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Jodrell Bank Observatory
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Dusty discs around evolved stars

Foteini Lykou [1], Albert Zijlstra [1], Olivier Chesneau [2]
[1] JBCA, The University of Manchester
[2] Dept. H. Fizeau, Observatoire de la Cote d'Azur

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Abstract

We present the discovery of dusty, edge-on discs around stars at different late-type evolutionary stages, Menzel 3, M2-9 and Sakurai's Object. All three objects have been observed at high-angular resolution with MIDI on the Very Large Telescope Interferometer (VLTI). Characterising the dusty discs in the core of these nebulae and at different evolutionary stages, provides invaluable constraints on the processes that lead to these impressive nebulae, which is one of the main scopes of this project. The properties of each disc have been explored with the means of radiative transfer modelling.

What we're looking for

Intermediate mass stars (1-8 M☉) undergo extreme mass loss during the late stages of their evolution. The mechanisms that dominate those stellar outflows are responsible for the shaping of the ejecta. The ejected material seems to depart from spherical symmetry during the late Asymptotic Giant Branch (AGB) stage, when it evolves into asymmetrical structures. These stars are giant factories of dust and heavy elements. Depending on their abundances during the AGB stage, they are either Oxygen-rich or Carbon-rich stars. In return, O-rich or C-rich dust (created in the atmospheres of AGBs) indicates the evolution phase at which is was ejected from the star. Complex phenomena perturb the mass-ejection in the late stages of stellar evolution: stellar magnetic fields, fast rotation or binarity are often involved, with the latter playing a more efficient role that needs to be confirmed. Such mechanisms can lead to the creation of a circumstellar, dusty disc. The compact and dense dusty cores in the centre of the nebula can be studied by means of infrared interferometry.

Infrared Interferometry

A planetary nebula (PN) is the ejected, ionised envelope of an evolved star. The star usually remains in the centre of the nebula and may be surrounded by a dusty disc. The PN may extend up to 0.1pc, while the disc may be 10–100AU, thus about 10^3 smaller than the observed nebula. The ability of optical telescopes to detect these objects is very limited, while interferometers are quite suitable for the job. We have used the MIDI instrument with 3 of the 8.2m Unit Telescopes, which gave us a resolution ~0.01 arcsec in the mid-infrared (N-band, 8–13.5 μm). We obtained six sets of spectrally dispersed visibilities for Menzel 3, four for M2-9 and six for Sakurai's Object (Fig.3).

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The Discs

Dusty discs observed by the VLTI around the central sources of nebulae, are the remnants of mechanisms that shape the gaseous ejecta into bipolar/multipolar nebulae. Our sample consists of three different stages of evolved stars, namely a bipolar planetary nebula (Menzel 3), a symbiotic star (M2-9) and a very-late-thermal-pulse object (Sakurai's Object) allowing us to compare and assess the evolution of those dusty structures throughout the final stages of stellar evolution. For each of the three cases, we have detected a dusty disc around the central ionising source in the mid-infrared with VLTI. Their intrinsic geometric and physical properties have been determined with the use of radiative transfer modelling (MC3D, Wolf 2003) and these are presented in Table 1.

Menzel 3, the Ant Nebula

Our VLTI observations revealed an amorphous silicate disc in the heart of the bipolar planetary nebula Menzel 3 and perpendicular to the nebula's lobes (Fig.1). The disc is nearly edge-on and optically thick in the N band (τ~3.5). Its inner rim is sublimation temperature. The enclosed mass of dust is 2 orders of magnitude less than that found in the lobes. A binary system, as suggested by an X-ray jet from the core (Kastner et al. 2003), may reside inside the disc with a separation of 1-2 AU. The absence of crystalline silicates suggests that the disc might be relatively young, compared to long-lived discs in binary post-AGB stars (Chesneau et al. 2007).

M2-9, the TwinJet Nebula

A silicate disc, similar to that of Menzel 3, has been discovered in the core of M2-9 (Fig.2). Figure 3 present our comparisons between models and observations, showing that a stratified model of a disc with a small aperture and high inclination matches the interferometric observations. The disc is heated by an AGB/post-AGB star and it is being truncated by UV radiation from the secondary (white dwarf). It is still being shaped by the interactions of the binary system and the subsequent change of the primary star into a white dwarf will modify it as well. The compactness of the disc puts strong constraints on the binary content of the system, given an estimated orbital period 90–120yr (Lykou et al. 2010, in publication).

