# The Compact Discs of Post-AGB stars

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Many post-AGB stars are predicted to show compact discs less than ~ 100 AU in size. The VLT is uniquely able to trace these size scales, using adaptive optics (NACO) and optical interferometry (VLTI). We here report on observations of four such objects, showing direct detections of these structures.

Stars like the Sun, with masses in the range 0.8–8 $M_\odot$, end their active lives with a catastrophic mass-loss event: the so-called *superwind*. Within a period of less than $10^5$ yr, between 20 % and 80 % of the total mass of the star is ejected. The superwind occurs on the Asymptotic Giant Branch (AGB). The AGB star consists of a degenerate carbon-oxygen core, surrounded by the nuclear burning shell, in turn surrounded by the convective hydrogen envelope. The superwind removes almost the entire envelope. When the envelope mass has been reduced to ~ $10^{-2} M_\odot$, the photosphere collapses, the superwind ceases and the star moves rapidly to the blue in the HR diagram. The star now begins to ionise the expanding ejecta, forming a planetary nebula. Roughly $10^4$ yr later hydrogen burning ceases and the remaining core of the star enters the white-dwarf cooling track. The nebula fades and eventually merges with the interstellar medium. The superwind is responsible for such diverse aspects as the white dwarf mass distribution (and therefore the SN Ia rate), interstellar hydrogen recycling (accounting half the hydrogen in the local ISM), and interstellar nitrogen, carbon and dust.

Planetary nebulae (PNe) show intricate structures, evidence that the superwind is not a constant, spherical flow. The HST planetary nebula gallery shows a staggering range of morphologies, including ellipticals, bipolars, and core-halo objects – a few are even round. The interacting stellar wind model (ISW) explains these structures by a spherical, fast post-AGB wind blowing into the earlier, slow AGB ejecta. A snowplough develops, amplifying any asymmetries already present. The model works well but requires that the original AGB wind is already strongly asymmetric. The origin of this initial asymmetry is still not fully clear, but the most accepted model involves a binary system. Three cases can be distinguished

1. Common envelope systems, where the companion triggers a fast mass loss. These system will rarely reach the AGB, as the common envelope is likely to develop already on the preceding Red Giant Branch. Orbital separations are of the order of 1 AU. Perhaps 10 % of 'protoplanetary nebulae' may derive from such systems, although fewer would evolve into PNe.

2. Wider systems, where the geometry of the mass loss is affected, but not the mass-loss rate itself. Orbital separations are a few to tens of AU. The system may form a circumbinary disc. They may account for ~ 25 % of the PN birth rate.

