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AGBs, Post-AGBs and the Shaping of Planetary Nebulae

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Received: 31 July 2018; Accepted: 29 August 2018; Published: 17 September 2018

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Abstract: During the last decades, observations, mostly with the Hubble Space Telescope, have revealed that round Planetary Nebulae were the exception rather than rule. A huge variety of features are observed, such as jets, discs, tori, showing that the ejection of material is not due to isotropic radiation pressure on a spherical shell and that more physics is involved. This shaping process certainly occur early in the evolution of these low and intermediate mass stars and must leave imprints in the evolutionary stages prior the PN phase. Thanks to news instruments on the most advanced telescopes (e.g., the VLTI, SPHERE/VLT and ALMA), high angular resolution observations are revolutionising our view of the ejection of gas and dust during the AGB and post-AGB phases. In this review I will present the newest results concerning the mass loss from AGB stars, post-AGB stars and related objects.

Keywords: AGB stars; post-AGB stars; planetary nebulae

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1. Introduction

The aim of this asymmetrical planetary conference series, started in 1994, has been to understand the cause of the spectacular morphologies displayed by planetary nebulae (PNe). It appears fairly clearly now that the departure from spherical symmetry observed for PNe is due to an extra momentum brought by a binary companion [1–4]. As it appears clear that a large fraction of PNe is being shaped by binaries, sign of interactions with companions on previous stages of stellar evolution (AGB and post-AGB) should be observable. This is made difficult by the fact that these objects are more compact and often embedded in dust. Fortunately, we now have instruments able to probe the very close environments of such stars, and even to map their surfaces. In the course of this conference series, we indeed switched from subarcsec resolution observations to the milliarcsec era. Figure 1 (courtesy of Pierre Kervella) displays the resolution achieved by some of the main current instruments at different wavelengths. We can now probe regions between 1 and 20 milliarcsec in size from the optical to the submillimetre domain. For a star at 100 parsec, this means we can map material as close 0.1 AU of the central star, i.e., that we can map the surfaces of nearby giant stars.

In this review I will show how these high angular resolution instruments are revolutionising our view of AGB and post-AGB stars and present some high-angular resolution observations of related (massive) objects that can help us understand the shaping of PNe.

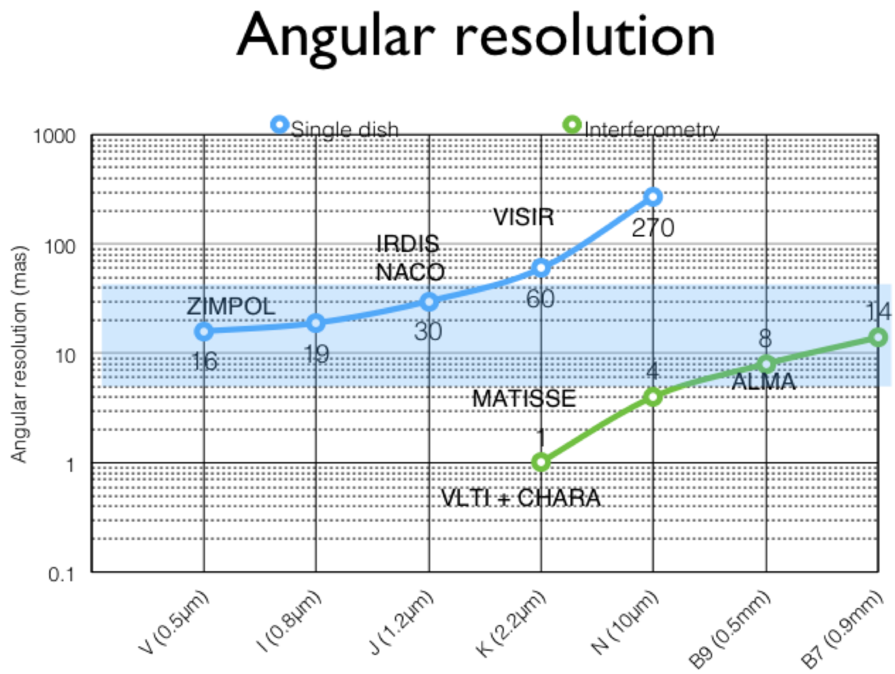

Figure 1. Angular resolution (in miliarcsec) as a function of wavelength for the instruments of the Very Large Telescope (VLT), the Very Large Telescope Interferometer (VLTI), CHARA and ALMA.

