages from the AGB to the PNe phase. The images of the inner parts of the PN Hen 2-113 reveal the presence of a dusty torus tilted with respect to all the other structures of the nebula. A void 0.3 arcsec in diameter was discovered with NACO around the central source. These data indicate the presence of a cocoon of hot dust (T$\sim$1 000 K) with a total mass 10^{-9}M$_\odot$ in the core of the nebula. This was not expected so close to a hot (T$_{eff}\sim$30 000K) central star, and our observations indicate that dust is present close to this central star. The NACO observations of Roberts 22 reveal an amazingly complex nebular morphology with a S-shape that can be interpreted in terms of the 'warped disc' scenario of Icke (2003). Comparing these observations with previous HST images seems to indicate that this S-shaped structure is expanding at $\sim$450 km.s^{-1}. Combined NACO and MIDI (the VLTI mid-infrared interferometer) observations of the nebula OH 231.8+4.2 have enabled us to resolve a very compact (diameter of 30-40 mas , corresponding to 40-50 a.u.) dusty structure in the core of the nebula. Finally, recent observations of the AGB star V Hydrae show that this star present a departure from spherical symmetry in its inner shell and is probably on its way to become an asymmetrical planetary nebula. These observations show that NACO is a great instrument for the discovery and study of small structures in circumstellar envelopes and PNe and a good complement to interferometric devices.

Key words: AGB, post-AGB , Planetary Nebula, Adaptive optics

1 Introduction

High sensitivity and angular resolution observations are of high interest for the understanding of PNe morphologies. Thus, the appearance of CCD detectors in the 80s and then the successful launching of the Hubble Space Telescope (HST) have helped to reveal an amazingly rich variety of PNe morphologies (see Balick and Frank

(2002)). With the installation of adaptive optics instruments on 8m-class telescopes, it is now possible to obtain good sensitivity images from the ground thanks to real time correction of the atmospheric turbulence. Combining this with the angular resolution achieved with such telescopes provides a great tool for the study of very small structures in the heart of PNe, as well as circumstellar envelopes around their precursors AGB stars and pre-PNe (PPN).

We used the adaptive optics imager NACO on the VLT, which can provide diffraction limited images in the near-infrared and spatial resolution around 60 mas in K and L bands, to observe 4 objects in different evolutionary phases from the AGB to the PNe stage. These object are surrounded by dust so that infrared imaging allows us to deeply study inner details of their envelopes or nebula. In this paper we present the results from our observations of the planetary nebulae Hen 2-113 and Roberts 22, the nebula OH 231.8+4.2 and the extreme AGB star V Hya.

2 Hen 2-113

Hen 2-113 (hereinafter HEN) is a PN with a [WC10] central star. HST observations of this object by Sahai et al. (2000) have shown that HEN exhibits a complex geometry, roughly bipolar with two bright, knotty, compact ring-like structures around the central star (See left panel of Fig. 1). This compact structure is embedded in a larger and fainter spherically symmetric AGB envelope remnant. Infrared observations of HEN were obtained with NACO and MIDI (Lagadec et al. 2006). We also attempted to detect and study small scales structures in the Mid-IR with the long baseline interferometer MIDI but the nebula appeared over-resolved with 46m baselines so that no interferometric data could be recorded. HEN exhibits a clear 1" torus-like structure superimposed to a more diffuse environment visible in the L' (3.8μm), M' (4.8μm) and 8.7μm bands. We interpret the two ring-like structures as due to the projection of the lobes of a diabolo-shaped structure observed with an inclination of about 40°.

Photometry of the central star in L$'$ and M$'$ band indicates that it is $\sim$300 and $\sim$800 times brighter than predicted by stellar models. Moreover, the central object appears resolved in L' band with measured FWHM of about 155 mas. Simple calculations indicate that this infrared excess can be explained by emission from hot dust grains. A mass of $\sim 10^{-9}$M$_\odot$ with T$\sim$900K can account for this infrared excess. By a totally independent way (fitting of the SED), Sahai et al. (2000) also indicated the possible presence of hot dust (T$\sim$900K and M $\sim 10^{-9}$M$_\odot$) inside the nebula. This is a clear evidence that hot dust is present real close to the hot [WC] star. Finding hot dust around a hot star (T$_{eff}$$\sim$30 000K) with a strong wind is surprising and we can wonder whether a single star alone is able to produce this dust in such conditions. Such dusty structures could be common to PPNe and PNe as it has been shown that colour measurements in other PNe observed with adaptive optics on Keck indicate the presence of hot dust close to the CS among a few of them (e.g. IRAS 16342–3814 (Sahai et al., 2005) and IRAS 18276–1431 (Sánchez-Contreras et al.,2007)).