3. Systems with minor effects on the mass-loss geometry. Typical separations are ~ 100 AU. The geometry may show the movement of the mass-losing star, as in the spiral nebula around AFGL 3068 (Mauron and Huggins 2006). The prototypical AGB star, o Ceti (Mira) has such a white dwarf companion ~ 100 AU away.
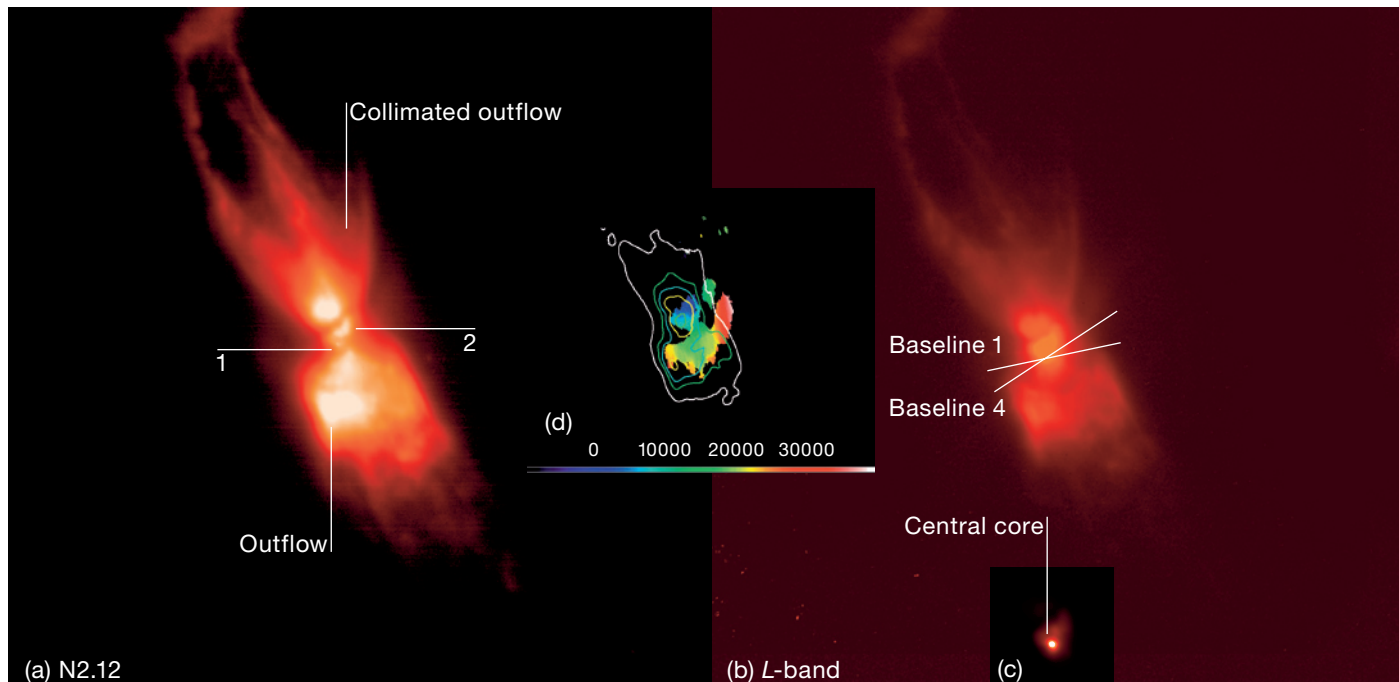
## Circumstellar discs

Many post-AGB stars show evidence for dense, dusty discs. They are unresolved but show up because of the high opacity in the disc which may obscure the star. The cold dust in the disc also adds a strong far-infrared excess with a typical spectral index (de Ruyter et al. 2006). The small sizes suggest that these discs are Keplerian and do not take part in the overall expansion of the (much larger) nebulae. In the ISW model, the small disc provides an initial asymmetry into which the subsequent fast wind causes the bipolar lobes to form. But detecting and resolving such discs requires extreme angular resolution which only now is becoming feasible from ground-based observatories.

The prototype of the bipolar post-AGB stars is OH231.8+4.2. It shows two (ionised) bipolar lobes on either side of a central obscuring lane. The obscured central star (QX Pup) shows Mira-like variability, indicative of an evolved AGB star. We obtained a range of observations, including AO-assisted infrared imaging (NACO), OH maser observations using the MERLIN array, and VLTI/MIDI. The resulting data are arranged in Figure 1. The left panel shows the 2.12 micron image, with the base of the two lobes clearly identifiable (the lobes themselves are much larger). The dark lane is seen to consist of several substructures with brighter regions embedded. The right panel, (b), shows an *L*-band image. Here the central region shows a bright core, and the main dark lane is shown to be located about an arcsecond south. A thin dark lane is seen towards the north. Panel (c) shows a focus on the compact core seen on panel (b). We obtained several VLTI/MIDI baselines across this source. Fringes were detected: we estimate the core to have a diameter of approximately 30–40 mas (Matsuura et al. 2006).

The distance to OH231.8+4.2 is derived from its association with the open cluster M13, as 1.3 kpc. The VLTI/MIDI source has a radius of 40–50 AU, which is within range of expectations for a circumbinary disc. The dark lane is very much larger, at 1000 AU, and may either be a thick torus or an ionisation shadow caused by the inner disc. Panel (d) shows OH maser data obained with MERLIN: the OH traces the dark lane very well. The colour indicates the velocity, in m/s. Almost all emission is blueshifted with respect to the systemic velocity, indicating that only OH emission in front of the source is seen. This can be explained if the OH maser amplifies the radio continuum from the inner ionised nebula. The velocities increase with distance from the centre, as expected from an ISW-driven bipolar outflow (Zijlstra et al. 2001).

