The growing importance of optical interferometry for the study of evolved stars

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Abstract

This is a short review of optical interferometry studies involving the VLTI in the field of evolved stars. The various aspects of mass-loss from these stars can be followed from the photosphere to the wind, and then to the circumstellar medium. Of particular importance is the possibility offered by this technique to characterize disks of dust or plasma.

Key words: Techniques: interferometric; Techniques: high angular resolution; Stars: circumstellar matter; Stars: mass-loss

1 Introduction

This paper deals with various sources that have all in common being evolved (i.e having left the main sequence) and experiencing some more or less spectacular mass loss. Most of them also share the property that their ejected material is not spherically distributed. This information is important as it allows to trace a variety of phenomena that are often hidden in the immediate vicinity of the star, from the base of the wind to several stellar radii or even astronomical units. As you shall read in the following, many sources are binaries (this is obvious for the systems which give birth to the nova phenomenon), but also many other sources are suspected to be binaries. Binarity is not an aspect of the sources that can be detected and neglected easily, particularly when we consider that for the less massive stars, massive planetary companions can often 'do the job'. It is not in the scope of this paper to do an extensive review of these issues, but you will find a subjective snapshot of some of the VLTI observations related to this context.

This review gathers information on papers published on evolved stars from optical interferometers these last years. Owing to the growing number of papers published with this technique, I shall focus of some results from the VLTI and in a biased manner. In order to escape this bias, the reader can also read some recent reviews of the activities concerning evolved stars and interferometry mentionned in the introduction of each section.

2 Evolved massive stars

Massive stars are not easy targets for optical interferometry. Their radius for a given luminosity is much smaller than for cool stars, and they are statistically located at larger distances. Moreover, it is more difficult to study their circumstellar material, owing to the high luminosity contrast compared to the photosphere. Moreover, dust cannot (theoretically) survive close to these objects, and cannot be used as an amplification of the signal from the nearby environment, as used for cooler objects. This is why currently only few massive objects have been extensively studied with this technique, and these objects are strongly biased to the (rare) massive stars exhibiting dust, and also the sources exhibiting the strongest and densest winds. As an example, the famous massive star η Carinae is a Luminous Blue Variable (LBV) that exhibits both a huge dusty circumstellar environment which results of a huge explosion and a dense wind which is ideally suited for interferometric observations. The VLTI has extensively observed it with each of its recombiners VINCI, MIDI and AMBER (van Boekel et al. 2003, Chesneau et al. 2005, Weigelt et al. 2007). A short review of this remarkable star by Sterken et al.(2007) can be read in the ESO messenger [1]. Nevertheless, this star should not be the tree hiding the forest and its remarkable properties should be put into context. In the following, some results will be presented on the perturbation of the (much weaker) wind of the *stable* blue supergiant Rigel, on the campaign aiming at investigating the dusty environment of dusty B[e] stars and evolved binary system like υ Sgr. The particular case of the Wolf-Rayet stars, the latest stages of the massive star evolution is presented in Millour et al. (2008) and is not treated in the present manuscript.

2.1 Wind perturbations from a B supergiant: the case of Rigel

The winds of hot stars are continuously variable on time scales associated with processes on the stellar surface. Consequently, the steady state, spherically symmetric descriptions usually used to model and interpret stellar wind diagnostics can only provide some sort of mean representation of these outflows. However, the contrast between the photospheric luminosity and the wind

[1] `http://www.eso.org/sci/publications/messenger/archive/no.130-dec07/`

emission is such, that the wind perturbations can only be studied by high SNR spectroscopic observations. Long baseline interferometry suffers from the same situation, but its high spatial resolution capabilities help to isolate the signal, provided that high spectral resolution is available (like the $R = 12000$ in the K band of AMBER). For the BA-type supergiants cyclic modulation of the stellar wind plays an important role. Obviously, the winds are modulated by a mechanism related to the photospheric rotation, presumably patches on the stellar surfaces produced either by non-radial pulsation (NRP) patterns or magnetic surface structures ("spots"). These supergiants are key targets for the VLTI as their angular diameter fits well its spatial resolution capabilities (3mas), and because the time variability of the phenomenon is slow enough so that the time coverage of the observations is not too demanding for the infrastructure (a few weeks to months).