V4334 Sgr, Sakurai's Object

In 1996, Sakurai's Object suddenly brightened in the centre of a faint planetary nebula. This very rare event was interpreted as being the re-ignition of a hot white dwarf that caused a rapid evolution back to the cool giant phase. From 1998 on, a copious amount of dust has formed continuously, screening out the star that remained embedded in this expanding high optical-depth envelope. The dusty structure is composed of amorphous carbon (Chesneau et al. 2009), consistent with dust being created during the AGB stage from a carbon rich star. The disc (Fig.4) is expanding radially since its first detection in 2002, but dust is not being replenished. The major axis of the disc (at a position angle ~132°) is aligned with an asymmetry seen in the old, round planetary nebula, which was re-investigated as part of this study. This implies that the mechanism responsible for shaping the dust envelope surrounding Sakurai's Object was already at work when the old planetary nebula formed.

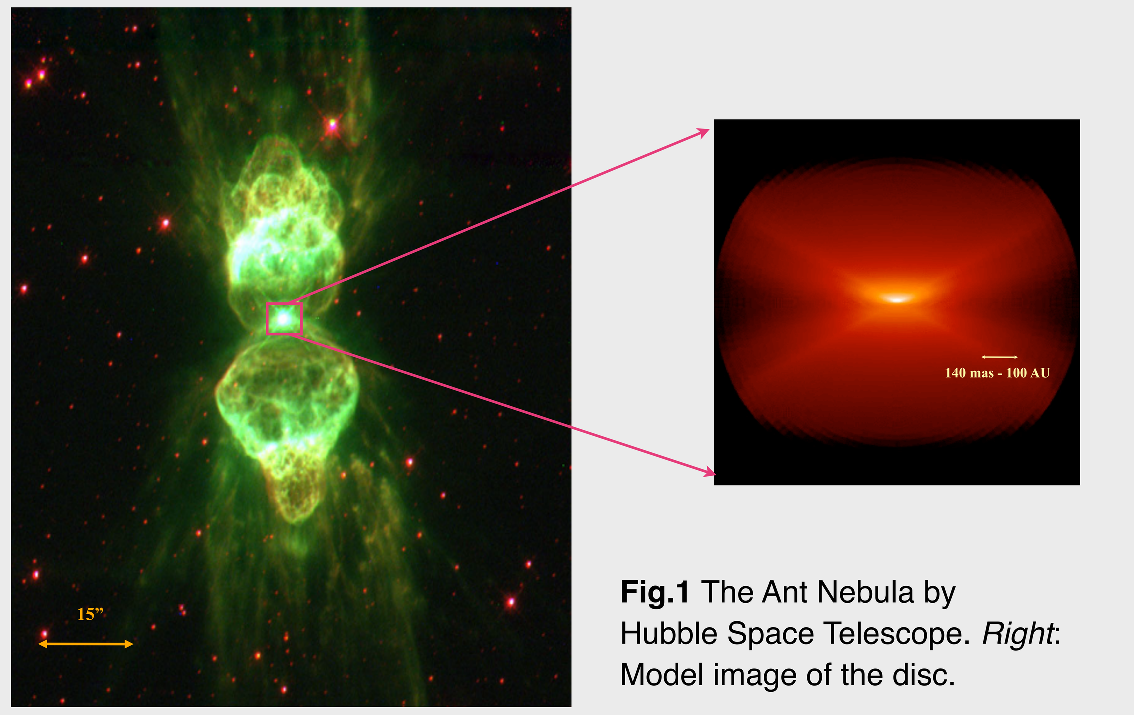
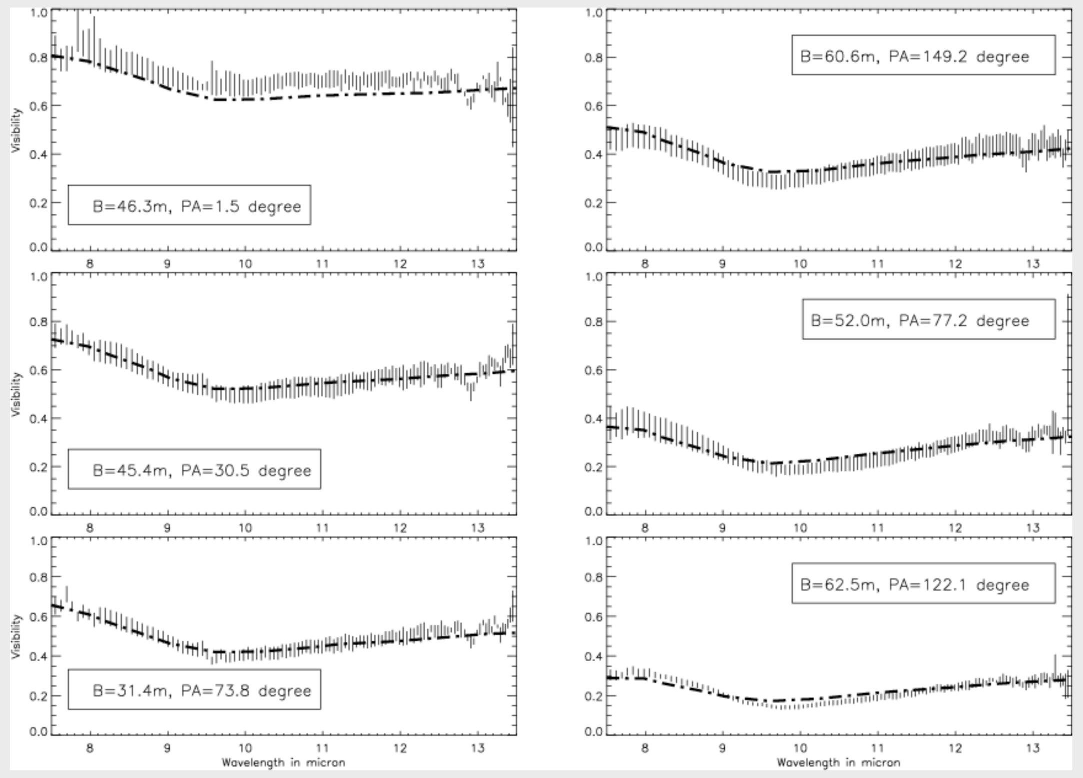


