Circumstellar envelopes of AGB stars and their progeny, planetary nebulae

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High angular resolution observations of AGB stars

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Abstract. Mass loss of AGB stars is a key process for the late stages of evolution of low and intermediate mass stars and the chemical enrichment of galaxies. It is not fully understood yet, as it is the result of a complex combination of pulsation, convection, chemistry, shocks and dust formation.

In this review I present what high angular resolution observations can teach us about this mass-loss process. Instruments such as SPHERE/VLT, Gravity and AMBER at the VLTI, and ALMA give us the possibility to map AGB stars from the optical to millimetre wavelengths with resolutions down to 1 milliarcsec. Moving from the surface of the star outwards, I present how high angular resolution observations can now produce images of the surface of the closest AGB stars and study convective motion at their surfaces, map their extended molecular atmospheres and the seeds for dust. The dust formation zone can also be mapped and its dust content characterized with mid-infrared interferometry, while ALMA can map the gas and its kinematics. I will conclude by showing how high angular resolution can help us study the impact of a companion on mass loss.

Keywords. techniques: high angular resolution, stars: AGB and post-AGB, stars: winds, outflows, stars: mass loss

1. Introduction

During the late stages of their evolution, low and intermediate mass stars reach the Asymptotic Giant Branch (AGB) phase, where they develop a high mass loss, leading to the formation of an envelope made of dust and gas. It is during this mass-losing phase that newly formed dust and gas, enriched with products from stellar nucleosynthesis, are enriching the interstellar medium. This mass loss is not fully understood yet and stellar evolution codes are not able to reproduce it without using ad hoc physics.

Our current understanding is that this mass loss is due to a combination of physical processes with different spatial and time scales (see e.g. Höfner & Olofsson 2018). Pulsation and convection will levitate the gas and extend the atmosphere. This will create shocks where cooler and denser gas will condense and form dust. Radiation pressure (due to absorption or scattering) will then trigger the mass loss, the gas being carried away via friction.

In this review, I will show how new instruments such as optical interferometry, extreme adaptive optics, and ALMA are revolutionising the field. We have entered the milliarcsec resolution era, see Fig. 1, and are now able to map nearby AGB stars and their circumstellar environments, thus bringing key constraints on the physical processes involved in the mass loss.

In the following sections I will present the different techniques and show what they tell us about the physics of the mass loss. I will show how high angular resolution observations

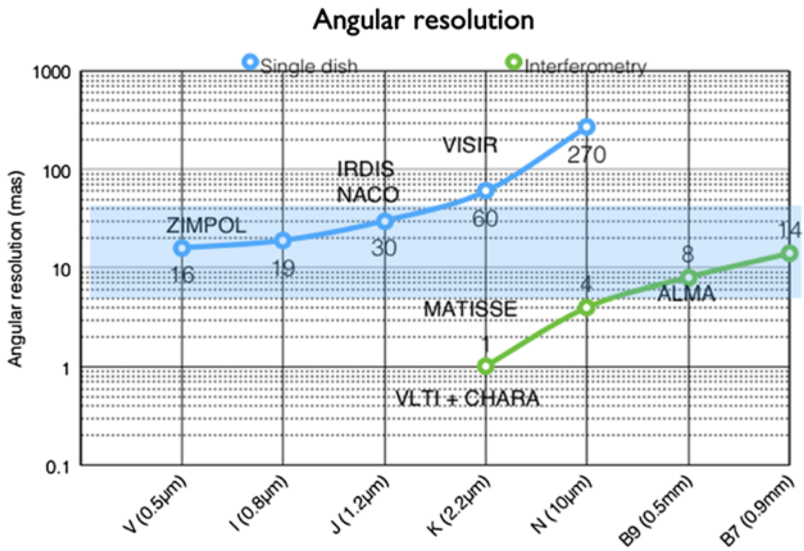

Figure 1. Angular resolution of current high angular resolution instruments operating from the optical to the millimetre wavelengths range, with both single dish and interferometric instruments. Credit: P. Kervella

can help answering key questions about the physics of the mass loss from AGB stars, and how they are bringing new constraints on the models of AGB stars.

With this aim in mind, we will be traveling from the surface of the AGB star outwards.