The time scales of the estimated stellar rotation period is 100 days. Extreme events like the high-velocity absorption have indicated that the circumstellar structures are stable for at least four rotational cycles. Rigel was monitored over more than 4 months in 2006 and 2007, in the Brγ line. A preliminary analysis shows that the line is slightly in absorption, but the visibilities decrease strongly in the line. This is a direct evidence that the Brγ line consists of a deep photospheric line partially filed out by an extended emission region. The spectrally dispersed phase closures, close to zero within error bars in the continuum, exhibit an interesting behavior through the line, providing some information on the kinematics and putative asymmetries of the line forming region. These results are the first use of an interferometer for detecting the so-called 'Corotating Interacting Regions' CIRs, in hot supergiants' winds, whose detection was investigated in Dessart & Chesneau (2002).

These pioneer observations can be an example for the study of faster wind (i.e. requesting lower spectral resolving power) from more challenging hot stars (like O stars, much smaller).

2.2 The B[e] stars: B type stars with dusty disks

The dusty environments (most probably disks) encountered around some B type stars produce some characteristic signatures that lead to the classification as B[e] stars. Principally, these signatures are a strong infrared excess, spectra dominated by permitted emission lines from hydrogen and other elements, and numerous forbidden lines from Iron for instance. The number of B[e] stars is limited, and this class is rather heterogeneous, encompassing (depending on the distance estimate) the supergiant class (SgB[e] stars), Young Stellar objects (YSOs, HaB[e] stars), compact core of young PN or symbiotic systems (32).

The dusty disks that characterize this spectral class are poorly understood. In particular their dust density distribution and geometry (inclination, opening angle) probably differ markedly from the gaseous disks observed around classical Be stars. An ambitious observing program has been undertaken at the Observatoire de la Côte d'Azur, involving the VLTI recombiners MIDI and AMBER but also some spectrographs like Feros and spectropolarimeters. The use of AMBER is particularly justified in the case of hot stars exhibiting strong winds and plasma disks contributing to the K band flux via their free-free emission, whereas the MIDI mid-IR signal is often by dust alone, providing information easier to interpret than in the near-IR. This large observing program, based on Open Time proposals, but also on MIDI Guaranteed Time, aims at getting for the first time information on these dusty environments (23; 22), but also on detecting (or putting strong constraints) on the presence of companions that may strongly favor dust formation. It is even tempting to claim that virtually *all* evolved B[e] stars indeed belong to binary systems. Such a claim is also tempting in the case of late carbon Wolf-Rayet stars (WC) producing dust, e.g. WR104 or WR98 (44; 40). The initial goal was to focus on SgB[e] stars, for which creating dust at close distance is theoretically challenging, but the list was including many unclassified objects. Some of these sources appeared to be binaries (such as MWC300 (42) or HD87643, see below), some others are probably YSOs (such as HD45677 or HD50138). An indirect confirmation came for the lower angular extensions of the environment of putative SgB[e] stars compared the putative HaeB[e] harboring much larger environments.

The VLTI observations of the SgB[e] star HD87643 were the most intriguing and particular efforts were undertaken to understand this target and its large infrared excess (the largest of the class). The MIDI visibilities exhibit a sinusoidal pattern that was first interpreted by the signature of a large ring, but no good quality fit can be reached with simple models. Extensive AMBER data provided the information to understand this complex source: a binary system harboring a dusty circumstellar disk, and whose components are also surrounded by disks. An image reconstruction from the AMBER data was the key to understand the source (Millour, Chesneau, Borges et al. accepted). Moreover, the high spectral resolution spectra of the NaI lines lead to a re-assessment of the distance to $\sim$1kpc (with still a larger error bar), before only indirectly and weakly constrained to a larger distance. HD87643 is therefore better ascribed as an interacting binary in an eccentric orbit, that seems to produce copious amount of dust at regular intervals of several years.