Fig.1 The Ant Nebula by Hubble Space Telescope. *Right*: Model image of the disc.



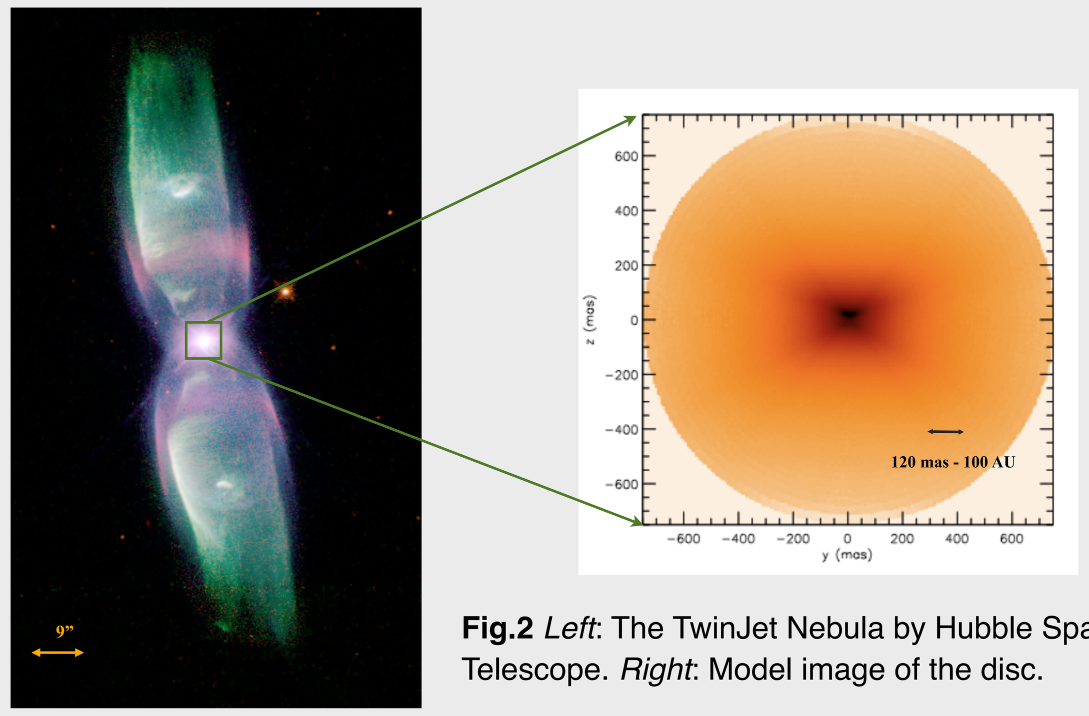
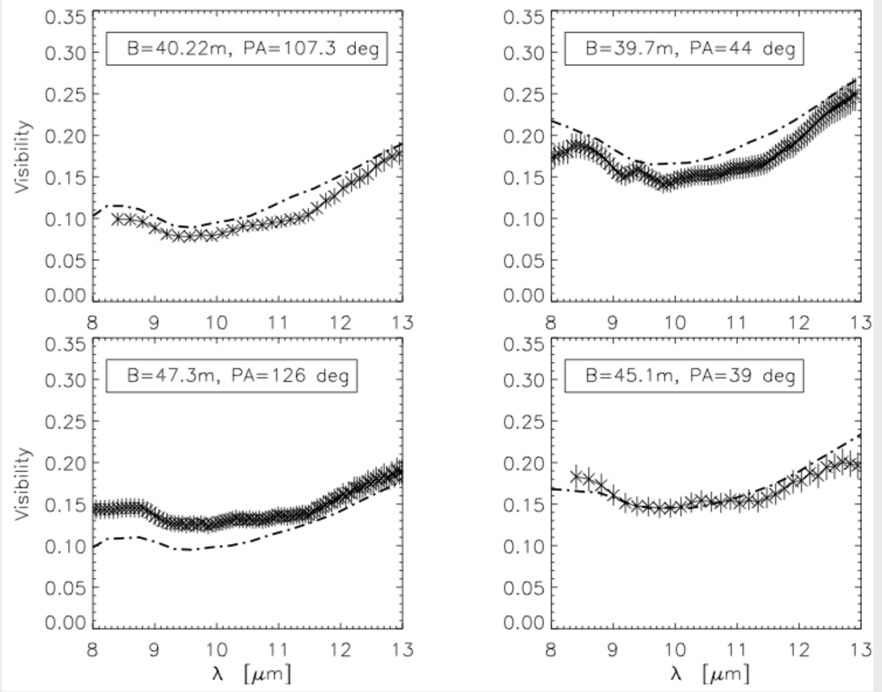
