FROM THE ATMOSPHERE TO THE CIRCUMSTELLAR ENVIRONMENT IN COOL EVOLVED STARS

M. Wittkowski\textsuperscript{1} and C. Paladini\textsuperscript{2}

Abstract. We discuss and illustrate contributions that optical interferometry has made on our current understanding of cool evolved stars. We include red giant branch (RGB) stars, asymptotic giant branch (AGB) stars, and red supergiants (RSGs). Studies using optical interferometry from visual to mid-infrared wavelengths have greatly increased our knowledge of their atmospheres, extended molecular shells, dust formation, and winds. These processes and the morphology of the circumstellar environment are important for the further evolution of these stars toward planetary nebulae (PNe) and core-collapse supernovae (SNe), and for the return of material to the interstellar medium.

1 Introduction

A stellar atmospheric model describes the temperature and density stratification of the atmosphere, i.e. the variation of temperature and pressure with height in the atmosphere. In addition to the vertical stratification there may be horizontal temperature and density inhomogeneities due to, e.g., rotation, magnetic fields, or convection. Together with opacities, these stellar model atmospheres predict the spectrum emerging from every point of a stellar disk. Most often model atmospheres are calibrated by and compared to integrated stellar spectra. However, spatially resolved observations can measure the intensity profile across the stellar disk and can thus provide stronger constraints on model atmospheres. Such observations have been successfully executed by direct imaging observations of the sun, and by interferometric observations for the case of stars other than the sun.

Cool evolved stars finish their evolution that is driven by nuclear fusion along the Hayashi track in the Hertzsprung Russel (HR) diagram. They are characterized by low effective temperatures between about 2500 K and 4000 K and low surface
gravities. They show extended atmospheres that have conditions favorable for the formation of molecules and dust. Dust is accelerated dragging along the gas, a process that leads to circumstellar shells and the expulsion of gas and dust into the interstellar medium via winds. From here on, the further stellar evolution of asymptotic giant branch (AGB) stars (initial masses up to about 8 solar masses) toward planetary nebulae (PNe) and of red supergiants (RSGs, initial masses above about 8 solar masses) toward core-collapse supernovae (SNe) is mostly driven by the mass-loss process. The details of this process are currently best constrained for carbon-rich AGB stars, i.e. stars for which carbon has been dredged up from the core into the atmosphere, as outlined by, e.g., Wachter et al. (2002) and Mattsson et al. (2010). The process is less constrained for oxygen-rich AGB stars (e.g., Woitke 2006, Höfner 2008) and for red supergiants (e.g., Josselin & Plez 2007). In order to constrain and to understand these processes, it is important to observationally establish the detailed stratification and geometry of the extended atmosphere and the dust formation region, and to compare it to different modeling attempts. Here, interferometry plays a crucial role by its ability to spatially resolve the atmospheres and innermost regions of the dust formation zone, where the mass-loss process is initiated.

A few selected examples of interferometric observations of stellar atmospheres and circumstellar environments include constraints of the limb-darkening effect (e.g., Quirrenbach et al. 1996, Wittkowski et al. 2001, 2004), comparisons with models of photospheric convection (e.g., Chiavassa et al. 2011), interferometric observations of oblate shapes of rotating stars (e.g., Domiciano de Souza 2003), constraints of stellar pulsations of Cepheids (e.g., Kervella et al. 2004) and Mira variables (e.g., Thompson et al. 2002), dust formation around Cepheids (e.g., Kervella et al. 2006) and Miras (e.g., Wittkowski et al. 2007), observations of disks in binary post-AGB stars (e.g., Deroo et al. 2007), or investigations of the central regions of PNe (e.g., Chesneau et al. 2007).

In the following section we describe in more detail interferometric observations of stellar atmospheres on the (first) red giant branch (RGB), the AGB, and of RSGs. We continue with dust shells and winds from these cool evolved stars, and finally describe recent observational results on asymmetries of their circumstellar dust environments. In the context of the VLTI school book, we focus on results obtained with the VLTI, but also include examples of important results from other interferometers. Evolutionary stages preceding and succeeding RGB, AGB, and RSG stars are not (fully) covered by this article, as for instance hotter giants and supergiants, post-AGB stars, PNe, or Wolf-Rayet stars.

