A VISIR Mid-infrared Imaging Survey of Post-AGB Stars

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Post asymptotic giant branch (AGB) stars are key objects for the study of the dramatic morphological changes that low- to intermediate-mass stars undergo during their evolution from the AGB towards the planetary nebula stage. There is growing evidence that binary interaction processes may play a determining role in shaping many objects, but so far direct evidence for binarity is still weak. We report on a systematic study of the dust distribution around a large sample of post-AGB stars that probes the symmetry-breaking in the nebulae around these systems.

According to our current understanding of stellar evolution, all stars with main sequence masses in the range 1–8 $M_\odot$ evolve via the asymptotic giant branch phase to the planetary nebula (PN) stage. As they ascend the AGB, their mass-loss rate increases from solar-like values of 10^{-14} $M_\odot$/yr up to 10^{-4} $M_\odot$/yr. The integrated mass lost from these stars is an essential component of galactic evolution, as it is the main source of *s*-process elements in the Universe and the main producer of carbon. AGB stars are also the main contributors to the dust phase of the interstellar medium (ISM). During the last stages of AGB evolution, the remains of the convective hydrogen envelope are ejected during final, quiescent and sporadic mass-loss events. Dust grains and molecules, predominantly CO, form in their winds, forming large circumstellar envelopes that can be detected in the infrared and millimetre domains.

A departure from spherically symmetric mass-loss is observed in a substantial fraction of suspected AGB to PN transition objects. In particular, multipolar structures are often associated with protoplanetary nebulae (PPNe). The three-dimensional morphologies of these objects are projected on the sky, thus making it difficult to determine the intrinsic morphology of PPNe and PNe. But it is estimated that around 80% of all PNe show aspherical morphologies. Hubble Space Telescope observations of PNe, for example, show a large range of morphologies, including elliptical, bipolar, multipolar or round nebulae.

Hydrodynamical models explain many of the observed structures from a structure-magnification mechanism, where a fast wind from the central star of the PN ploughs into the earlier slow AGB wind, amplifying any density asymmetry already present: this is the generalised interacting stellar wind model (GISW). Another model has also been proposed to explain the shaping of PNe. In this model shaping occurs at the end of the AGB phase, when fast collimated jets are triggered and shape a bipolar nebula. If the direction of the jets changes with time, then multipolar nebulae can be formed. Such jets could be formed through interaction with a companion, e.g., in an accretion disc (see Balick & Frank [2002] for a review).

Much of the theory of the shaping of PN and PPN relies on the presence of circumstellar material in either a dusty torus or a disc. Our team has discovered some discs/tori in the heart of PNe (Lagadec et al., 2006; Chesneau et al., 2006; Matsuura et al., 2006; Chesneau et al., 2007) using adaptive optics on ESO's Very Large Telescope (VLT) and mid-infrared (MIR) interferometry at the Very Large Telescope Interferometer (VLTI). But the role of these discs/tori in the shaping of the nebulae is still unclear, as we know neither the fraction of the total dust mass that is present in these central cores, nor the fraction of objects exhibiting such a disc/torus structure.

In order to observe the inner region of post-AGB stars, we need MIR observations, as the dust optical depth is smaller at longer wavelengths. The MIR is the only wavelength range at which we can observe the inner morphology of stars from the AGB to the PPN phase. Furthermore, the main source of radiation for these sources in the MIR is direct emission from dust, while at shorter wavelengths it is scattered light. Mid-infrared imaging is thus the best way to study the dusty structures inside these evolved stars.

Many MIR imaging observations of post-AGB stars have been made in the past. But the only available MIR imaging survey (Meixner et al., 1999) has been made with 3-metre-class telescopes and suffers from limited angular resolution for the morphological study of the observed objects; in addition the survey selection is biased, as known bipolar nebulae were observed. The survey consisted of only 17 resolved sources. Some work has been done using 8-metre-class telescopes, but always focusing on particular individual bright, well-known objects.

Here we present the results from the first mid-infrared *N*-band imaging survey of a large number of post-AGB stars with 8-metre-class telescopes. We aim at a systematic survey probing the inner dusty regions of post-AGB stars.