(a) N2.12

(b) *L*-band

(c)

Collimated outflow

1          2

Outflow

(d)

0    10000  20000  30000

Baseline 1

Baseline 4

Central core

Figure 1: Composite of OH231.8+4.2. (a) 2.12 micron image. For scale, the banana-like structure (2) is 0.7 arcsec across. (b) *L*-band image: The position angles of the VLTI baselines are indicated. (c) A zoom on the bright core seen in the NACO *L*-band image. (d) OH maser velocities measured with MERLIN; the colour scale is in m/s.

OH231.8+4.2 is the first source to show all components expected from the ISW model: an inner disc with size consistent with a circumbinary disc, a bipolar outflow, and a velocity field as predicted by a fast wind–slow wind interaction. The only missing ingredient is the putative binary companion. The very high opacity of the inner region may make this hard to find.

## A tale of two chemistries

The disc forms relatively early on the AGB. If, during the AGB, the continuing dredge-up forms a carbon star, the disc will show the earlier, oxygen-rich chemistry while the current wind is carbon-rich. The oxygen-rich chemistry leads to silicate dust, whilst the carbon-rich wind is dominated by silicate carbide dust, and once the star becomes hotter, PAH features are seen. A number of post-AGB stars display both PAH at shorter wavelengths, and features attributed to crystalline silicates at longer wavelengths. This combination of incompatible chemistries requires distinct regions, where the PAH are located in the UV-irradiated (warm) outflow and the silicates in the opaque, cold disc. The original example of this structure is the Red Rectangle, where ISO spectra revealed the presence of the crystaline silicates. Direct imaging
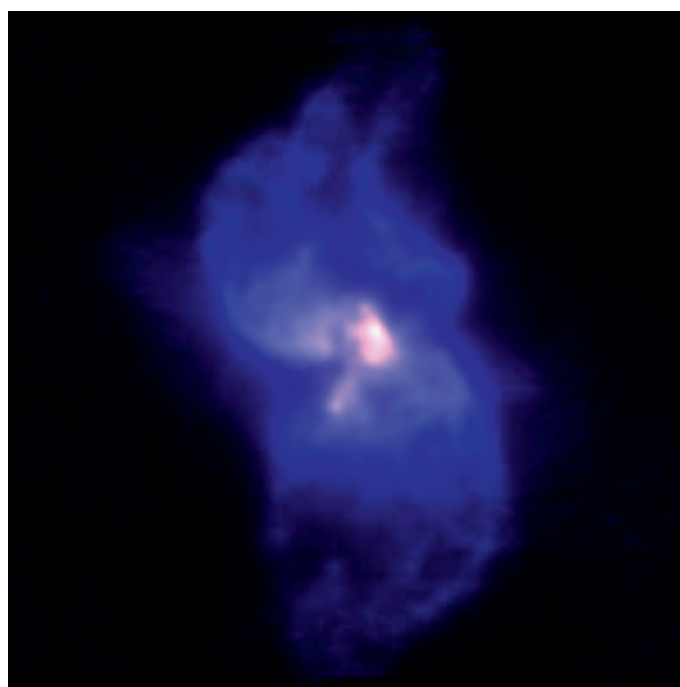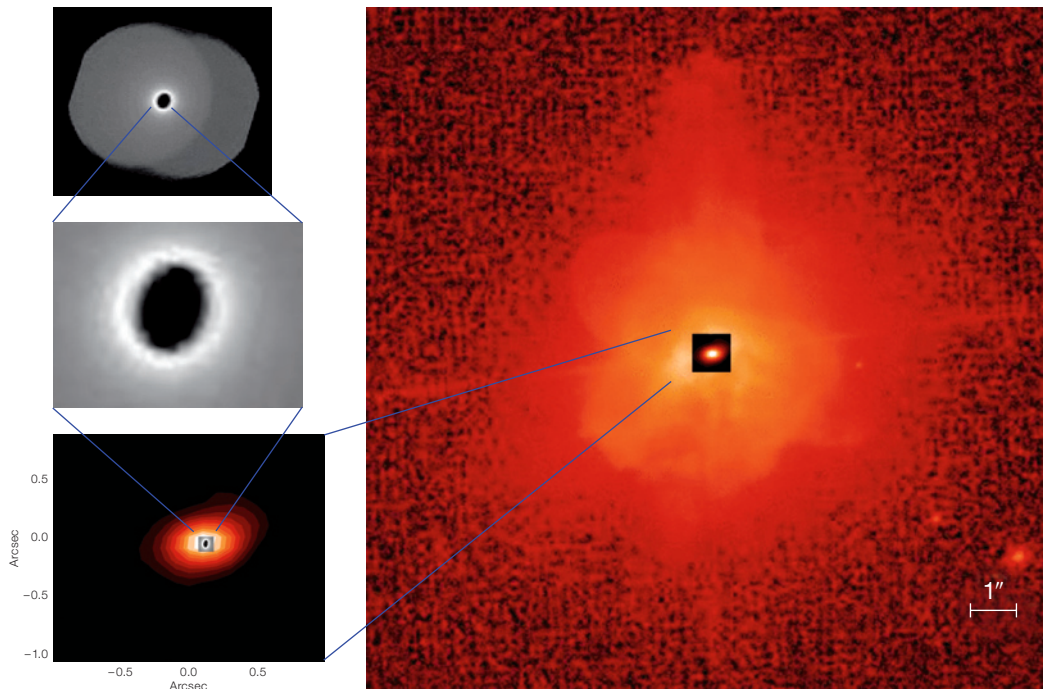