2 Stellar atmospheres of cool evolved stars

Interferometric observations of stars provide to first order stellar radii and such measurements have been the prime scientific target of early interferometers. The next-order effect of resolving a stellar surface is a measurement of the limb-darkening effect, where stars appear brighter at the center of the stellar disk and darker at the limb of the stellar disk. This phenomenon is a consequence of the
vertical temperature stratification of the stellar atmosphere combined with the line-of-sight of the observation. Along any line of sight the observer will see into a geometrical depth of the atmosphere that corresponds to an optical depth of unity. Toward the center of the star, deeper atmospheric layers are seen, which are hotter because of the vertical temperature stratification; toward the limb of the star shallower atmospheric layers are seen, which are cooler. Observations of this effect thus constrain the vertical temperature stratification of the atmosphere, which is one of the prime outcomes of a model atmosphere. The strength of the effect depends on the temperature stratification of the star and on the wavelength of observation.

Model atmospheres are based on different model geometries, plane-parallel geometries and spherical geometries. The plane-parallel model is semi-infinite for all viewing angles, i.e. all paths are optically thick. It has a singularity at a viewing angle of 90 deg., where the intensity drops suddenly to zero. The spherical model has an optically thin limb. This causes an inflection point of the intensity profile and a tail-like extension. More details on the effects of model geometries can be found in Sect. 3.4 of Wittkowski et al. (2004). Observationally, effects of the true spherical nature of stars are more pronounced for stars that have very extended atmospheres, as in the case of cool evolved stars discussed here.

It has been observationally established that the photospheres of AGB stars and red supergiants are surrounded by atmospheric molecular layers (e.g., Mennesson et al. 2002, Perrin et al. 2003, 2004, 2005). In these cases the model geometry is more complex than a simple plane-parallel or spherical geometry. Instead, the intensity profiles are strongly wavelength dependent and show multiple components or strong tail-like extensions (cf. Scholz 2003).

2.1 Radius definitions and fundamental stellar parameters

The definition of a stellar radius is not easy because of the complex geometries of the stellar atmospheres, as described above, and the complex resulting intensity profiles, cf. Scholz (1997). This is in particular true for cool evolved stars, which show extended atmospheres and extended molecular layers.

Different definitions have stellar diameters have been used in the literature in the context of interferometric observations:

- **Uniform disk radius**: A uniform disk (UD) diameter is obtained from a fit of a uniform disk model to the measured visibility data, i.e. determining to first order the radius of a uniform disk that has the same integral flux as the true intensity profile. Since the true intensity profile is not a uniform disk but limb-darkened or even more complex (see above) and depends on the wavelength, this uniform disk will be wavelength-dependent and does not correspond to a certain physical layer of the star. However, it can be corrected to a limb-darkened or Rosseland-mean (see below) radius using model atmospheres.

- **0% intensity radius**: The 0% intensity radius corresponds to the radius where
the intensity drops to zero. This is the radius that is obtained by fitting a
model atmosphere to interferometric data. However, for a spherical geo-
metry, the intensity never drops to zero but is set to zero at an arbitrary outer
boundary condition. It can be corrected to a Rosseland-mean (see below)
radius using model atmospheres.

- **50% radius or FWHM**: A 50% radius or a full width half maximum (FWHM)
diameter corresponds to the radius at which the intensity drops to 50% of
its maximum value. This radius is better defined than a UD radius or a 0%
intensity radius in the case of very extended intensity profiles. It depends
on the bandpass in the same way as the UD diameter.

- **Rosseland radius**: The Rosseland radius corresponds to the atmospheric layer
where the Rosseland-mean optical depth equals 2/3. This definition is phys-
ically most meaningful, as it is independent of wavelength and corre-
sponds to the radius as used in defining physical quantities such as the luminos-
tity or the effective temperature. However, it is not a direct observable but has
to be derived from observations based on model atmospheres. It may also
be contaminated by extended molecular and dusty layers that are located
above the photosphere but contribute to the Rosseland-mean opacity. It
may observationally best be determined by comparisons of observations in
near-continuum bandpasses together with model atmosphere predictions.

A physically meaningful determination of a stellar radius is also important to de-
rive fundamental stellar parameters, most importantly effective temperature and
luminosity. Several teams used the VLTI to concentrate on accurate measure-
ments of stellar radii and fundamental parameters of cool evolved stars, including
Richichi & Roccatagliata (2005), Wittkowski et al. (2006b), Cusano et al. (2012),
Cruzalèbes et al. (2013), Arroyo-Torres et al. (2013, 2014), Paumard et al. (2014).