2. Surface of the star: convection

Theoretical models (see e.g. Freytag *et al.* 2017) predict that the surface of AGB stars is covered by a few large convective cells. Observations with high angular resolution can tell us about the timescales of these cells, their sizes, and the contrast between the cells and their surroundings, giving us constraints on the 3D theoretical models of AGB stars.

This can be achieved with IR/optical interferometry, with instruments such as AMBER/VLTI, PIONIER/VLTI, GRAVITY/VLTI, IOTA, and CHARA. The VLTI can now recombine light from up to 4 telescopes, and CHARA up to 6. This, combined with the advancement of image reconstruction codes (Monnier *et al.* 2014) means that optical/IR interferometry can now produce images with a resolution down to the milliarcsec scale. This means that we can now map the surface of the closest AGB stars.

Using this technique, (Paladini *et al.* 2018) obtained a very spectacular image of the surface of the nearby AGB star π^1 Gruis, Fig. 2. The PIONIER/VLTI observations of this compact, dust free AGB star reveal a complex convective cell pattern at its surface with an average contrast of 12 %. The characteristic size of the convective cells represent ∼27 % of the diameter of the star.

More and more convective patterns are being imaged at the surface of evolved stars with optical/IR interferometry, like for the AGB star R Scl (Wittkowski *et al.* 2017), and the red supergiant (RSG) stars Antares (Ohnaka *et al.* (2017a), Montargès *et al.* 2017), Betelgeuse (Haubois *et al.* 2009) and CETau (Montargès *et al.* 2018).

If the interferometric instrument has a spectroscopic resolution of a few thousands, one can also map the convection across spectral lines. Ohnaka *et al.* (2017a) applied this technique to map convection across the CO line for the RSG star Antares, and thus map the movement of the convective cells via the Doppler effect. The atmosphere appears

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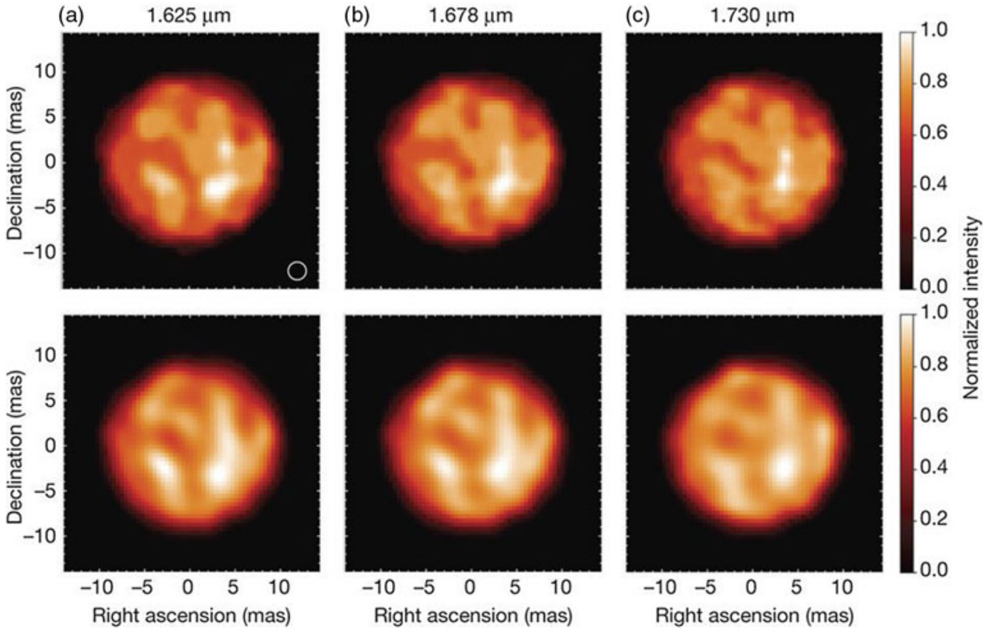

Figure 2. Image reconstruction of the surface of the AGB star π^1 Gruis from Pionier/VLTI observations at three different wavelengths Paladini *et al.* (2018). The two rows are reconstruction using different models. The similar morphology observed in the six panels show that the image reconstruction is robust and reveal a complex surface, covered by a few convective cells.

different across the CO line profile and the velocity field is inhomogeneous. Changes in the convection pattern are seen within a year.