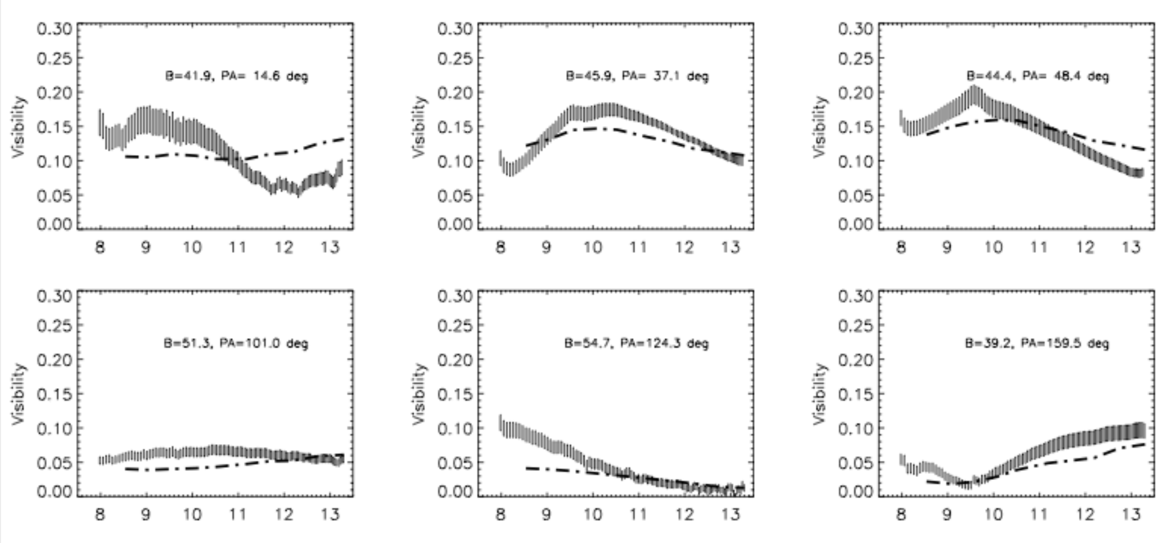


Fig.2 *Left*: The TwinJet Nebula by Hubble Space Telescope. *Right*: Model image of the disc.