2.2 **Red giants and the limb-darkening effect**

Measurements of stellar radii using for instance a uniform disk approximation can
be obtained even if the disk is not fully resolved, i.e. by visibility measurements
within the first lobe. Direct observations of the limb-darkening effect require a
higher spatial resolution that fully resolves the stellar disk, i.e. requires visibility
measurements within the second lobe. These are more difficult to obtain because
they require longer baselines and -more importantly- they require observations of
low visibilities corresponding to vanishing fringe contrasts. Early observations of
the limb-darkening effect of red giants were obtained by Quirrenbach et al. (1996)
with the MARK III interferometer, Hajian et al. (1998) and Wittkowski et al. (2001)
with the NPOI interferometer, and by Wittkowski et al. (2004, 2006a) with the
VLTI.

There are in principle two ways to probe the limb-darkening effect:

- Interferometric observations in the 2nd lobe of the visibility function at one
  bandpass. This method directly probes the shape of the intensity profile.
Measuring the variation of a (UD) diameter versus wavelength. This method probes the wavelength-dependent strength of the limb-darkening effect.

Model atmospheres are best constrained using a combination of both methods, i.e. by observations in the 2nd lobe of the visibility function at several bandpasses.

Fig. 1 shows as an example a measurement of the limb-darkening effect of the M giant Menkar (α Ceti) obtained with the VINCI instrument of the VLTI by Wittkowski et al. (2006a). It shows that the uniform disk model and the model atmosphere prediction are virtually identical within the first lobe of the visibility function and differ only in the second lobe. The maximum of the visibility within the second lobe is then a measure of the strength of the limb-darkening effect. Comparisons of different models and different bandpasses show a trend that the limb-darkening effect is stronger at shorter (visual) wavelengths and weaker (i.e. closer to the UD prediction) at longer (infrared) wavelengths and that it is stronger for cooler stars, which have more extended atmospheres, than for hotter stars.

Finally, it should be noted that 3-dimensional (3-d) model atmospheres including effects of photospheric convection predict a slightly different strength of the limb-darkening effect compared to 1-dimensional (1-d) models of the same stellar parameters. Hotter, rising granules have a warmer temperature structure than cooler, descending dark lanes. The mean temperature structure of a 3-d model then differs from that of a 1-d model (e.g. Hayek et al. 2012). This effect has been observed interferometrically by Aufdenberg et al. (2005) for Procyon. High-precision interferometric observations in continuum bandpasses may thus in future provide further constraints on stellar convection and 3-d model atmospheres.

2.3 Atmospheres of AGB stars

AGB stars are affected by stellar pulsations starting with irregular pulsation in mostly overtone modes on the low-luminosity AGB to regular pulsation in funda-
Fig. 2. VLTI/AMBER observation of the Mira-variable AGB star S Ori. The red line denotes the best-fit UD model, the green line the best-fit Gaussian model, and the blue line the best-fit dynamic model atmosphere $M18n$ from Ireland et al. (2004a, 2004b). From Wittkowski et al. (2008).

mental mode of Mira variables (cf., e.g., Wood 1999). The pulsation in the stellar interior leads to atmospheric motion. Shock fronts reach the atmosphere, levitate the gas, and lead to a very extended atmospheric structure and to conditions that are favorable for the formation of molecules. This leads to a scenario where molecular layers lie above the continuum-forming photosphere. The resulting intensity profiles are very complex and wavelength-dependent showing features such as multiple components, step-like functions corresponding to the locations of the shock fronts, or tail-like extensions. The corresponding visibility profiles deviate from UD models already in the first lobe of the visibility function, unlike for a regular cool giant as described above in Sect. 2.2.

Depending on whether or not carbon has been dredged up from the core into the atmosphere, AGB stars appear in observations to have an oxygen-rich or a carbon-rich chemistry.