Optical/IR interferometry is thus becoming a great tool to map convection at the surface of AGB stars and to see its evolution with time, bringing key constraints for theoretical models of AGB stars.

3. The gas phase

As mentioned before, the combination of pulsation and convection will expand the atmosphere of the star, where molecules will form. The chemistry in the gas phase will depend on the abundance ratio between carbon and oxygen, as most of the under-abundant species will be locked in the stable CO molecule. We will thus have two kind of AGB stars, oxygen-rich and carbon-rich stars. High angular resolution observations can now help answering the following questions:

- What is the gas distribution above the surface?
- How does it move?
- How does dust form from the gas phase?

Infrared interferometry with high spectral resolution (a few thousands) in the K band can lead to the determination of the size of the CO and H_2O line emitting zone (at 2.0 and 2.29 μm). Ohnaka *et al.* (2016) studied the O-rich AGB star W Hya, revealing an extended molecular atmosphere (MOLSPHERE) with water molecules extending up to 1.5 R_* and CO up to 3 R_*.

Wittkowski *et al.* (2016) performed similar observations of AGB stars (and RSGs) and compared it with state of the art models. Both 1D CODEX (Ireland *et al.* 2011) and 3D CO5BOLD (Freytag & Höfner 2008) models are able to reproduce the extent of the MOLSPHERE for AGB stars, but not for RSGs (some extra mechanisms, such as e.g.

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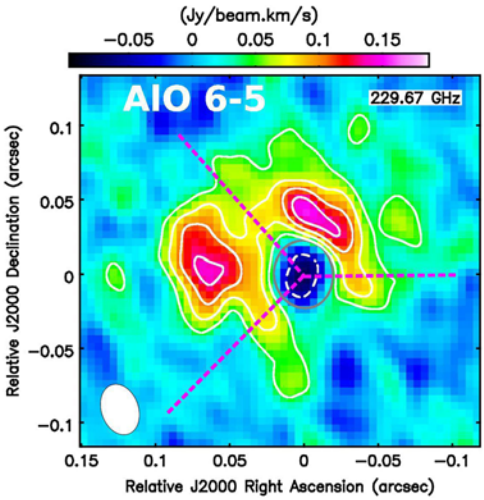

Figure 3. ALMA map of AlO (potential seed for dust formation) around the AGB star *o* Ceti. AlO is located in an incomplete ring at $\sim 2\,R_*$ (Kamiński *et al.* (2016)).

radiation pressure on lines must occur in RSGs and are not taken into account in the models).

So, we can now map extended emission from molecules around AGB stars, but one of the key process to understand is how to condense gas to dust. Dust forms after a chain of chemical reactions that will form larger and larger species.

This is quite well understood for C-rich stars (see e.g. Gautschy-Loidl *et al.* 2004).

For oxygen-rich stars, titanium oxides (TiO, TiO_2) and aluminium oxides have been proposed as the first seeds for dust formation.

Some recent works on oxygen-rich stars with ALMA lead to the detection of aluminium oxides. Kamiński *et al.* (2016) mapped a ring of AlO at $\sim 2\,R_*$ around Mira, Fig. 3. The ring is incomplete, as there is no emission from the south-east of the ring, and the lack of AlO emission at $4\,R_*$ could be a sign of depletion into dust. To confirm that, one would need contemporary monitoring with ALMA (to map AlO depletion) and an infrared interferometer (such as MATISSE/VLTI) to see AlO emission fading where dust is forming. ALMA observations of R Dor and IK Tau revealed that emission of AlO and AlOH, precursors of alumina (Al_2O_3) dust, was extending well beyond the dust condensation radiation, so that the condensation cycle of oxides of aluminium is not fully efficient (Decin *et al.* 2017). However, there are clear observational signs that Al_2O_3 seem to be the first dust to form around AGB stars, and the seeds leading to form dust seem to be aluminium oxides.

4. The dust phase

As mentioned in the introduction, dust is forming behind shocks, where the gas is cold and dense enough to condense into dust.

The questions we want to answer with high angular resolution are:

- Where does dust form?
- What kind of dust forms?
- What is the size of the dust grains?