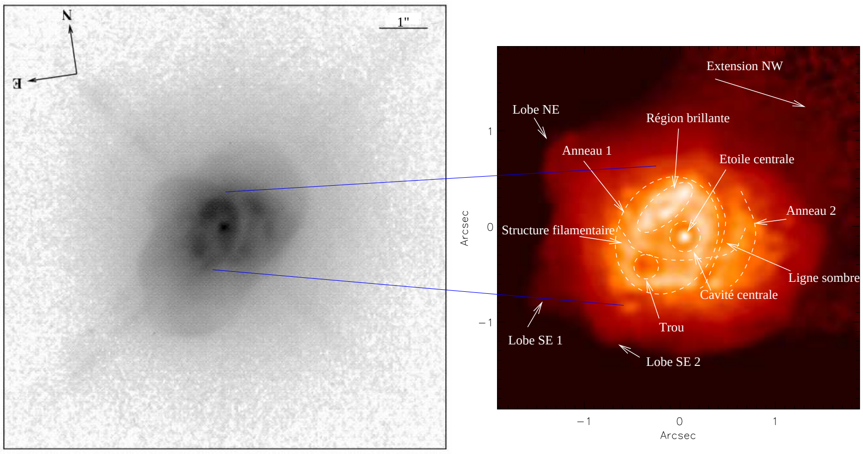

Fig. 1. Left: optical HST image of Hen 2-113 (Sahai et al. 2000). Right: NACO image of Hen 2-113 at 3.74μm (Lagadec et al. 2006).

3 Roberts 22

Roberts 22 (IRAS 10197-5750) is a bipolar PN, displaying OH maser emission at 1612 and 1665 MHz. The circumstellar envelope expands with a velocity of about 20 km s^{-1} (Zijlstra et al. 2001). Optical spectroscopy shows that the Hα line profile has wings extending up to $\pm$ 450 km s^{-1}, a signature of high-speed outflows.

In this work, we present new observations of this young PN obtained with NACO at 2.12 μm. The nebula around Roberts 22 has previously been imaged in the optical

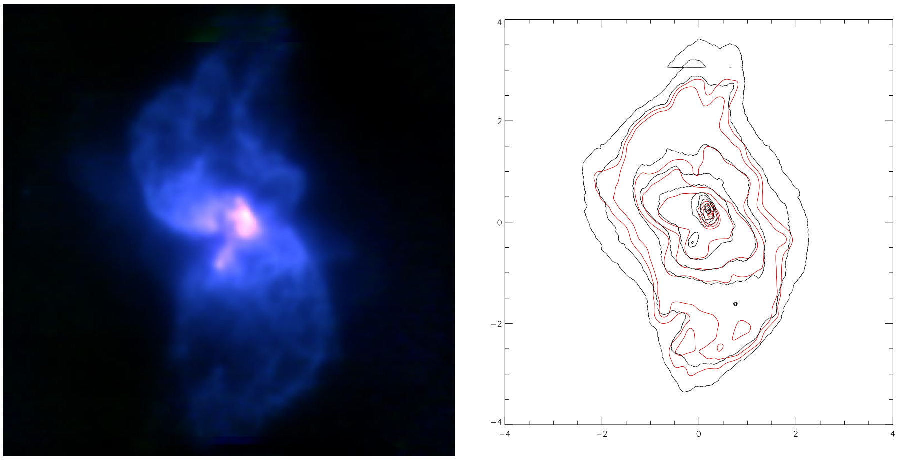

Fig. 2. Left: NACO image of Roberts 22 at 2.12 μm. Right, contours of Roberts 22 images at 2.12μm. Black contours: our NACO observations; red contours: 2003 HST observations.

by the HST (Sahai et al. 1999). These observations show that the nebula is bipolar, with bright lobes shaped like a butterfly's "wings". A dark equatorial body due to dense dust that obscures the central star is also observed. This dark equatorial structure is oriented at a position angle of 120° and is close to, but not exactly parallel to the sides of the parallelogram formed by the bright lobes. The bright lobes are surrounded by a faint halo, which morphology is similar to that of the bright lobes.