2. AGB Stars Morphologies

Before becoming a PN, stars with masses between 0.8 and 8 $M_\odot$ evolve along the Asymptotic Giant Branch (AGB). Convection and pulsation of AGB stars extend their atmosphere and can trigger shocks that can lead to dust formation. Radiation pressure on these dust grains (via absorption or scattering) can trigger the mass loss from these stars, gas being then carried along via friction [5] (and references therein). Understanding these mechanisms is the key to understand dust and gas ejection along the AGB and the formation of circumstellar envelopes that will become PNe once the central star will leave the AGB and get hotter and ionise the gas.

Optical/IR nterferometers such as the VLTI are now able to reach resolutions down to 1 milliarcsec. Combining images with more than two telescopes and using different setups (separation, position angle on the sky), it is now possible to reconstruct images in the near-infrared and to resolve the surface of the closest AGB stars. With such observation, using PIONIER/VLTI, Paladini et al. [6] mapped convective cells (with typical sizes of ∼27% of the surface of the star) at the surface of the AGB star π_1Gru. When one add spectral resolution to such observations (as could be done with AMBER/VLTI), one can map molecules close to the surface and the photosphere of giant stars. This was done e.g., for the carbon stars R Scl [7], for which different gas layers (C_2H_2, CO and HCN) where shown to be more extended than the stellar surface, forming a so-called MOLSPHERE. Dust also appears to be non uniformly formed close to the star. Similar observations of W Hya also enabled to map a MOLSPHERE with CO extending up to ∼3 R_* [8].

Extreme adaptive optics instruments such as SPHERE/VLT can also produce images with resolution down to 15 milliarcsec and very high contrast in the optical and near-infrared. In the optical, this enables to map the light scattered by dust, and using polarimetric measurements, to study the dust properties. The closest AGB star R Dor was thus the first AGB star for which a direct image of its surface was obtained [9]. W Hya was also observed with SPHERE [8]. Three dust clumps were mapped, showing that the dust ejection was clumpy and not uniform, and that dust formation is induced by pulsation and convection. The dust properties are observed to evolve with time, with variations within 8 months. Such a behaviour, with non uniform and clumpy dust formation was also observed for the AGB star IRC+10216 [10]. Modelling of the polarization map of oxygen-rich AGB stars revealed the presence of micron-sized dust grains, indicating that the mass-loss process could be due to scattering (emission from AGB stars peak around 1 micron and scattering by dust is more efficient when grains have similar size to the peak emission of the star), as predicted by S. Hoefner [5].

Optical/NIR high angular resolution observations of AGB stars have thus revealed that dust formation was not uniform, leading to non-spherical inner envelopes of AGB stars. One could then wonder how the presence of a binary companion could affect these envelopes. Direct detection of binaries around AGB stars is made difficult by the pulsation of the star and the fact it is embedded in dust [4]. The submillimetter interferometer ALMA, thanks to its spectral and spatial resolution (see e.g., [11]) has then been a great tool to indirectly detect binaries around AGB stars. The interaction with a wide binary can indeed lead to the formation of spirals around AGB stars [12]. Such spirals are being commonly detected around AGB stars with ALMA and other millimetter interferometers such as SMA and SMT [13–18]. But these AGB stars in binary will most likely not form bipolar PNe, as they will not get sufficient angular momentum from their distant companions. Closer companions should form equatorial over densities that will favour a polar ejection of material.

The presence of discs and jets has been inferred by millimetre observations for the AGB stars V Hya and Π_1 Gru [19,20], but no AGB star was directly imaged showing the AGB star and its companion, a disc, and material outflowing perpendicular to its disc. Such a system was discovered around one of the nearest AGB star, L_2 Pup, using optical and near-infrared high angular resolution imaging [21,22]. Polarimetric observations enabled to obtain high contrast images of the disc (the star is not polarised will disc scatter and thus polarise light), with an inner rim of 6 AU. Interaction between the disc and the binary system, resolved by SPHERE (with a separation of 2 AU), form structure s that propagate in a direction perpendicular to the disc. This object is very probably a bipolar nebula in a very early stage. Combining these SPHERE observation with ALMA ones [23,24] enabled to show that the disc was in keplerian rotation. The central star had an initial mass of $\sim$1 $M_\odot$ and the companion could be a massive planet. The angular momentum of the disk surpasses the one expected from the star, supporting the scenario of disc formation through angular momentum transfer via a binary.