ALMA observations of W Hya resolved its atmosphere (Vlemmings *et al.* 2017). They detected a hot spot in the southwest, with properties indicating that it is due to shocks, Fig. 4. They also observed the CO(v=1, J=3-2) line, to study gas infall and outflow from

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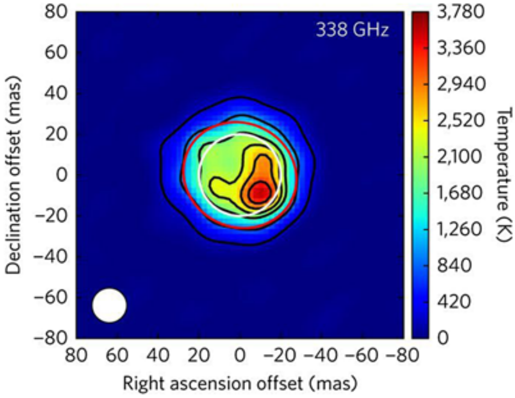

Figure 4. ALMA continuum map at 338 GHz of the surface of the AGB star W Hya (Vlemmings *et al.* 2017). The hotspot in the southwest is unresolved and is certainly due to shocks.

this star. They showed that the total gas mass traced by CO is three orders of magnitude larger than the mass lost by the star during one pulsation period. This means that the CO gas will spend at least 1000 years in the region mapped by the CO observations. As the timescales for shocks and stellar activities are much smaller, all the ejected gas will experience shock heating. Non equilibrium chemistry clearly has to be taken into account in models of dust formation.

Dust forms at less than $3\,R_*$, emits at infrared wavelengths and has spectral features in the mid-infrared. Mid-infrared interferometry is thus the key tool to resolve dust at the dust formation radius and study its properties. Till now, mid-infrared interferometers were using only two telescopes and providing visibilities (i.e., measurements of the size of the emitting zone) and closure phase (i.e., an estimation of the symmetry of the emitting zone) across the N band (between 8 and 13 μm). Using MIDI/VLTI, Karovicova *et al.* (2013) observed 3 O-rich AGB stars and showed that their observations were consistent with Al_2O_3 grains condensing at $2\,R_*$, while silicates were further away, at 4-5 R_*.

Paladini *et al.* (2017) performed a mid-infrared spectro-interferometric survey of AGB stars and showed that asymmetries were common at the dust formation location of oxygen-rich stars. Mid-infrared interferometry can thus now tell us what kind of dust is forming where, and determine the spatial distribution of the dusty shells.

Direct imaging can also bring constraints on the grain dust properties. The extreme adaptive optics imager SPHERE, installed on the VLT, can perform polarimetric measurements with a resolution down to ∼15 milliarcsec in the optical. The instrument is designed to directly image exoplanets and has high resolution and contrast capabilities. One way to enhance the contrast between a planet and its host star is to perform polarimetric observations. The light from the star is not polarised, while the light from the planet is scattered light and thus polarised. This applies to dust close to stars and can thus be used for AGB stars.

Using SPHERE polarimetric observations, Ohnaka *et al.* (2016) resolved clumpy dust clouds at about $2\,R_*$ around the AGB star W Hya. A second epoch of observations enabled them to study the variations of dust properties. Their observations lead to a grains size determination and indicate that small grains (0.1 μm) are observed at minimum light, while large grains (0.5 μm) are predominant just before the maximum.

It also revealed variation within 9 months, with the appearance of new clouds while some disappeared (Ohnaka *et al.* 2017b). The size of the dust clumps and the timescale of

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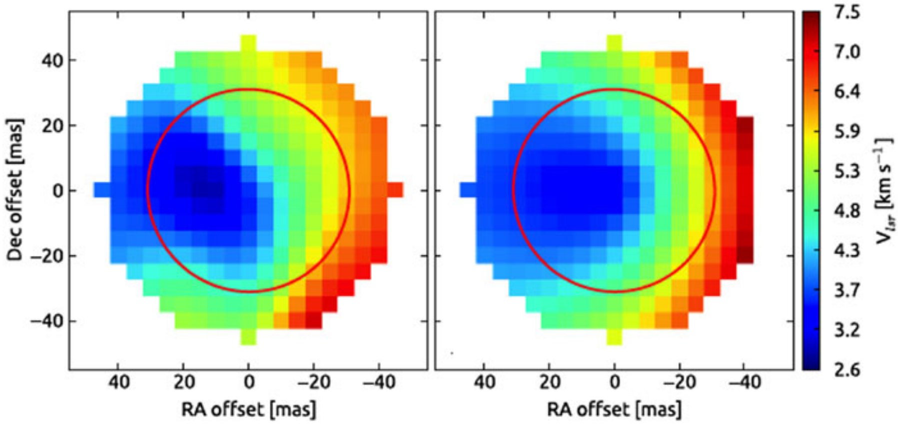