2.3 An evolved binary system of β Lyrae type: υ Sgr

The study of binary systems with (initially) massive objects is particularly interesting. The most massive stars can hardly exchange material with a massive companion as their winds are strong enough so that their respective winds collide. Binary systems involving less massive stars (still in the range 5-20 solar mass) can experience mass exchange and the β Lyrae system is illustrative of such a system caught in the act. β Lyrae itself is not well suited for VLTI observations, and we selected some systems like υ Sgr. We note that these southern targets are poorly known.

The system υ Sgr (HD 181615) with a A type low mass supergiant, is the brightest member of the type of extremely hydrogen-deficient binaries stars (HdB stars). The HdB stars are a rather rare class of evolved binary systems that are in a second phase of mass transfer, where the primary has ended the core helium burning phase. υ Sgr might represent one of the possible future of β Lyrae, but in the context of binary evolution, things are never simple. Pragmatically speaking, υ Sgr is interesting as it is bright in visible, near- and mid-IR, as it harbors a dusty disk with an inclination low enough so that the stars can be studied spectroscopically in the visible(29). An observing campaign was undertaken involving MIDI and AMBER observations. The mid-IR visibility measurements and the SED were compared with the models made with the MC3D code using 2D geometry in order to determine the geometry and chemical composition of the circumbinary envelope. A geometrically thin disk with an inner radius of $R_{\rm in} \sim 3$AU with dust of chemical composition 60% of carbon and 40% of silicates accounts reasonably well for the observations. The PA of the source is well constrained, but the inclination, the most critical parameter for constraining tightly an orbital model still loosely defined, ranges from 20° to 50°. Rarely enough, we point out that the distance of the source is accurately constrained, meaning for instance that the dust mass inferred can directly be compared with some estimation of the masses of the components, and be put in the context of the mass loss history of the system. The missing crucial information is the direct resolution by an interferometer of the two components.

3 The last stages of low to intermediate mass stars

When leaving the main sequence, the low and intermediate mass stars cool down and increase their size and their luminosity. These targets are well suited for the arrays operating in the near and mid-IR as the apparent radius of the stars is large, and their stellar spectrum peaking in the near-IR. Moreover, most of these objects produce a large amount of dust, distributed in a circumstellar environment whose geometry is indicative of many physical phenomena of great interest. Many articles report on investigations of the evolved stars photospheres and their winds. The reader is referred to the reviews from Keiichi Ohnaka (50), Peter Deroo (19), or Markus Wittkowski (63).

3.1 Pulsations and wind properties for RGBs and AGBs

An extensive study of the mass-loss of some Mira stars in connection with their stellar pulsations involving multiple coordinated multi-wavelength observations implying VINCI, then AMBER, and MIDI together with VLBA were carried out by Wittkowsky and collaborators (Wittkowsky et al. (2004, 2006a,b); Boboltz & Wittkowsky (2007); Karovicova et al. (2008)). This approach is very useful to better understand the mass loss process and its connection to the pulsation mechanism. While near-infrared observations provide information about the conditions near the stellar surface, mid-infrared observations are used to explore the characteristics of the molecular shells and the dust formation zone. VLBA observations provide additional information about the properties of the environment using the maser radiation from some common molecules (SiO, H2O, OH). The most recent and developed studies concern the pulsating Mira S Ori by Wittkowski et al. (2008), V Oph by Ohnaka et al. (2008) and other cool giants (Neilson et al. 2008).