**Atmospheres of oxygen-rich AGB stars** Most important molecules in atmospheres of oxygen-rich AGB stars are TiO, H$_2$O, CO, SiO. Self-excited pulsation models of oxygen-rich Mira-variable AGB stars (Ireland et al. 2004a, 2004b, 2008, 2011) have been successful to describe interferometric observations of these sources including their extended atmospheric molecular layers (e.g., Woodruff et al. 2004, Fedele et al. 2005, Woodruff et al. 2009, Wittkowski et al. 2011, Hillen et al. 2012). Fig. 2 shows an example of an interferometric measurement of an oxygen-rich Mira-variable AGB star, S Ori obtained with the VLTI/AMBER instrument by Wittkowski et al. (2008). The bumpy visibility curve is a signature of molecular layers lying above the photosphere. At wavelength where the molecular opacity is low, we see the photosphere, the star appears smaller and the visibility larger. At
Fig. 3. VLTI/MIDI and VLBA/SiO maser observations of the Mira-variable AGB star S Ori. The bright blue color indicates the modeled photosphere, the darker blue color the modeled extended atmosphere, and the green color the Al2O3 dust shell. Overplotted are the reconstructed images of the 42.8 GHz and 43.1 GHz SiO maser emission. From Wittkowski et al. (2007).

wavelength where the molecular opacity is larger, we see the molecular shell (here most importantly CO and H2O), the star appears larger and the visibility lower. It is clearly visible that the measured visibility curve is very different to a UD model already in the first lobe of the visibility function, unlike in the case of a normal RGB star as shown in Fig. 1. The visibility variations with wavelength resemble reasonably well the predictions by dynamic model atmospheres. The figure also illustrates that the VLTI/AMBER instrument is well suited to probe molecular layers around evolved stars because of its spectro-interferometric capabilities, i.e. the simultaneous observation of visibilities at many different bandpasses. Similar molecular features have subsequently been observed with the VLTI/AMBER instrument for oxygen-rich AGB stars of different masses and luminosities including three OH/IR stars (Ruiz-Velasco et al. 2011), four additional Mira stars (Wittkowski et al. 2011), and the intermediate-mass AGB stars RS Cap (Martí-Vidal et al. 2011) and β Peg (Arroyo-Torres et al. 2014). Ohnaka et al. (2012, 2013b) studied the CO first overtone lines of the giants BK Vir and Aldebaran using the high-resolution mode of the VLTI and found as well evidence for additional CO layers lying above the model-predicted photospheres.

Additional information on the morphology and velocity structure of the molecular shells can be obtained by radio observations of SiO masers that reside within
the extended atmospheric layers. Cotton et al. (2004), Boboltz & Wittkowski (2005), and Wittkowski et al. (2007) combined infrared interferometry and VLBA observations of SiO masers and found that SiO masers are located close to two continuum photospheric radii and are co-located with the extended molecular atmosphere observed by infrared interferometry and possibly with the inner Al$_2$O$_3$ dust shell observed by mid-infrared interferometry (see Sect. 3 below). The maser spots of S Ori (Wittkowski et al. 2007) showed a radial gas expansion with a velocity of about 10 km/sec, which is consistent with velocities predicted by dynamic model atmospheres. Gray et al. (2009) combined recent dynamic model atmospheres with a maser propagation code. They found that modeled masers form in rings with radii consistent with those found in very long baseline interferometry (VLBI) observations and with earlier models. Maser rings, a shock and the optically thick layer in the SiO pumping band at 8 µm appeared to be closely associated. As an illustration, Fig. 3 shows the structure of S Ori as derived by Wittkowski et al. (2007) at one epoch, including the photosphere, the extended molecular layer, the Al$_2$O$_3$ dust shell, and the 42.8 GHz and 43.1 GHz SiO maser emission.

Asymmetries in the atmospheres of oxygen-rich AGB stars Ragland et al. (2006, 2008), Pluzhnik et al. (2009), and Wittkowski et al. (2011) detected deviations from point symmetry in the atmospheres of a number of oxygen-rich Mira stars through the measurement of non-zero closure phases. The spectro-interferometric capabilities of the VLTI/AMBER instrument used by Wittkowski et al. (2011) indicate that the closure phases are strongly wavelength-dependent and correlate with the positions of the molecular bands, where larger deviations from zero closure phases are observed in molecular bands and smaller deviations at near-continuum bandpasses. This may indicate inhomogeneities or clumps within the molecular layers. It is likely that these are relatively small inhomogeneities within overall circular shells, as the visibility functions are fairly well reproduced by centro-symmetric model atmospheres. Moreover, the image of the Mira star T Lep reconstructed from VLTI/AMBER data also shows an overall spherically symmetric shell (Le Bouquin et al. 2009).