3. Shaping of Post-AGB Stars

After the AGB phase, the envelope get detached but is not ionised yet, this is the post-AGB phase. This phase is generally characterized by a double-peaked spectral energy distribution, with a peak in the optical due to emission from the star, and a peak at longer wavelength (in the infrared) due to emission from dust. However, if a post-AGB is in a binary system, a disc or a torus can be formed, leading to the presence of warm dust (at the dust condensation temperature at $\sim$1000–1500 K), filling the gap between the optical peak of the star and infrared dusty one [25].

I would actually like to make use of this review to raise a common problem in evolved stars nomenclature. Post-AGB and proto-Planetary Nebulae are not the same ensemble. Indeed, while all proto-PNe will give raise to a PN (by definition, as proto-PNe are PNe in the making), it is not the case for all the post-AGBs. The formation of a PN requires the presence of gas close enough to the star to be ionised once the star gets hot enough. Thus, if the envelope is removed before the star gets hot, the star will go through the post-AGB phase, but will never make a PN. Thus, the dusty RV Tau stars (a.k.a. the van Winckel's objects) are binary post-AGB stars surrounded by a disc and mostly with no circumstellar material outside the disc and most of them will most likely not form a PN.

Another issue I would like to raise is the wavelength dependence of post-AGB objects' morphologies. A bipolar post-AGB star with an equatorial disk and material outflowing in a direction perpendicular to its disc will look different in the optical and in the infrared. Indeed at short wavelengths we are more sensitive to light scattered by the disc and we thus obtain images elongated perpendicular to the disc. But if we observe in the infrared, what we see is the emission from dust and elongation along the disc direction. Similarly a bipolar nebula with holes will appear bipolar in the infrared, while searchlight beams of light scattered through the holes will be observed in the optical.

Morphological classification needs to be clear about that, as the same object observed at different wavelengths will have different morphologies.

Observationally speaking, most of the post-AGB objects seem to be aspherical [25]. They harbour two kinds of equatorial over densities. This can be either a torus, which is usually massive ($\sim$1 $M_\odot$), in slow expansion (a few km/s) and with a limited angular momentum. They are short-lived, as, if the gas supply cease, they quickly vanish. Such a torus was recently mapped with ALMA [26], around IRAS 16342, the water fountain. It harbours a dense (3×10^6 cm^{-3}), slowly expanding (20 km/s) torus, which appeared to have been formed before the observed jets (the torus has a dynamical age of 160 years vs. 110 for the jets).

The other kind of equatorial structures observed is discs in keplerian rotation, with a larger angular momentum and thus lifetime. Such discs where revealed by ALMA for a few post-AGB objects, such as the Red Rectangle [27] and AC Her [28]. The ALMA observations of IW Car [29] are a great example of what the angular resolution combined with spectral resolution of ALMA can teach us about such objects. It reveals a binary post-AGB star with a disc, with outflow perpendicular to the disc (which has a dynamical age of 10,000 years) and that there is 8 times more material in the disc than in the outflows.

Finally, optical/near-infrared interferometry is now able to produce images, making it less scary and easier to understand for non-specialists than closure phases and visibilities. With an instrument like PIONIER/VLTI, et al. [30] were thus able to obtain a very impressive result: the first image of a post-AGB system with a circumbinary disc. They detected a compact circumpanion accretion disc, where the outflow very likely originates. It would now be interesting to follow-up this object to see the time evolution of the accretion and the outflows.

4. Shaping of Related Objects

In the previous paragraphs, I have shown how high angular resolution observations with instruments such as the VLTI, SPHERE/VLT and ALMA were revolutionising our view of the shaping of evolved stars from the AGB to the PN phase. To conclude, I would like to also emphasize that similar study of related object can teach us a lot about the shaping of PNe (this will by the way be one of the topics of the next Asymmetrical Planetary Nebulae conference).

Combining SPHERE and ALMA observations of the Red Supergiant Betelgeuse, Pierre Kervella and his team completely changed the way we are now seeing this emblematic star. Plumes of gas are seen extending out the photosphere up to 3 stellar radii, and an incomplete dust shell is resolved at $\sim$3 R_* [23]. The observed asymmetries are also consistent with what is predicted from 3D convection models. ALMA observations enable them to clearly "see" the rotation of the star in $\sim$36 years and to show evidence for a polar ejection certainly due to convection [31].

Similarly, the post-RSG spectroscopic binary system AFGL 4106 was observed with SPHERE (Figure 2). The binary system is clearly resolved for the first time and the amazingly complex morphology of the envelope is revealed, with signs non-continuous ejections in many directions (Lagadec et al., in prep).