3.2 Planetary nebulae with dusty disks

The ISO observations have shown that many well-developed Planetary Nebulae (PNs) exhibit in their center a dusty core, that often occurs to be very compact. The discovery of a dark lane in the STIS/HST spectra of the PN CPD-56°8032, was interpreted as a disk (15) and prompted us to investigate whether the MIDI/VLTI interferometer could help characterizing this compact dusty environment. Two 'twin' targets were chosen: CPD-56°8032 and Hen2-113. These targets, whose Wolf-Rayet central stars and nebulae 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, well studied by means of ISO observations. The chosen baseline, UT2-UT3 ($\sim$46m), was in the lowest range allowed by the fixed UTs, but was already too long for these 'extended' environments. The torus in Hen2-113 (described in Lagadec et al. 2006) has a typical diameter of 0.6" and could be imaged with the VLT/NACO adaptive optics system in L' band. The torus/disk of CPD-56°8032 appears more compact, 0.15" in diameter (i.e. unresolvable in mid-IR with a 8m telescope), but is still very extended for such a long baseline.

A global picture of CPD-56°8032 emerged from the ISO (aperture 14" x 22") and MIDI (aperture 0.6" x 0.6") spectra, the HST images and the MIDI 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. From the visibilities, a sharp, inclined ring (diameter of ∼200AU) could be inferred, but we stress that the very limited *uv* coverage could not provide tight enough constraints on the geometry, and in particular the inclination. The inner rim temperature is about 500 K, but the rim faces the 225km.s^{-1} wind from the central Wolf-Rayet star and this dusty structure may be caught is a stage of fast dissipation.

OH 231.8+4.2 is a well studied pre-planetary nebula exhibiting a bipolar nebula and a compact dusty core. The central source is a binary system formed by an Mira variable and a hot companion whose characteristics are not well defined. In the near to mid-IR, the core is deeply embedded into a highly optically thick dusty envelope. This core is unresolved at 0.1" scale in K and L bands with NACO. 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 (37). New measurements recently obtained in the direction of the bipolar axis show that the core is better ascribed by a spherical shell rather than by a stratified disk. The system is probably caught in a phase of intense mass-transfer, in which the dense dusty wind of the cool primary is highly perturbed by the presence of a hot companion orbiting inside.

CPD-56°8032 and OH 231.8+4.2 are very interesting targets that would deserve a more extensive interferometric mapping. However, MIDI is a simple 2-beam recombiner, lacking closure phase information and such an effort should be undertaken with MATISSE, the second-generation 4-beam successor of MIDI (Lopez et al. 2008). These first targets observed with MIDI/VLTI were too complex to be investigated in depth at low cost via our partial interferometric observations. The inclination of these targets affects their aspect in a manner difficult to infer by a 2-telescope recombiner. Our team decided to focus on bipolar systems with a compact dusty core, whose inclination is close to 90°(edge-on configuration [2]). The famous bipolar nebulae Mz3 (the Ant) and M2-9 (the Butterfly) exhibiting the tighter waists among the extreme cases of asymmetrical PNs, were naturally chosen as primary targets for this attempt.

The Ant Nebula is one of the most striking bipolar planetary nebulae known.

[2] It is interesting to note that other groups chose systems with pole-on configuration ($i \sim 0°$) . Assuming circular symmetry, a few baselines can efficiently constrain the density law and structure of the disk(55).

