The VLTI view of compact dusty environments around evolved stars

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Summary. The VLTI equipped with a near-IR (AMBER) and a mid-IR (MIDI) recombiners is one of the most versatile optical interferometer world-wide. Its ability to trace the dust at high spatial resolution (1-10mas) is well suited for the study of many aspects of the late evolution of stars and in particular, to deal with the asymmetry in PNe back to the AGB. Many results can be expected soon and the most recent VLTI observations of evolved stars are presented, focusing on the study of dusty disks embedded in bipolar PNe. Recently, thanks to the MIDI instrument, the inner rim of a disk in CPD-568032 could be studied in detail (R_{rim}=75mas,110 AU), a disk in the center of the Ant nebula (Menzel 3) has also been detected (10x30mas, 15x45AU) and observations of the Butterfly nebula (M2-9) are under way. The interferometric measurements of the strongly optically thick core of OH231.8 indicate a dusty compact source whose complexity is currently out of reach of the limited imaging capabilities of the VLTI, and we stress out that some cautions have to be taken when the word 'disk' is employed. The potential of the VLTI for the observations of bright novae is also shown, together with some in-depth studies of famous symbiotic systems. PNe observations with the VLTI are just beginning, are currently performed by a small number of persons and represent the tip of the iceberg of what could be done by this facility. The VLTI is dedicated for the use of a wide community and, as such, could be part of the observational strategy of many participants of this meeting.

Key words: Planetary Nebulae – Mz 3, M2-9, Hen2-113, CPD-56°8032, OH231.8+4.2, Novae – RS Oph, V1280 Sco, Symbiotics – HM Sge, AGB: π1 Gru, Techniques: interferometric; Techniques: high angular resolution; Stars: circumstellar matter

1 The VLTI

The Very Large Telescope Interferometer (VLTI) consists in the coherent combination of the four 8m VLT Unit Telescopes (UTs) and of the four movable 1.8m Auxiliary Telescopes (ATs). Two recombiners are currently offered to the community. AMBER is an interferometric beam combiner working in the near-infrared (mostly H and K bands). It is able to simultaneously handle 3 beams coming from

3 identical telescopes. AMBER interferograms are spectrally dispersed with a resolution R of about 35, 1500 and 12000. MIDI operates in the N band and recombines two beams (R=30 or 230). The domain of applicability of interferometry in terms of sensitivity, spatial and spectral resolution has been greatly extended with the VLTI, but the targets must be carefully chosen. An interferometer measures the contrast of the fringes produced by several telescopes, using beams propagated with about 30 mirrors. The transmission is not large (about 1%) and any potential source has to be bright, although this condition is not sufficient. The fringe contrast of unresolved sources is 1, whereas the contrast of extended sources drops rapidly to zero. This means that even for a bright, but too extended source, the detectability of the fringes can be problematic. A potential source for MIDI must exhibit a core extending from 5 to 100 mas to be scientifically interesting, and from 1 to 20 mas typically for AMBER observations. This is the flux (or magnitude) of this core (the correlated flux) that determines the feasibility of the interferometric observations for a given length of baseline, whatever the single-dish beam flux. Typical lower limits for correlated flux with MIDI are about 1 Jy (N=4) with UTs and 20 Jy (N=0.75) with ATs; with AMBER, K=7-4.5 in low resolution mode (UTs/ATs), and K=4-1.5 with R=1500. Some N band sources appeared to be over resolved with the chosen baselines: the core of the PN Hen2-113, imaged with the single dish UT, but over-resolved for a 40m baseline ([16]), or the OH/IR star OH 26.5+0.6, barely resolved with a UT, but for which no fringes could be detected with a 100m baseline ([10]). Any compact sources of about 4Jy (clumps or star flux visible through the dust envelope) would have produced detectable fringes and was therefore excluded for this 700 Jy source. Despite these stringent conditions, numerous bright and compact evolved stars are well suited for this technique. We shall focus here on the targets related to the appearance of the asymmetries detected in the latest stages of the stellar evolution of low to intermediate mass stars.

2 CPD-56°8032

The discovery by De Marco et al. ([12]) of a dark lane in the STIS/HST spectra of the PN CPD-56°8032, was interpreted as a disk and prompted us to investigate whether the MIDI/VLTI interferometer could help characterizing this compact dusty environment, and may be applied to other asymmetrical PNe. CPD-56°8032 and Hen2-113 were chosen for this first attempt. These targets, whose central stars and nebula share many characteristics, exhibit a core dominated by dust emission, and a complex dust chemistry witnessed by the simultaneous appearance of oxygen-rich (silicate) emission and carbon-rich features in the form of strong PAHs emission.