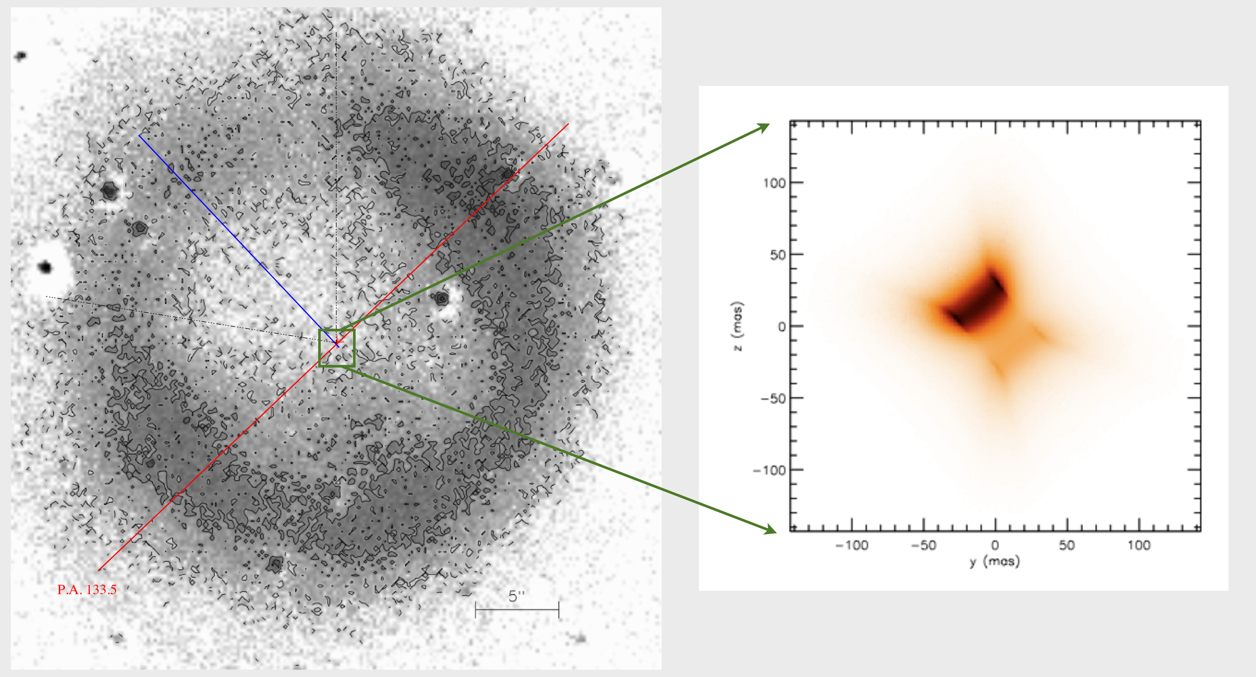


Fig. 3 Modelled visibilities (dash) of the discs (*top*: Menzel 3; *middle*: M2-9; *bottom*: V4334 Sgr) for each observed baseline compared to MIDI data. Projected baseline identification is seen on each plot.

Fig. 4 *Left*: [OIII] Contour plot of the planetary nebula around V4334 Sgr by VLT (Hajduk et al. 2005). Red line indicates orientation of the asymmetry at 133.5°. *Right*: Model image of the disc.

Table 1 Disc properties defined by radiative transfer models and the literature.

PARAMETERS	Menzel 3	M2-9	V4334 Sgr
Rin - Rout (AU)	9 - 500	15 - 900	65 - 500
mass of dust	~9x10^{-6} M☉	~1.5x10^{-5} M☉	~6x10^{-5} M☉
distance (kpc)	1.4	1.2	3.5
Teff (K)	35,000	15,000	12,000
luminosity (L☉)	10,000	2,500	10,000
inclination	~74°	~ 74°	~75°
height at 100AU	~17 AU	~36 AU	~47 AU

Conclusions

✦ Dusty structures (discs/tori/spirals) are found in different stages of late stellar evolution: from AGBs as VHya, to PNe as M2-9 (Lykou et al., in pub.) and Menzel 3 (Chesneau et al. 2007) to VLTP events as Sakurai's Object (Chesneau et al. 2009).

✦ The origin of discs is clearly linked to mass loss, as it is seen in the evolving disc of M2-9. Discs remain stable for long periods of time after the cease of mass loss (e.g. Menzel 3). In both cases the dust mass stored within the discs is 1% of that residing in the lobes.

✦ Our research indicates that discs around evolved stars are remnants of the shaping mechanisms that formed the surrounding nebulae. Those shaping parameters remain present past the planetary nebula phase, as seen in Sakurai's Object. If binarity is the main shaping agent, then it seems that the angular momentum vector is stable for longer timescales.