Target selection and observations

The large sample of observations came from five distinct observing runs from VISIR/VLT, Michelle/Gemini North and T-Recs/Gemini South.

Our sample contains the brightest post-AGB stars observable from Paranal and includes PPNe, R CrB stars, RV Tauri stars and "Water Fountains". R CrB stars are hydrogen-deficient post-AGB stars with known obscuration events. RV Tauri stars are pulsating post-AGB stars, located at the high luminosity end of the Population II Cepheid instability strip. These RV Tauri stars are likely to harbour compact dusty discs. Water Fountains are oxygen-rich PPNe characterised by the presence of blue and red-shifted OH and H_2O masers, hence their curious class name. Some *bona fide* PN and evolved massive stars were also observed.

Most of the observations were obtained with the MIR instrument VISIR on the VLT. The excellent observing conditions during our run (0.43 mm of precipitable water vapour in the atmosphere), combined with the burst mode on VISIR, allowed us to obtain high quality diffraction-limited images. The burst mode readout allows every single frame of an exposure to be saved. In this way it is possible to follow rapidly evolving events or to improve the spatial resolution by taking short enough exposures to freeze atmospheric turbulence, as in lucky imaging (e.g., Law et al., 2006). This mode can be used only for objects that are bright enough to provide a high enough signal-to-noise (S/N) in a single elementary frame.

We thus observed 93 evolved stars in a quasi-uniform way in the mid-infrared, with a spatial resolution of the order of 0.3 arcseconds (which is the diffraction limit at this wavelength).

Two kinds of objects: resolved cores and detached shells

From the set of 93 objects we observed, 59 appear as point sources. Among the extended targets, we resolved a wealth of different structures, such as resolved central cores, dark central lanes, detached shells, S-shaped outflows. If we consider only the PPNe from our sample, we arrive at a sample of 52 detected objects.

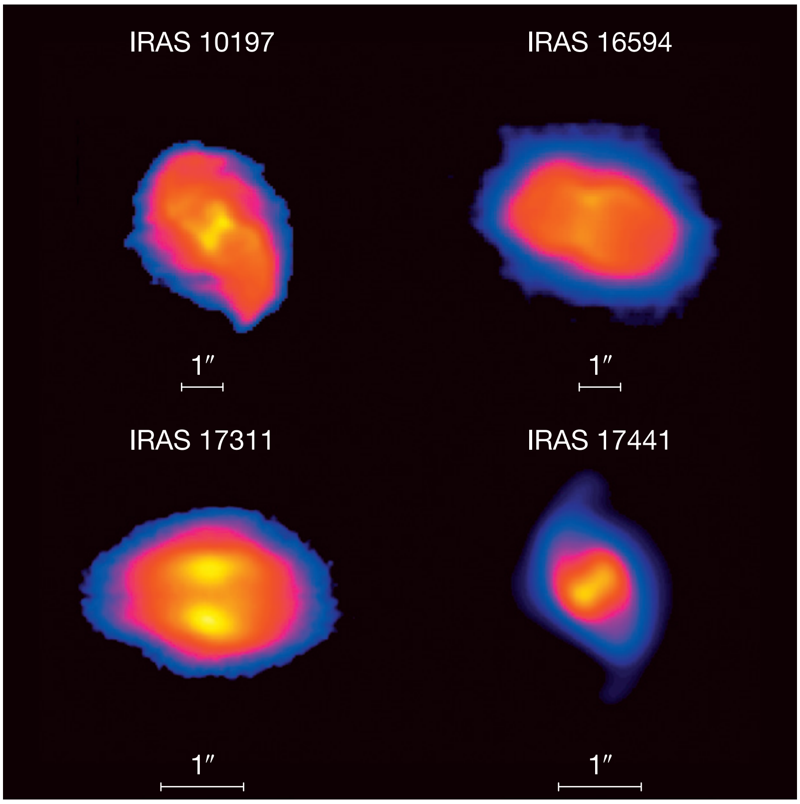

Figure 1. VISIR 10 μm images of a sample of post-AGB stars with resolved central cores. The designation of each target is given and the spatial scale is shown.