Figure 5. ALMA velocity map (left: observations; right: model) of R Dor showing clear signs of rotation (Vlemmings *et al.* 2018).

their appearance seem to be in agreement with the results of convection, indicating that convection must play a role in the dust formation process (by extending the atmosphere).

Stewart *et al.* (2016) monitored the closest carbon-rich AGB star (IRC +10216) with various high angular resolution instruments (Keck, VLT, and occultation by the rings of Saturn observed by Cassini). They also confirm that dust formation is non isotropic and variable within this period, with clumps fading and appearing.

It thus appears clear that the structure of the extended atmospheres of AGB stars have density inhomogeneities or are clumpy and shocks are present. The chemistry models presented by Van de Sande *et al.* (2018) take these effects into account. This affects the chemistry via the density structure, but also the UV radiation field, which can penetrate deeper in some locations. Thus, species not expected to be present at local thermodynamical equilibrium are formed, such as HCN in O-rich stars and water in carbon stars.

5. Impact of a companion

It is now becoming clear that a majority of planetary nebulae are bipolar, and that the observed bipolarity is due to an extra angular momentum provided by a companion (Boffin *et al.* 2012). This extra angular momentum can lead to the formation of equatorial overdensities such as disks or tori and/or jets, that can be focused by magnetic fields (Balick & Frank 2002).

Such companions should be observable around AGB stars, i.e., in the phase before the planetary nebula phase. Recent high angular observations of AGB stars with ALMA have revealed the presence of spiral structures in their envelopes (see e.g. Maercker *et al.* 2012, Ramstedt *et al.* 2014). This can be explained by the wind roche lobe overflow model proposed by Mohamed & Podsiadlowski (2012). But the binary forming these spirals have a large separation, so that these systems most likely will not form bipolar nebulae due to a lack of angular momentum.

Observations of R Dor both with SPHERE and ALMA are interesting for understanding the potential effect of a nearby companion. SPHERE observations of R Dor resolved the stellar surface, and showed that its morphology was varying with time scales of months, certainly due to a variation of opacity due to TiO molecules (Khouri *et al.* 2016). No sign of interaction with a companion are seen in these data. However, two independent ALMA observations reveal a clear rotation pattern for R Dor, Fig. 5. It was previously, using lower angular resolution data, attributed to a disk in rotation

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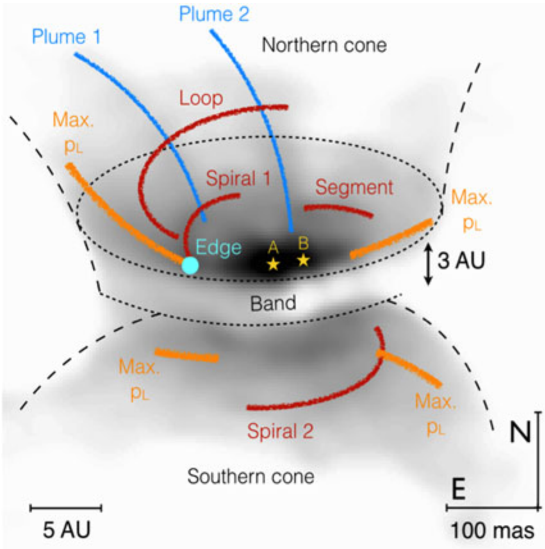

Figure 6. SPHERE optical image of the AGB star L_2 Pup, with the presence of an equatorial disc revealed in scattered light (Kervella *et al.* 2015). A companion is also discovered, and plumes of material are being ejected in a plane perpendicular to the disc.

(Homan *et al.* 2018). Higher angular resolution observations indicate that this is instead due to rotation of the stellar surface (Vlemmings *et al.* 2018). The angular momentum needed to explain the observed rotation requires the presence of a yet unseen companion. This star might form a bipolar nebula, but the best AGB candidate to form a bipolar PN is certainly L_2 Puppis.