The chosen baselines, of the order of 46m, were in the lowest range allowed by the fixed UTs, but they were already too long for these 'extended' environments. The torus in Hen2-113 (described in Lagadec et al. [16] and these proceedings) has a typical diameter of 0.6" and the torus/disk of CPD-568032 appears more compact, 0.15" in diameter, but still very extended for such a long baseline. As a consequence, the interferometer is insensitive of most of the 30 Jy extended flux in the core and it detected only the 1-2 Jy originating from the disk's sharp inner rim.

A global picture emerged from the ISO (14"' x 22") and MIDI (0.6" x 0.6") spectra, the HST image and the visibility curves. The outer nebula shows multiple lobes excavated in a dense environment. The ISO spectrum is dominated at long wavelength by the signature of crystalline silicates, while in the N band, the emission is compact and almost unresolved for a 8m telescope, except in the PAHs bands. These inner regions produce a continuum probably dominated by featureless carbon grains emission, and the balance between the different PAHs features seen in the MIDI spectrum is dramatically changed compared with the ISO spectrum. From the visibilities, a sharp, inclined ring (diameter of ~200AU) could be inferred. The derived inclination of 28° is in apparent contradiction with the edge-on disk suggested by the STIS/HST spectrum. Radiative transfer models showed that the disk is optically thin in the N band and highly flared, probably caught in a dissipation stage. The inner rim is at about 500 K, but faces the 225km.s^{-1} wind from the central Wolf-Rayet star. A passive disk was used for interpreting these observations, but a torus geometry may be more pertinent. CPD-56°8032 is a very interesting target that would deserve a more extensive interferometric mapping. However, MIDI is a simple 2-beam recombiner, lacking closure phase information and such observations would be time-consuming. Such an effort could be undertaken with MATISSE, the second-generation 4-beam recombiner successor of MIDI.

3 OH 231.8+4.2

OH 231.8+4.2 is a well studied pre-planetary nebula. The central source is a binary system formed by an M9-10III Mira variable and a hot companion (probably a A0V star, [25]). It is worth mentioning that, rarely enough, the distance of this source, 1.5 kpc, and the inclination of the bipolar axis with respect to the plane of the sky, 36°, are well known ([6], Desmurs et al. these proceedings). In the near to mid-IR, the core is deeply embedded into a highly optically thick dust envelope. This core is unresolved at 0.1" scale in K and L bands with a UT (see images in Lagadec et al. these proceedings, and [19]). The ~10 Jy flux from the core drops to less than 1 Jy in the deep silicate absorption feature. The fact that the source is so optically thick implies, at least, that a putative 'disk' at i=54°should be highly flared and dense to intercept emission in the line-of-sight. The first MIDI measurements, using baselines roughly perpendicular to the bipolar lobes were able to provide an extension of the source (assuming a Gaussian model) from 30mas at 8μm to 50mas at 13μm, i.e 40-70 AU at 1.5kpc). The interferometric observations were also able to state that nearly no correlated flux of stellar origin is detectable. Considering that the structure is flattened in a plane perpendicular to the bipolar axis its aspect ratio between the projected minor and major axis should be ~55%. The new visibilities obtained recently in the direction of the bipolar axis confirm only partially this picture: although the visibilities are higher implying a smaller extension in this direction, the ratio between the extensions at perpendicular directions is less than 30% at 8μm and less than 10% at 13μm. The core cannot be ascribed by a spherical shell, but it is not sure that the term 'disk' is pertinent for a structure with such an opening angle. In this context the VLBA observations are very helpful ([6], Desmurs et al. these proceedings): the medium is optically thin at these wavelengths and the spatial resolution is better than the VLTI one, about one mas only. A 12 AU diameter equatorial 'torus-like' structure traced by SiO masers exhibits a complex velocity field involving rotation and also infall of material toward the central star. As for CPD-568032, a 8μm mapping with a large *uv* coverage is needed to better understand the geometry of the hot dust emission.

4 Bipolar nebulae: Mz 3 and M2-9

CPD-568032 and OH 231.8 are targets too complex to be investigated at low cost via our partial interferometric observations. Moreover, the intermediate inclination of these targets affects their aspect in a manner difficult to infer. After these first attempts, our team and others decided to focus on compact systems whose inclination is either close to $90°$(edge-on configuration) or $0°$(pole-on configuration). For the latter case, assuming circular symmetry, a few baselines can efficiently constrain the density law and structure of the disk (see a recent example for the T Tauri star TW Hya, [22]). We decided to focus on the famous bipolar nebulae Mz3 and M2-9 exhibiting the tighter waists, among the extreme cases of asymmetrical shaping.