For the largest objects that are clearly resolved, we notice that the PPNe can be divided into two categories. On the one hand the objects with a dense central core, in the form of a bright central source or a dark lane, with most of the emission coming from the poles, indicate the presence of a large amount of dust, making the central regions optically thick even in the MIR. Four examples are shown in Figure 1. On the other hand, some objects do not have such a dominant central core, and we can observe either a detached shell or the central star (examples in Figure 2). The objects without a central core all have an elliptical morphology, while the objects with a central core are either bipolar or multipolar. Both types of sources are differentiated in their spectral energy distribution (SED): the objects with a dense central core or an equatorial dark lane have a rather flat SED in the near-infrared wavelength range, due to the presence of hot dust close to the central star; the objects with detached shells are characterised by the presence of a clear double-peaked distribution to the SED, with a first peak at a wavelength shorter than 1 μm due to the central star, and a second peak due to the cool dust in the shell. The flux is much lower in the near-IR due to the absence of dust close to the central star. Figure 3 shows examples of both SEDs.

The very strong correlation between the presence of a dense core and the bipolar morphology is an indication that the dense cores play a role in the shaping of the nebulae. Two main classes of models have been proposed to explain the shaping of nebulae. The first class of models is based on the GISW models and here a fast wind from the central star of a PPN or PN interacts with a slower wind, a remnant of the AGB phase, assumed to be toroidal. In the second class of models, the primary shaping agents are high-speed collimated outflows or jets that are created at the end of the AGB phase or at the beginning of the PPN phase. The interaction of these jets with a spherical AGB wind will create lobes that are in fact

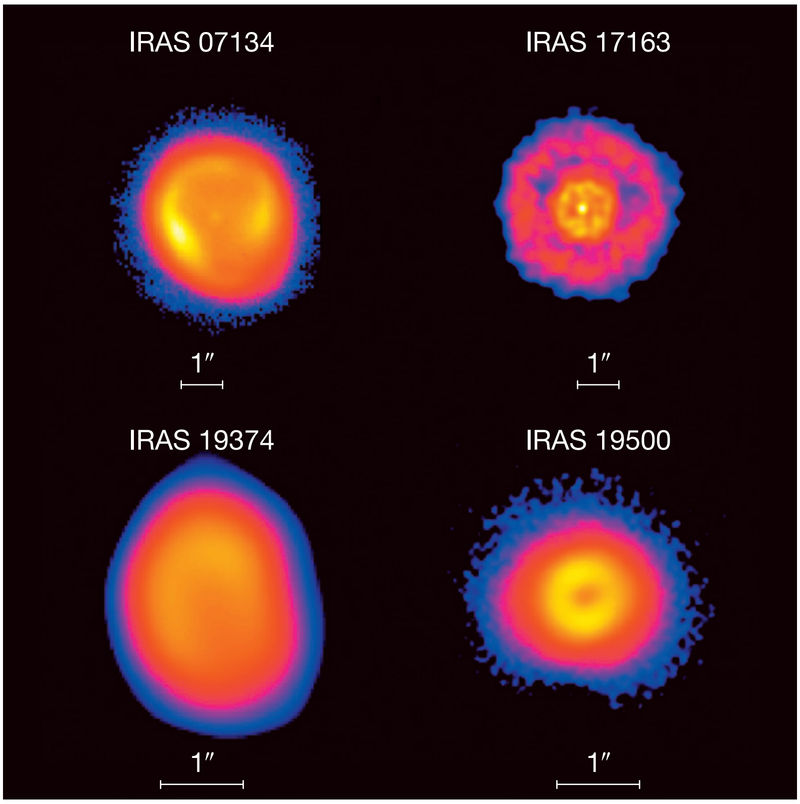

Figure 2. VISIR 10 µm images of a sample of post-AGB stars with detached shells. Annotations are as in Figure 1.