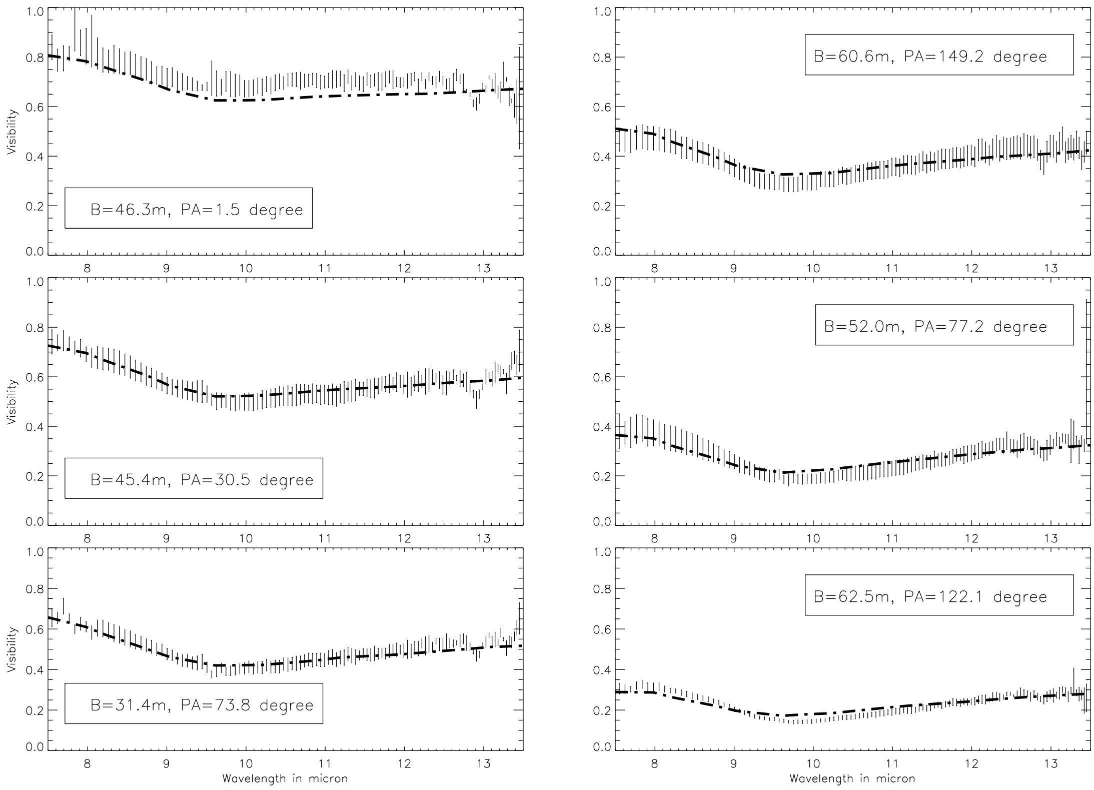

Fig. 1. *It is particularly rewarding to see a model fitting so beautifully the data. Here is an example from Chesneau et al. (2007) of the fit of the MIDI visibilities from the dusty core of the Ant planetary nebula with their error bars, compared with the best model consisting of a passive stratified disk of silicate (dashed-dotted lines). The reduced χ^2 for the full data set is 1.68 (although we note that the extended [NeII]12.8µm line is not taken into account in the model). The error on the visibilities range from 3% to 8%.*

The morphology of the Ant Nebula is a bright core, three nested pairs of bipolar lobes and a ring-like outflow. The core is unresolved by the VLT/NACO from K to L bands. Mz 3 was observed using UT2-UT3 and UT3-UT4 baselines, and the observations could rapidly be interpreted in terms of a flat 10 x 20 mas structure. There was indeed no doubt that a disk was detected and this prompted us to use directly a radiative model to interpret these observations (8). A simple passive disk could fit almost perfectly the data (one of the best match to date from a disk model and interferometric observations, see Fig.1), giving confidence about our estimation of its mass content and its geometry. This model will be used to constrain the mass-loss history of the system, but information of the progenitor(s) is missing, as it is hidden from our view.

Preliminary results on the PN M2-9 show that the putative 'disk' inside the nebula is more extended than the one in Mz3. This is in line with the larger mass (factor ∼4) and with the SED suggesting dust at somewhat cooler average temperature than Mz3 (57). Moreover, the first visibilities reveal some spectral 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. Such features are much more difficult to infer in the ISO spectra. The analysis of these results is at the moment too early to draw firm conclusions, but the 'disk' around M2-9 appears already more massive and probably much older than the one of Mz 3, despite the fact that the kinetical ages of the nebulae are quite similar.