Atmospheres of carbon-rich AGB stars In carbon-rich stars most of the oxygen is locked in the CO molecule, and the atmosphere is enriched of carbon bearing molecules such as C$_2$, C$_3$, HCN, C$_2$H$_2$, CH, CN. Early interferometric studies on C-stars were mainly devoted to stellar parameter determination (diameter and effective temperature) and made use of geometric models, as dedicated model atmospheres were not available. A few examples of these works are Quirrenbach et al. (1994), Dyck et al. (1996), and van Belle et al. (1997). Model predictions for interferometric observables were presented by Paladini et al. (2009). They showed that in the near-infrared there is no window to directly measure the continuum of carbon stars. This is particularly true for evolved objects with mass-loss rates above $10^{-8}$ $M_\odot$ yr$^{-1}$. Models of mass-losing stars exhibit a strong dependency of the radius vs. wavelength, and show visibility profiles that are
Asymmetries in the atmospheres of carbon-rich AGB stars

As in the case of O-rich AGB stars, the inner envelopes of carbon stars are also characterized by asymmetric structures (Ragland et al. 2006, van Belle et al. 2013, Cruzalèbes et al. 2013). There are various interpretations, including asymmetries driven by large convective cells, ellipticity due to stellar rotation, or clumps in the molecular layers. A possible insight will be gained with the new generation of interferometric "imagers" at the VLTI (i.e. the PIONIER, GRAVITY, and MATISSE instruments).

2.4 Atmospheres of red supergiants

It has been observed that photospheres of red supergiants are surrounded by molecular layers in a similar way as oxygen-rich Miras (e.g., Danielson et al. 1965, Perrin et al. 2005, Ohnaka et al. 2009, Montargès et al. 2014), although their pulsation amplitudes are much lower than for Miras. In a series of papers, Wittkowski et al. (2012) and Arroyo-Torres et al. (2013, 2015) used the VLTI/AMBER instrument to observe six red supergiants and confirmed the presence of extended molecular layers for their objects. They compared the data to hydrostatic PHOENIX model atmospheres showing that the PHOENIX models fit well the spectra, i.e. that the molecular opacities are included in the model, but that they do not predict the observed extensions of the molecular layers in the H2O and CO bands, i.e. that the models are too compact compared to the observations. Likewise, pulsation models and convection models with parameters of RSGs could so far not explain the observed extensions. Ohnaka et al. (2009, 2011, 2013) studied individual CO lines of the red supergiants Betelgeuse and Antares using the high-spectral resolution
mode of the VLTI and found evidence for large patches of CO gas moving outward and inward with velocities of up to $\sim 30$ km/sec. They also found densities of the outer atmospheres that are much larger than those predicted by current convection models. At the time of writing this article, it is thus an unsolved problem which mechanism levitates the atmospheres of RSGs.

It is expected that convection leads to large observable convection cells at the photospheric layers of RSGs (cf. Chiavassa et al. 2010 and in this book). Imaging studies with optical interferometers may soon be able to confirm the presence of such convection cells and to characterize them.

3 Dust shells and winds from cool evolved stars

The dust formation, including the formation of first seed particles and the further dust condensation sequence, depends on the chemistry of the AGB atmosphere.

Dust shells of oxygen-rich AGB stars The details of the dust formation and acceleration processes from oxygen-rich AGB stars are a matter of current research. Dust shell parameters were measured in particular by mid-infrared interferometry (e.g., Danchi et al. 1994; Monnier et al. 1997, 2000; Weiner et al. 2006; Lopez et al. 1997; Ohnaka et al. 2005; Wittkowski et al. 2007; Sacuto & Chesneau 2009; Karovicova et al. 2011, 2013; Zhao-Geisler et al. 2011, 2012; Sacuto et al. 2013). There are mainly three scenarios that are being discussed, as recently outlined in more detail by Karovicova et al. (2013):

1. Dust formation starts with TiO clusters, which can serve as growth centers for both $\text{Al}_2\text{O}_3$ and silicates; $\text{Al}_2\text{O}_3$ can also condense on its own with condensation temperatures around 1400 K (Gail & Sedlmayer 1999). $\text{Al}_2\text{O}_3$ grains may become coated with silicates at larger radii and can serve as seed nuclei for the subsequent silicate formation (e.g. Deguchi 1980).