The results of Mz 3 could rapidly be interpreted in terms of a flat 10 x 20 mas structure, and therefore there was no doubt that a disk was detected. This prompted us to use a radiative model to interpret these observations. This work is described in the contribution from F. Lykou (these proceedings) and in an accepted letter ([7]).

The preliminary results of M2-9 are promising. They first show that the putative 'disk' inside the nebula is more extended than the one in Mz3. A larger mass (factor $\sim$4) is inferred in Smith & Gehrz (2005) and they report that the SED suggests dust at somewhat cooler average temperature than Mz3. Second, the first visibilities reveal some features indicative of crystalline silicates, generally associated to long-lived disks, i.e a disk probably older than the bipolar structures seen in the HST images. The analysis of these results is at the moment too early to draw firm conclusions.

What kind of targets could be observed in the near future? Some discussion during the conference focused on the need to know better how the accretion disk of a companion can help shaping the nebula via winds or jets. Our present strategy to focus on nearly edge-on bipolar nebula prevents us to see such accretion disks. A promising approach would consist in selecting and observing bipolar nebulae seen *pole-on*, so that both the external dusty disk and a putative accretion disk could be investigated by MIDI and AMBER.

5 Symbiotic systems

MIDI is well suited to study the D-type (dusty) symbiotic systems and AMBER better suited for S-type systems. These objects are interacting binary stars with an extended cool giant as primary component and a hot compact component, presumably a white dwarf (WD), as secondary. These systems exhibit by nature a complex spatial configuration and one can guess that the large amount of dust seen in these D-type systems resides in the form of torus-like structures in the orbital plane, as seen in the HST images of some resolved systems (for instance Hen 2-147 [27]). In order to interpret the ISO spectra obtained for many dusty symbiotics, models involving multiple spherical dust shells were developed, whose sizes can be directly probed by mid-IR interferometry. We observed the system HM Sge with MIDI ([23]) and used the visibilities to test the validity of models involving single and double dust shells published in the literature ([26],[5]). Generating multiple shell models via radiative transfer codes is easy, but the way the fluxes from the two stars affect the shells is often treated under several more or less artificial assumptions. When one

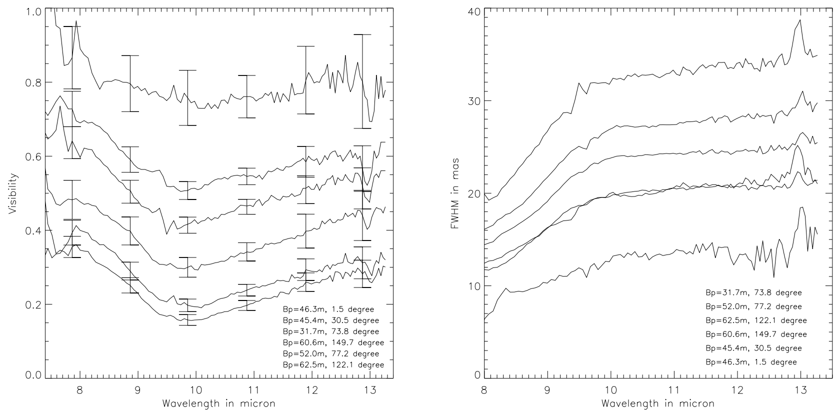

Fig. 1. Right: the MIDI visibilities obtained on Mz 3, the highest levels corresponding to the smallest extensions in the sky, with baselines aligned with the bipolar axis. The large amplitude of visibility variations witnesses a flat structure. Left: the typical angular extensions assuming a Gaussian distribution of flux. The order of the baselines is now inverted, from large to small sizes. The steep increase of the size due to the silicate feature at 9μm is superimposed to a slow increase of the continuum size suggestive of a disk-like structure.

needs to predict interferometric observables such as visibilities, the relative position of the shells must also be taken into account, and this offset is far from negligible in the case of HM Sge since the WD is located 40 mas away from the Mira. The results of the tests showed that the bulk of the dust emission originates from the dense and quasi-spherical Mira wind, and that all double shell models failed to fit the observed visibilities. A growing asymmetry is detected toward the short edge of the N band that can be interpreted with two different configurations. In the first scenario, the emission from a colliding wind (hot dust) is added to the spherical emission of the Mira. Such a 'perturbed' model should exhibit an asymmetry that can theoretically be detected using the phase of the fringes, but the accuracy of the mid-IR measurements is such that this constraint is weak (near-IR measurements are better suited to test this effect). In the second scenario, the dust density is increased toward the orbital plane and the changing aspect ratio of the source with wavelength is a direct consequence of the disk structure and flaring of the system (assuming i$\sim$20-40°). The impact of the VLTI on the study of symbiotic stars is potentially large: the targets are bright and this facility provides a spatial information that is currently strongly needed for validating the numerous models developed to interpret the SEDs of these sources ([1],[2],[3]).