The NACO image of Roberts 22 reveals a complex morphology of its nebula (Lagadec et al, in preparation). The parallelogram-shaped structure observed by the HST is faintly visible in our NACO images. But inside this structure, the nebula has a complex roughly S-shaped morphology. The tail of this S-shaped structure are observed outside of the parallelogram-shaped halo. This structure is very clumpy with holes certainly due to a lack of material. These holes are bigger toward the north and south edges of the S-shaped structure. The tail of this structures seems to be organized in filaments. Three filaments are clearly observed in the north. Two filaments are also observed in the south. A third incomplete one might be present on the South-East.

Some unpublished images of Roberts 22 have been obtained by the HST at 2.12μm, i.e. at the same wavelength as ours, but 3 years before. We thus compared both images to look for evolutions in the shape of the nebula. To make both images comparable we had to artificially decrease the spatial resolution of our NACO image by convolving it with a Gaussian having the same FWHM as the HST Point Spread Function. We then superimposed the two images using 4 field stars. The contours of the two resulting images are shown in Fig.2. We have to keep in mind that it is very difficult to compare two images taken with different instruments as their sensitivities are different, furthermore here, as one image was taken from the ground and the other one from space. Nevertheless, these images seems to indicate that the NACO image is more extended toward the North-West and South-East (i.e. along the direction of the S-shaped structure) by $\sim$0.1". At the distance of the nebula ($\sim$2kpc), such an extension in 3 years corresponds to an expansion velocity of $\sim$450 km.s^{-1}, which is the speed of the high velocity outflows measured in H_α. It is thus very tempting to claim that the S-shaped structure in the heart of the nebula is expanding at a speed of 450 km.s^{-1} and that the outflow is almost in the plane of the sky. However, to confirm this, integral field spectroscopy of Roberts 22 will be needed.

4 OH 231.8+4.2

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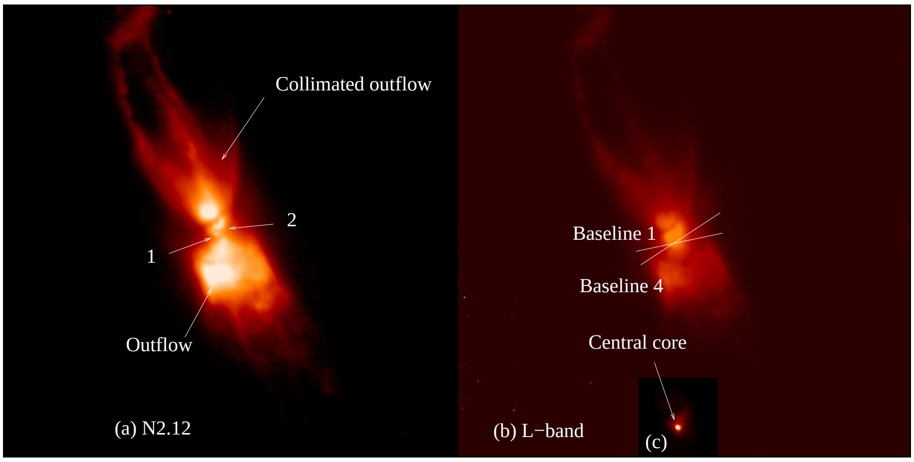

Fig. 3. Left: NACO image of OH 231.8 at 2.12μm. Right NACO image of OH 231.8 at 3.78μm. The caption show a zoom on the core of the nebula.