2. Heteromolecular condensation of iron-free magnesium-rich (forsterite) silicates based on Mg, SiO, H$_2$O (Goumans & Bromley 2012). Such grains may exist at small radii of 1.5 R$_\odot$ to 2 R$_\odot$ (Ireland et al. 2005; Norris et al. 2012). Micron-sized grains may drive the wind (Höfner 2008).

3. SiO cluster formation as seeds for silicate dust formation. SiO cluster formation was thought to take place at temperatures below 600 K. However, new measurements indicate higher SiO condensation temperatures, and may be compatible with observed dust temperatures around 1000 K (Gail et al. 2013).

Karovicova et al. (2013) favor scenario (1), as the combination of $\text{Al}_2\text{O}_3$ and warm silicate grains fits well observed spectra and visibilities. However, additional dust grains with relatively flat spectra are needed to explain the observed optical depths for some of their targets. Sacuto et al. (2013) favor scenario (2), but require the addition of a significant amount of $\text{Al}_2\text{O}_3$ grains to fit the observed visibility
spectra. Taking both results together, Al$_2$O$_3$ grains and iron-free magnesium-rich (forsterite) silicates may co-exist at small radii.

**Dust shells of carbon-rich AGB stars** Two different dust species are observed in the atmospheres of carbon-rich AGB stars: amorphous carbon, and silicon carbide (SiC). The amorphous carbon is feature-less in the spectrum, and also in the visibilities. Interferometrically speaking, the presence of amorphous carbon can be recognized by comparing the diameter of the star at different wavelengths. If an amorphous dust opacity is present, the star will appear larger (i.e. lower visibilities) at long wavelengths with respect to the near infrared diameter. The SiC dust appears with a more or less pronounced emission in the spectrum centered at 11.3 $\mu$m. In the visibility profile the presence of SiC will increase the size of the star at the wavelength of this feature with respect to wavelengths between 9 $\mu$m and 10 $\mu$m. The wind in the atmosphere of carbon AGB stars is driven by radiative pressure on small dust particles. This scenario was tested interferometrically by comparing self-consistent model atmospheres including a dust driven stellar wind with interferometric observations (Sacuto et al. 2011). Recent interferometric studies of dust shells in carbon star were presented by Ohnaka et al. (2007), Zhao-Geisler et al. (2012), and Ladjal (2011). These authors report interferometrical variability in the N$^-$band, and identify a wide region for the dust formation zone that ranges from 5 up to 18 stellar radii.

**Dust shells of red supergiants** Red supergiants show mass-loss rates comparable to and exceeding those of oxygen-rich AGB stars (e.g. de Beck et al. 2010). There are also indications that their dust formation process and dust condensation sequence may in principle be similar as well (Verhoelst et al. 2006, 2009, Perrin et al. 2007), although the corresponding process is not yet understood (cf. also Sect. 2.4 above). Ohnaka et al. (2008b) studied the dust envelope of the red supergiant WOH G64 in the Large Magellanic Cloud with the VLTI/MIDI instrument and detected an optically and geometrically thick silicate torus, a result that also lead to a refinement of the stellar parameters of this source. The mass-loss process, in particular the mass-loss rates and the geometry of the circumstellar dust shell, is important for the different paths of further evolution of massive evolved stars toward the different types of core-collapse SNe (e.g. Groh et al. 2013).

4 **Asymmetries in the dusty region of AGB stars**

One of the hot topics in the field of evolved stars over the last few decades concerns the geometry of the mass-loss process, and how it influences the following phase of stellar evolution when the star expels its envelope as a PN. Although $\approx$ 70% of the observed PNe are not spherically symmetric (e.g. Miszalski et al. 2009), and neither are the winds of post-AGB objects (e.g. Bujarrabal et al. 2013), the AGB wind morphology is widely regarded as such. So far, the most accepted explanation that accounts for the asymmetries observed in the PN phase is the
presence of a nearby companion in the environment of the (once) mass-losing star. Observations of an interaction between a companion and stellar wind on the AGB were only successful for a handful of objects (Mauron & Huggins 2004, Dinh-V.-Trung & Lim 2008, Mayer et al. 2011, Maercker et al. 2012, Mayer et al. 2013). This implies that either there are plenty of undiscovered binary stars hidden in the envelope of AGBs, or the asymmetries on the following evolutionary stage are caused by the stellar wind.