It is tempting to associate the origin of the narrow waist of the extreme bipolar planetary nebulae by the influence of a hidden companion that perturbs deeply the mass-loss process of the primary star, and many asymmetrical nebulae could witness the presence of companions in symbiotic systems. In this context, it is not excluded that the Ant or the Butterfly may be nascent cataclysmic systems, in which the conditions of a nova outburst are fulfilled. The most convincing indication of the presence of a companion in Mz3 is the detection of X-ray jets (28), whereas for M2-9 a white-dwarf companion is required to explain the impressive light-house effect detected [3] .

3.3 The Born-again phenomenon and the R CrB stars

The evolution toward the White Dwarf cooling tracks can be interrupted by the outcome of a Late or Very Late Thermal Pulse (VLTP), the latest flash ignition of the helium-shell, a physical process that intervenes in many aspects of the late evolution of stars with initial masses between 1 and 8 solar mass. The peculiarity of a VLTP is that the reignition of the helium-shell occurs when the star is well advanced in the white dwarf cooling track, and can be surrounded by a relatively old and faint PN. This 'final flash' returns the star very briefly to the Asymptotic Giant Branch (AGB) stage, explaining why these sources are often called 'Born-again' objects. As such a final flash is astronomically very brief (a few tens of years) and the observation of this event is rare, despite the fact that a statistically significant amount of stars (10-25%) evolving off the AGB can experience this phenomenon (25). In 1996, Sakurai's object (V4334 Sgr) brightened considerably in the centre of a faint Planetary Nebula. From 1998 on, a copious amount of dust formed continuously, screening out the star and until now, the star has remained embedded into this putatively spherical envelope in expansion. It is the only member of this rare class of the recent history. V605 Aql underwent a final flash in 1917 and appears today to be still embedded in a disk-like dusty structure (Clayton et al. 2006, Hinkle et al. 2008). MIDI observation of this rapidly evolving source led to the discovery of an unexpectedly compact (30 x 40 milliarcsec, 105 x 140 AU assuming a distance of 3500pc), highly inclined, dusty disk (Chesneau et

[3] `http://antwrp.gsfc.nasa.gov/apod/ap070618.html`

al. 2008b). Moreover, the major axis of the disk (132°±3°) is aligned with an asymmetry of the old planetary nebula that was re-investigated in this study. This implies that the phenomenon at play in shaping the Sakurai's object environment was already intervening when the old planetary nebula formed. The similarity of the Sakurai's object to V605 Aql is an interesting and very important result: would it imply that both envelopes were affected by a low-mass companion? Is the VLTP intrinsically asymmetrical, and if so, for which reason?

When the Born-again stars come back to into the AGB track, they share many observational characteristics with some postasymptotic giant branch (post-AGB) stars called the R Coronae Borealis (RCrBs) stars, a small group of hydrogen-deficient, carbon-rich supergiants. These stars undergo massive declines of up to 8 mag due to the formation of carbon dust at irregular intervals. The VLTI can bring substantial improvement on the knowledge of these particular objects by spatially resolving and temporally monitoring the formation of dust clouds in RCrBs, and by studying the large scale geometry of their envelope with the aim of detecting equatorially-enhanced dusty structures.

Direct detections with 8-m class adaptive optics of RCrBs dusty clouds located at about 0.2-0.3 arcsec from the center ($\sim$1000 stellar radii) were recently reported for RY Sgr, the brightest R CrB of the southern hemisphere(14). MIDI observations of RY Sgr allowed Leao et al. (2007) to explore the circumstellar regions much closer to the central star ($\sim$20-40 mas) in 2005, and to detect a bright clump at the epoch of observation. The visibility curves exhibit a sinusoidal shape at large spatial frequencies (baseline B $\geq$100m), whereas, at shorter spatial frequencies (B $\sim$ 40-65m) the visibility curves follow a Gaussian decrease (although a careful modeling is necessary to ascertain that no second lobe is expected from the unperturbed wind). The bright and apparently single dusty cloud (at this scale), represents $\sim$10% of the total flux of the whole system at 10μm, slightly less that the stellar flux. The cloud is located at about 100 stellar radii (or 30 AU) within a circumstellar envelope whose FWHM is about 120 stellar radii. The same target was observed in June 2007, with baselines limited to 65m. Neither a clump detection nor a dramatic change of the dusty wind was expected, but surprisingly the visibility curves betrayed a large expansion of the dusty envelope in the time interval. A careful reduction of the MIDI spectra in 2005 and 2007 did not allow to detect any change of the N band flux.