OH 231.8+4.2 is the nebula around the star QX Pup. It shows two (ionized) bipolar lobes on either side of a central obscuring lane. The obscured central star shows Mira-like variability, indicative of an evolved AGB star. Optical spectroscopy indicates the presence of a hot A-type binary companion to the AGB central star (Sánchez-Contreras et al., 2004). We obtained NACO observations of this nebula (Matsuura et al., 2006). The resulting data are arranged in Fig. 3. The left panel shows the 2.12 micron image, with the two lobes clearly identifiable. The right panel, b), shows the L-band image. Panel c) shows a focus on the core seen on panel b). Here the central region is shown to contain a bright, very compact, unresolved source. To see if this structure was a dusty disc similar to the ones observed at the heart of some PN (see Chesneau et al. and Lykou et al., these proceedings), we observed this central source with the VLTI mid-infrared interferometer MIDI. This is a two telescope interferometer, using two VLT UT 8.2 telescopes for our observations. It thus has a resolution proportional to the distance between the two telescopes in the direction formed by the two telescopes (the baseline) and the resolution of a 8.2 meter telescope in the perpendicular direction. In a previous work (Matsuura et al. 2006), we obtained observations using several VLTI/MIDI baselines nearly perpendicular to the observed bipolar outflows of the nebula. The unresolved source in our NACO images was resolved, with a diameter of approximately 30-40 mas.

However, as our measurements have been only made in one direction, it was impossible to know the shape of the observed compact structure. It could indeed be a disc or a spherical shell for example. We thus obtained new observations with baselines having different orientations along the pole of the nebula. The observed visibilities are presented Fig. 4 (for more details on observations with MIDI, we refer

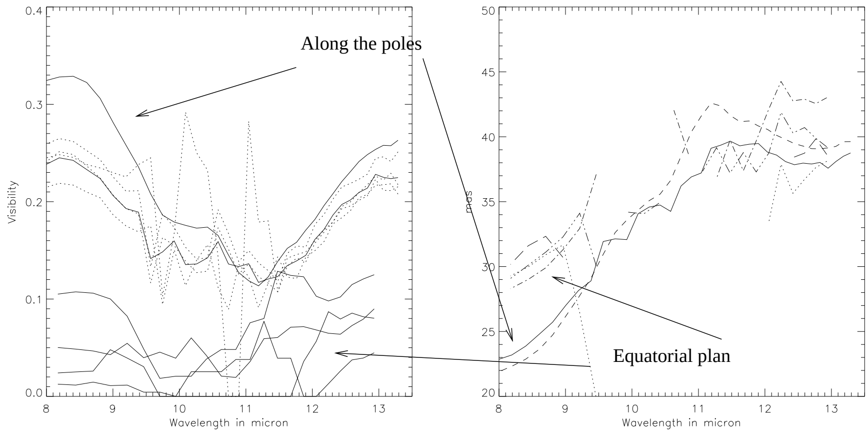

Fig. 4. Left: MIDI visibilities of OH 231.8+4.2 for different baselines. Right: Gaussian fit to these visibilities.

to the contribution by Chesneau et al., these proceedings). The Gaussian fit to the visibilities provide a measurements of the size of the observed structure along the baseline direction. The right panel of Fig. 4 shows that the shape of the structure depends on the wavelength. At 8 μm, the dusty structure is 1.3 times more extended along the equator than along the poles of the nebula. At 13 μm, this structure has almost the same dimension in all the directions. These visibilities are difficult to fit in the picture of a nearly edge-on disc. There is a flatten structure at 8μm that could correspond to the inner rim of the dusty environment, embedded in a more spherical dusty halo (the dense dusty wind of the Mira). Radiative transfer modelling is needed to confirm this hypothesis.

5 V Hya

V Hydrae (V Hya), is an evolved cool carbon star located at 380 pc from the sun (Knapp et al. 1997) with a high mass loss rate. V Hya is associated with a very fast ($>$ 100 kms^{-1}) outflow that was observed in the CO J=2-1 and J=3-2 spectra (Knapp et al. 1997). Knapp et al. (1997) also proposed that the fast-moving gas is expanding along the East-West direction. From recent HST observations, Sahai et al. (2003) reported the discovery of a newly ejected high-speed jet-like outflow in this star. These observations, combined with the previous interferometric CO (J=1-0) map of V Hya, favor the picture of an expanding, tilted and dense disk-like structure, oriented north-south, present inside the inner envelope.