Symbiotic stars are another kind of interesting related binary systems. They contain a mass-losing AGB star whose material is accreted by a compact object, usually a white dwarf. R Aqr is a prototypical object of this class and was one of the fist object to be mapped with SPHERE [32]. It countains a Mira variable, a hot companion and a spectacular jet outflow. These data reveal the inner part of the jet, showing it is emerging from the companion and precessing. They were able to measure the density of the jets, which will be of great interest for modellers to discriminate different jets scenarios. The binary system is clearly resolved (8 AU of separation), and its orbit is being monitored. This system should thus soon become a benchmark for the physics of jets in accretion systems.

Another kind of related objects are the binary Wolf-Rayet systems, were dusty spirals are formed due to the interaction of the winds of a WR star and its O companion, forming huge amounts of dust (up to 10^{-6} $M_{\odot}year^{-1}$). SPHERE enabled to directly image such a spiral for the first time [33] and to map 5 revolutions of the spiral and revealed that the system was not a binary but a triple system.

Finally, SPHERE also enables to map the inner part of the circumstellar material around one of the most iconic object in the sky: Eta Carinae. It is a massive binary system containing a Luminous Blue Variable star and a O-type star, with a total mass between 100 and 200 $M_{\odot}$, which erupted in the mid 19th century, leading to the formation of a giant bipolar nebula, nicknamed the Homunculus, with a morphology very similar to typical PNe. Another eruption, known as the "lesser eruption" occurred in 1890, creating blobs known as the Weigelt blobs. The SPHERE observations revealed many new blobs and the motion on the sky of the known blobs since their discoveries in 1988.

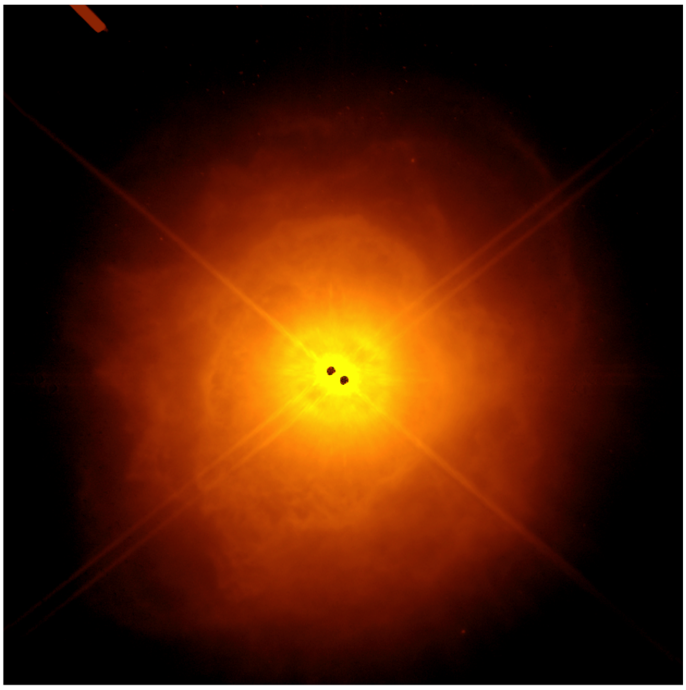

Figure 2. SPHERE/VLT observations of the post-RSG system AFGL 4106 (Lagadec et al., in prep). This system was a known spectroscopic binary. The binary system is directly resolved for the first time here (separation 0.3 arcsec). The interaction fo the post-RSG star with its massive companion lead to a very complex, non isotropic, ejection of material.

5. Conclusions

To conclude this review, in the last years, a lot of advances have been made on the study of the surface and nearby environments of AGB stars. The first maps (via interferometry and direct imaging techniques) of the surfaces have revealed convection cells covering a significant fraction of the stars' surfaces. The stars also pulsate, and this convection and pulsation lead to dust formation. The dust shells observed appear clumpy next to the surface of the stars and evolving in time, so that an onset of asymmetry is observed near the surface of AGB stars.

Spiral patterns appear to be common around AGB stars and due to companions with rather large separations: these stars more likely will not form bipolar nebulae, as the angular momentum transfer between the AGB star and it companion is not efficient enough. It is thus interesting to notice that most of the AGB stars observed most likely will not form bipolar planetary nebulae, while most of the PPNe (if not all) are likely to form bipolar PNe: does the sample of known AGB and PPNe know match? More work seems to be needed to find the AGB stars that will lead to bipolar PNe and PPNe that will not form bipolar PPNe.

Funding: This research received no external funding.

Conflicts of Interest: The authors declare no conflict of interest.

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