3.4 Novae

A classical nova eruption results from a thermonuclear runaway on the surface of a White Dwarf (WD) that is accreting material from a companion star in a close binary system. All aspects of the outbursts, from the temporal development of the fireball, followed by a dust formation phase or the appearance of the coronal phase, witnessed by numerous high excitation lines, that can be studied with the VLTI, both in near and mid-IR. The detailed geometry of the first phases of novae in outburst remains virtually unexplored. The recent outburst from the recurrent[4] nova RS Oph showed how complex such an ejection can be, as seen in the radio-interferometers and the HST images of the bipolar nebula formed rapidly ((4; 46)).

AMBER observations were secured only 5.5 days after discovery(10), providing an excellent K band dataset, including two bright emission lines, Brγ and HeI2.06μm. The triplet of baselines used was not sufficient to determine the geometry of the outburst, but it could provide good constraints on the size of the K band continuum (dominated by the optically thick emission of the nova), of the Brγ line forming region (located in the nova wind), and of the HeI 2.06μm extended forming regions (located close to the shock propagating inside the slow and dense wind of the red giant). An important information could also be extracted inside the Brγ line isolating two kinematical components, an equatorially enhanced 'slow' ($\sim$1800km.s^{-1}) ejection, and the jet-like E-W emission at 'high' speed ($\sim$3000km.s^{-1}). Associated to the motions measured in the plane of the sky from the HST images taken 150 days later, a good picture of the true velocity field of the outburst emerges. The RS Oph observations were based on a single snapshot, followed by a few AMBER measurements 60 days later, but the source could not be really be monitored.

One year later, a great opportunity to observe one of the brightest classical novae was not missed by the VLTI. Soon after its discovery, the slow nova V1280 Sco showed an intense event of dust formation, fading abruptly in visual, and becoming very bright in the near and mid-IR. This nova was monitored during 4 months, providing the first spatially resolved observations of a dust forming nova (Chesneau et al. 2008a). The first observations, secured 23 days after the discovery with AMBER, showed that the source was very compact, less than 1 mas, then few days later, after the detection of the major dust formation event, the source diameter was 13 mas as measured by AMBER and MIDI. The measurement of the angular expansion rate of the optically thick dust shell, together with the knowledge of the expansion velocity, provided a direct estimate for the distance of the object. In absence of clear evidence of asymmetry, each stage is currently modeled using the spherical radiative transfer code `DUSTY`, providing numerous information on the physical conditions that lead to such an efficient and long duration dust formation event. It

[4] Contrary to classical novae for which the recurrence time can be of the order of 10,000yrs or more, the recurrent novae are characterized by several outbursts registered in an historical period of time. The recurrence timescale of RS Oph is one of the shortest of its class, of the order of 20yrs.

was for instance possible to estimate the daily production of dust and infer the total mass ejected.

3.5 Conclusion

The observations of evolved stars with the VLTI is not limited by the array or the instrument. This is not a matter of sensitivity or spatial resolving power but these observations are simply limited by the manpower of the small community using this great instrument. Many spectral types have not been investigated in depth, the symbiotic star just for citing an example. The results presented here have to be considered to be a kind of 'appetizer' for a new generation and there is no doubt that the VLTI could lead to a breakthrough in the understanding of these sources.

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