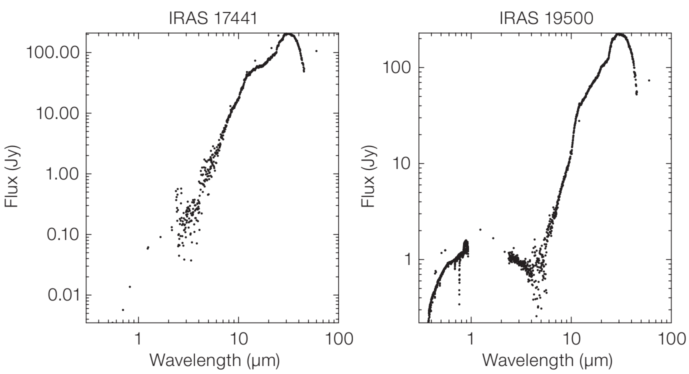

Figure 3. Typical spectral energy distributions of the two classes of objects observed. Left: an object with a dense equatorial dusty torus and a bipolar/multipolar morphology. Right: an object with a detached shell and an elliptical morphology.

cavities. If the direction of the jets changes with time, multipolar nebulae can be shaped.

Both models require the presence of a central torus/disc in the core of the nebula. Our observations clearly indicate that the bipolar and multipolar nebulae do have such a central structure in their core.

Departure from circular symmetry

All the PPNe we resolved in our survey show a clear departure from circular symmetry. Some circular shells are resolved, but only around massive evolved stars. A dramatic change in the distribution of the circumstellar material is often observed when a star evolves from the AGB to the PN phase (Balick & Frank, 2002).

Most AGB stars have a large-scale circularly symmetric morphology, while PNe display a variety of morphologies from elliptical to bipolar or multipolar. Optical imaging surveys of PNe indicate that 80 % of the PNe show a clear sign of departure from circular symmetry, and thus that approximately 20 % of PNe are spherical. The shaping of the PNe is thought to occur at the very end of the AGB phase or the beginning of the PPN phase. It is thus surprising that in our sample of 25 resolved PPNe, we do not find any circular ones.

The fact that we do not observe any circular PPNe could be a sample selection effect. We selected our targets as bright IRAS 12 µm sources. To be a bright emitter at these wavelengths, an object needs to have dust with a temperature of approximately 300 K, which must therefore be located close to the central star. This is the case for the stars with a central core, which are aspherical. The spherical PPNe are fainter than the non-spherical ones in the mid-infrared, due to the lack of a central torus/disc emitting in this wavelength range. At the end of the AGB phase, the envelopes of the AGB progenitors of circular PPNe are ejected and rapidly cool down while expanding. There are thus very few spherical PPNe that are bright in the mid-infrared. Furthermore those bright PPNe are compact and thus difficult to spatially resolve. The best way to detect such spherical envelopes is thus at longer wavelengths, and such detached shells are actually observed in the far infrared with the Herschel Space Observatory.

Formation of point-symmetric structures

A few objects that we resolved display a point-symmetric morphology, with an S-shaped envelope. One of our targets, IRAS 17441 (shown lower right in Figure 1), displays a tilt between the orientation of the resolved central dusty torus and the tips of the observed S-shaped structure. Such a tilt was observed by Volk et al. (2007), and measured to be almost 90 degrees. They suggested that a precession of the dusty torus could explain the observed S-shaped structure of the nebula. They estimated the dynamical age of the envelope, assuming a distance of 1 kpc and an expansion velocity of 100 km/s, to be approximately 100 yr. According to this model, the torus should thus precess with a rate of around 1°/yr. As our observations were made four years after the observations presented by Volk et al. (2007), we should see a tilt of the torus of about 4° between the two observations. The images provided by these authors show that the orientation of the torus that they observed is exactly the same as the one we observed. The torus in the core of IRAS 17441 is thus not precessing at such a high rate.