Infrared interferometry is a prime technique to provide the closest glimpse to the onset of the stellar wind, where big scale asymmetries induced by the mass-loss process could form. Image reconstruction may be the easiest way to detect asymmetries, but unfortunately this is not yet routine when dealing with interferometry. Asymmetries have so far been detected by direct investigations of visibility data in the Fourier plane. There are two ways to detect departures from symmetry with interferometry in the Fourier plane: (i) by comparing visibilities observed with the same baseline lengths (and at the same epoch for variable targets such as AGB stars), but different position angles; (ii) by detecting a non zero phase signature. When we speak about phase we need to distinguish between closure and differential phase. The closure phase was extensively explained in a previous VLTI school by Monnier (2007). The differential phase is defined as the phase difference between different spectral channels. In this contribution we will mention the differential phase that is provided by MIDI, which has been explained by, e.g., Ohnaka et al. (2008a) or recently by Tristram et al. (2014).

Fig. 5. Model of the best-fit asymmetric-disk model of the silicate carbon star BM Gem at 10 µm from Ohnaka et al. (2008a).
Over the last decade few asymmetries were reported on the AGB, but the interpretation is very difficult, as one would expect. Tatebe et al. (2006) reported the detection of asymmetries in the dust region of six M- and S-type AGB stars. The asymmetry seen in R Aqr was ascribed to binary interaction, while the origin of the asymmetries in the other stars remained unclear. It is known from direct imaging that the innermost region of the prototype of carbon stars IRC+10216 is clumpy. This was confirmed with non zero closure phase observations with ISI by Chandler et al. (2007). Even in this well studied case, it is not clear if the clumps follow a random direction or a preferential one (like disc or spiral). This is mainly due to the small \( uv \)-coverage of the observations. Two J-type stars were observed by VLTI/MIDI, and showed a clear signature of departure from symmetry in the differential phase (Deroo et al. 2007; Ohnaka et al. 2008a). A general consensus about these objects is that they are binaries with an unseen companion, probably a main sequence star (Morris 1987, Lloyd Evans 1990, and Yamamura et al. 2000). The observations were interpreted as circum-binary or circum-companion discs, in which the oxygen-material has been stored while the AGB star transformed from an oxygen-rich star to a carbon-rich star (cf. also Ohnaka et al. 2006). As an illustration, Fig. 5 shows the best-fit asymmetric ring model of the silicate carbon star BM Gem at a wavelength of 10\( \mu m \) from Ohnaka et al. (2008a). This ring model can be characterized by a broad ring with a bright region offset from the unresolved star, and can be interpreted as a system with a circum-companion disk. We note that the shape of the differential phase for the two stars by Deroo et al. and Ohnaka et al. is very different. This might be the effect of the different chemistry, mixed with the effect of different geometries.

A similar signature was detected for the two Mira variables R For and RT Vir (Paladini et al. 2012, Sacuto et al. 2013). The asymmetry could be interpreted as a clump, without involving a disc structure. The authors were able to reproduce the visibility and differential phase with a simple model composed by a UD representing the central star, a Gaussian for the extended envelope, and a Dirac function representing a bright dust clump. The shape of the differential phase of R For was matching the one observed by Deroo et al. (2007). An asymmetry was also found in the dusty region of the O-rich star with a peculiar CO profile SV Psc by Klotz et al. (2012). In this case the asymmetry is again interpreted as the presence of a disc or of a companion. Again the poor \( uv \)-coverage makes data interpretation complex and at this stage it is not possible to conclude if disks are present at this spatial scale, and if they are associated with hidden unknown binary companions, or with the mass loss mechanism. Interestingly, the number of asymmetries detected in AGB stars with optical interferometry is rather small compared to the number of papers published. Ohnaka et al. (2005), Wittkowski et al. (2007), Sacuto et al. (2008, 2011), Zhao-Geisler et al. (2011, 2012), Karovicova et al. (2011, 2013), Klotz et al. (2013) did not detect any asymmetries of the circumstellar dust shells. This might imply that the asymmetric structures detected with MIDI are not very common among the AGBs. Alternatively, they might appear only at low visibility values (below 0.1), while most of the observations presented so far did not sample this part of the visibility curve.
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