Previous mid-IR images show that the circumstellar envelope of V Hya is roughly spherically symmetric in the central parts but present an elongation in the East-West direction at intensity levels lower than 20 % of the central intensity peak (Lagadec et al. 2005). The observed elongated feature in the East-West direction could be associated with the dust emission from material blown away perpendicularly to the equatorial disk, consistent with the model proposed by Sahai et al. (2003).

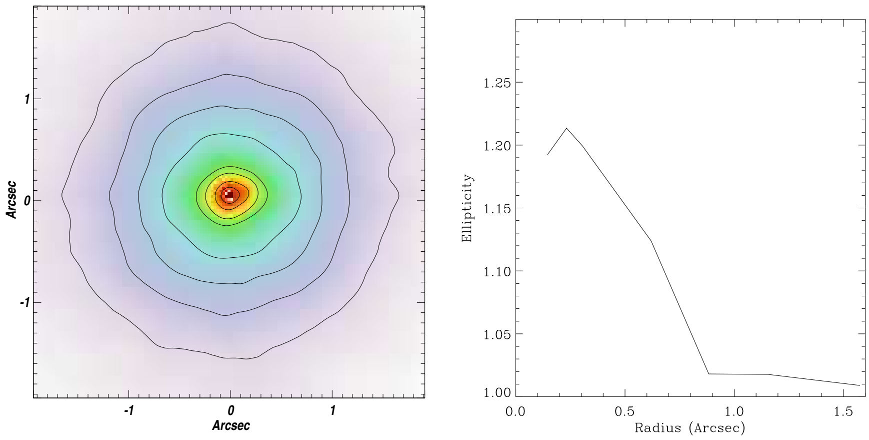

Fig. 5. Left: NACO image of V Hya at 3.74μm. Right: Ellipticity of the envelope as a function of the radius.

We imaged the circumstellar envelope around V Hya using NACO at 3.8μm (Fig. 5, Mékarnia et al., in preparation). We clearly see that at large scale, the circumstellar envelope of V Hya is quasi-spherical. But in the heart of the nebula, the dust emission shows an extension along the East-West direction. This is clearer on the right panel of Fig. 5, which shows the ellipticity of the observed circumstellar envelope as a function of the radius. Within 1" to the star, the ellipticity steadily decrease from $\sim$1.2 to $\sim$1. V Hya thus displays a departure from spherical symmetry in its heart, like what is observed for the closest AGB star, IRC +10 216 (Leão et al. 2006). This elongation in the core of the envelope has the same orientation as the jet observed previously in CO. V Hya appears as an AGB star that was previously spherically symmetric, now being shaped by a high velocity jet. V Hya is thus an AGB star on his way to become an asymmetrical PPN and then PN. These observations thus show the importance of high speed jet for the formation of planetary nebula, as early as during the AGB phase.

6 Conclusion

The observation we presented here show that adaptive optics imaging imaging with NACO on the VLT is of great use to the study of small structures around evolved stars. We have shown that the shape of the nebula around Hen 2-113 could be explained by the projection of a diabolo-shaped structure and that hot dust was present close to its [WC10] central star. The NACO 2.12 μm image of the PN Roberts 22 revealed a very complex S-shaped structure embedded in a more diffuse rectangular-shaped envelope. Observations of these nebula at two different epochs seems to indicate that the S-shape is in expansion at a speed of $\sim$ 450 km.s^{-1}. Our combined NACO/MIDI observations of OH 231.8+4.2 have revealed the presence of a very compact flattened dusty structure in its core (40-50 a.u.). The shape of this structure is not the same at 8 and 13 μm, due to emission from hot dust heated by the hot companion. Finally, the NACO image of the AGB star V Hya shows that its envelope is spherical at large scale and elongated toward a direction roughly East-West in its core. This asymmetry is probably due to a jet shaping the AGB circumstellar envelope that will become an asymmetric planetary nebula which should provide beautiful images for the conference APN 5446 or more.

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