It appears that we cannot explain the observed S-shaped structures with a precession of the central tori. This could be due to the fact that we underestimated the dynamical age of the nebula or that another mechanism is responsible for the S-shaped structure. A more plausible explanation is that the S-shaped structure is not due to the precession of the torus itself, but to precessing outflows inside this torus. The presence of such outflows has been observed in the PN NGC 6302, which has a morphology very similar to that of IRAS 17441 (Meaburn et al., 2008). These outflows are of a Hubble-type, which means that their velocity is proportional to the distance from the source. A torus similar to the ones observed in the core of these objects is also seen in the core of NGC 6302. The properties of such outflows can be theoretically described by a sudden ejection of material, a "bullet". Such bullets naturally account for multipolar flows, which could arise naturally from the fragmentation of an explosively driven polar-directed shell. We postulate that the S-shaped structure observed in IRAS 17441 is due to high speed outflows triggered at the end of the AGB phase, or the beginning of the PPN phase, likely during an explosive event.

Chemistry and morphology

Amongst the PPNe clearly resolved in our survey, 18 have known dust chemistry: either oxygen-rich, carbon-rich or a dual dust chemistry with both carbonaceous and oxygeneous dust grains in their envelopes. For the oxygen-rich sources, we find that 10 out of 11 are bipolar or multipolar, while the remaining one is elliptical. For the carbon-rich sources, we find that two are bipolar or multipolar and two elliptical. The three objects with a dual dust chemistry are multipolar or bipolar. This is in agreement with the recent work by Guzman-Ramirez et al. (2010), which shows a strong correlation between dual dust chemistry and the presence of an equatorial overdensity. The dual dust chemistry could be due either to the formation of PAHs in an oxygen-rich torus after CO photodissociation, or to the presence of a long-lived oxygen-rich disc formed before the star turned carbon-rich due to the third dredge-up.

Stanghellini et al. (2007) also studied the correlation between dust composition and morphologies. They determined, from a study of 41 Magellanic Cloud PNe, that all PNe with oxygen-rich dust are bipolar or highly asymmetric. Our study agrees with this finding, and it seems that oxygen-rich PPNe appear to be bipolar or multipolar. The low C/O ratio of these bipolar nebulae could be due to the interaction with a binary companion during a common envelope phase, or, in the case of single star evolution, result from conversion of carbon to nitrogen. The common envelope interaction will lead to the ejection of the envelope earlier than in the single star evolution scenario, leading to a less efficient dredge-up of carbon, and thus a lower C/O ratio. The conversion of carbon to nitrogen occurs for massive AGB stars in the hot bottom-burning process. It is thus likely that the bipolar PPNe have progenitors with larger masses than the elliptical ones. This is in agreement with the work by Corradi & Schwartz (1995), who showed that bipolar PNe tend to have a higher progenitor mass. Soker (1998) proposed that this result could be explained in the paradigm of binary system progenitors, as primaries that undergo a common envelope phase, and thus become bipolar, tend to have a higher mass.

Future directions

A large fraction of the dust in galaxies is produced during the late stages of the evolution of low- and intermediate-mass stars. This dust is ejected into the ISM during the PPN phase. Our observations show the existence of two paths for this dust ejection, via a detached shell or an expanding torus. It is now becoming clear that the bipolar objects with an equatorial torus have been formed via the interaction with a binary companion. This opens up a new field of research to study the impact of the presence of a binary companion on the dust formation by evolved stars. In order to better understand the importance of PPNe for the life cycle of dust, it would be interesting to study how these different paths affect the dust production by these objects. Spatially resolved VISIR mid-infrared spectra of these sources will allow us to study the dust composition at different locations in these PPNe, enabling us to better understand the evolution of dust during the PPNe phase, from its formation to its ejection, and how the presence of a dense dusty disc affects its composition.

Finally, the mass loss from evolved stars is a key ingredient for our understanding in many fields of astrophysics, including stellar evolution and the enrichment of the ISM via stellar yields. The aim of an ongoing ESO large programme (PI: C. Paladini), which will combine MIDI + VISIR + Herschel observations of a sample of evolved stars, is to constrain the geometry of this mass loss at different spatial scales. We will then be able to fully understand the dust evolution from its formation in a circumstellar envelope until its injection into the ISM, and better understand the life cycle of dust.

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