6 The binary system at large separation π1 Gruis

π1 Gruis is one of the closest S star (d=153pc), a chemically enriched evolved red giant of spectral type close to an M star. Near-IR and mid-IR interferometric observations are well suited for studying the inner molecular and dust formation regions and $\pi 1$ Gruis was naturally chosen by our group as a bright and nearby target to observe. The fact that $\pi 1$ Gruis is a visual binary with a G0V companion at 2.7" was not considered as important. The Field-Of-View (FOV) of the MIDI interferometric observations with the ATs is the beam of the 1.8m telescope, i.e. $\sim$1300mas at 10μm. The companion is even at the limit for the acquisition images that have a FOV of a few arcsec only. The study of the envelope was already well advanced when Chiu et al. ([11]) reported the detection of a disk and a fast outflow based on millimetric observations. The MIDI visibilities, at first sight, do not suggest any departure from sphericity, but one has to be careful since our baseline are so long that the signal is dominated by the (spherical) central star (about 20mas) and not really the (potentially disturbed) envelope. Is the far companion responsible of the disk formation? Frankowski et al. ([15]) suggest, based on Hipparcos data, that a close companion could also be hidden close to the star. It is too early to answer this question, but this system appears as a very interesting case that deserves more extensive near- and mid-IR interferometric observations.

7 Interferometric observations of Novae

A classical nova eruption results from a thermonuclear runaway on the surface of WD that is accreting material from a companion star in a close binary system. The temporal development of the fireball, followed by a dust formation phase or the appearance of many coronal lines can be studied with the VLTI. The detailed geometry of the first phases of novae in outburst remains virtually unexplored. The recent outburst from the recurrent nova RS Oph showed how complex such an ejection can be, as seen in the radio-interferometers and the HST images of the rapidly formed bipolar nebula formed rapidly ([4],[20]). AMBER observations were secured only 5.5 days after discovery ([9]) providing an excellent K band dataset, including two bright emission lines Brγ and HeI2.06μm. The triplet of baselines used was not determining the geometry, but could provide the typical size of the K band continuum (dominated by the mostly optically thick emission from the nova), Brγ (formed in the nova wind), and the more extended HeI 2.06μm line (formed close to the shock propagating inside the slow and dense wind of the red giant). An important information could also be extracted on the two components kinematics inside the Brγ line, an equatorially enhanced 'slow' ($\sim$1800km.s^{-1}) ejection, and the jet-like E-W emission at 'high' speed ($\sim$3000km.s^{-1}). These observations were based on a single snapshot and the temporal evolution of this source could not be monitored. More recently, the classical nova V1280 Sco was monitored during 4 months, providing the first spatially resolved observations of a (hopefully spherical!) dust forming nova.

8 To be or not to be a disk?

The studies presented here are illustrative of the numerous applications of the VLTI for the study of evolved stars. Many articles, referring more on the evolved stars photosphere and their winds could also be cited, such as the recent extensive study of the mass-loss of some Mira stars in connection with their stellar pulsations: S Ori by Wittkowski et al.([28]) and V Oph by Ohnaka et al. ([21]). Another aspect not treated here, is the detection, in the dust forming site, of big dust clumps seen in the most extreme envelopes, such as the ones reported in R CrBs and recently observed around RY Sgr by MIDI (Leão et al. [18]).

One common feature of the work presented above, is that our common language simplifications are often not reflecting the diversity of dust distributions around the complex objects observed. Out of the targets cited here, only Mz 3 surely harbors what is usually denoted as a 'disk'. The flared, dissipating structures seen around the Wolf-Rayet stars in CPD-568032 and Hen2-113 would probably be better fitted using homogeneous torus of dust than a stratified passive disk. The situations gets even more complicated with OH 231.8 and dusty symbiotic systems like HM Sge for which a dense, spherical Mira wind is more or less perturbed by a companion. Disk-like geometries are no longer pertinent in that context, and imaging capabilities are necessary to clarify the complex interaction between the stars and their environment. The VLTI is already in the Phase B study of the second generation recombiners that should be able to recombine the 4 ATs or 4 UTS simultaneously (MATISSE in the mid-IR [17]). Also very promising is the convergence in terms of spatial resolution between the optical and millimetric interferometry techniques. The Plateau de Bure's interferometer new long baselines provide now a spatial resolution in the millimetric domain comparable with the resolution of a single-dish UT at 10μm ($\sim$300mas) and ALMA should extend this complementarity to the scale of the dusty disks currently discovered with the VLTI.

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