L_2 Puppis is a nearby AGB star (64 pc), and it was observed by SPHERE (Kervella *et al.* 2015) in the optical, both in classical and polarimetric imaging. An edge-on disc is clearly seen in scattered light (thus appearing as a lane with no emission) on the SPHERE image, Fig.6, where a companion is also seen at 2 AU. The polarimetric map reveal that inner rim of the disk is located at 6 AU and that plumes of material are being ejected in a plane perpendicular to the disc.

ALMA observations of L_2 Puppis, with an angular resolution similar to those of the SPHERE observations ($\sim$ 15 mas), were performed by Kervella *et al.* (2016) to study the gas distribution and dynamics around this AGB star. They confirmed the presence of the disc and that it is in keplerian rotation. This led them to an estimate of $\sim$0.7 $M_\odot$ for the central star of the system and $\sim$12 $M_{\rm Jup}$ for the companion. The companion appears thus to be a planet and not a star. From evolutionary models, they estimated that the initial mass of the central star was very close to the mass of the sun, and that the ALMA observations might be giving us an idea of what will happen to the sun in 5-6 billion years. Let's take bets and wait and see?

6. Conclusion and perspectives

Thanks to new instrumentation such as the extreme adaptive optic system SPHERE on VLT, optical/infrared interferometry, and ALMA, high angular resolution observations are helping us understand the complex mass-loss process of AGB stars. It is now possible to map convection at the surface of stars, shocks above this surface due to convection and pulsation, and dust formation behind these shocks. The atmospheres of AGB stars are not spherical and isotropic where dust is forming, as dust appears to form in clumps above convective cells or shocks. Companions, or hints of companions, of AGB stars are

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being found, and it is now clear that a non negligible fraction of AGB stars will interact with a companion. Even if not all these interactions will lead to mass transfer, the density structure of the circumstellar envelope will be affected. Impressive developments on theoretical models have been, and are being, made to use this information and take into account the effect of non-spherical circumstellar envelopes, clumpiness, and non-LTE effects.

From an observational point of view, two kinds of observing programs need to be performed, either to better understand the physics of the mass loss from AGB stars or determine the quantitative impact of AGB stars to the enrichment of the Galaxy. Both programs should be very ambitious as they require observations from multiple telescopes using different techniques and operating at various wavelengths.

To understand the physics of the mass loss, time series observation of a representative sample of AGB stars (O-rich, C-rich, with and without companions, and at different evolutionary stages). Combining ALMA, optical/IR interferometry would then allow monitoring of these stars along their pulsation cycle and map the convection, shocks, gas depletion into dust, dust formation, dust properties, and wind acceleration.

Quantitavely determining the impact of AGB stars on the chemical enrichment of nearby galaxies can be achieved as we are outside of these galaxies and can map them fully rather rapidly and we have a good estimate of the distance of stars in the galaxies, which can be assumed to be the same as the galaxies themselves. A similar method has been applied e.g. to determine the dust input from AGB stars to the interstellar medium in the Large Magellanic Cloud (Srinivasan *et al.* 2009, Matsuura *et al.* 2009). In the Galaxy, it is difficult to get the distance to all the AGB stars, and due to extinction in the Galactic plane, some are too obscured to be observed. But thanks to Hipparcos and Gaia, distances to the closest AGB stars is now known (within 200-300 pc). Observations of all the stars in a volume limited and complete sample of nearby stars would help us getting statistics about the properties of these stars. Observations at millimetre wavelengths will tell us about the gas properties, in the infrared about the dust, and high angular resolution can teach us about the density distribution. It is thus important to obtain observations of AGB star in such a sample and combine this with state of the art radiative transfer model to quantify the impact of AGB stars on the chemical enrichment of the Galaxy.

Finally, dust in AGB circumstellar envelopes emit in the mid-infrared and have spectral signal in the N band (between 8 and 13 μm). The best way to study the dust spatial distribution is thus to obtain high angular resolution observations of AGB stars in the mid-infrared. The new generation VLTI instrument MATISSE (Lopez *et al.* 2014) will offer a unique opportunity. It will be offered to the community for observations starting in 2019. It will enable us to obtain images of the different dust species around AGB stars from the dust formation radius outwards.

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