Figure 2: NACO three-colours image of Roberts 22, combining $H_2$, Brγ and 2.24 μm continuum images. The field of view is 7″ × 7″.

Figure 3: Mosaic of images of CPD-56°8032. **Right:** HST (F435). **Bottom left:** MIDI 8.7 μm image (deconvolved); **middle:** model of the observed inner rim of the disc based on VLTI data; **top:** 10 μm model image of the disc observed by MIDI.

of the silicate disc would require 20-micron observations.

Roberts 22 is one such post-AGB star which shows evidence for both oxygen and carbon-rich chemistry. It is a reflection nebula, with an obscured central star: a spectral type of A2 I was inferred from the scattered light from the two lobes. HST images of this bipolar nebula show a dark lane across the centre of the object, with additional dark regions to the north, close to where the dark lane is least clear. The oxygen-rich nature is proven by the presence of OH maser emission. Figure 2 shows our VLT/CONICA image. Compared to the HST image, the dark lane is less clear (although still evident from the wedge on the left) but a bright central, resolved source is seen at the centre. The OH maser coincides with the wedge: it lacks the redshifted emission at the central position, and this indicates a compact ionised source in the centre which is optically thick at 18 cm. The outer emission shows pronounced bending, and in fact structures are visible at many position angles. Little of this was visible in the optical HST image: it is possible that the scattered optical light is too much influenced by the limited available escape routes from the central source, to show the intrinsic structure. The multiple

flows and directions can be interpreted in terms of the 'warped disc' scenario of Icke (2003). The OH emission shows that the 'wedge' is oxygen rich. The location of the PAH emission is at the edge of the equatorial disc.

### The IR-[WC] stars

[WC] stars are PNe central stars which show emission lines very similar to those of the massive WR stars. Their origin is not well understood, but the absence of hydrogen in the stellar spectra suggests they have been fully stripped of their hydrogen envelope. A few of these objects are extremely strong infrared emitters, with infrared excess (the ratio of dust luminosity over Lyα flux) higher than in any other PN. Most or all of these IR-[WC] stars show the chemical dichotomy, with both very strong PAH emission and pronounced crystalline silicates.

CPD-56°8032 and He 2-113 are two members of this group. Figures 3 and 4 show images of these two objects. Figure 3 shows, on the right, an HST image (F435) of CPD-56°8032. The nebula has an irregular appearance surrounding the bright central star. The VLTI/MIDI single dish image shows a bright core at 8 micron: after deconvolution, the core is found to

be resolved with an elliptical diameter of 0.4 × 0.3 arcsec. The VLTI/MIDI shows very weak fringes, with visibilities depending on position angle. We model these fringes using an ellipsoidal ring, with an aspect ratio of 0.5 (equivalent to a ring viewed on angle of 30°) and a radius of 75 mas. For an assumed distance of 1.35 kpc, the inner radius of this inner ring is 97 AU. There is no indication for any preferred axis in the system from our HST images and VLTI/MIDI observations.

The expectation that the inner disc is the location of the silicates is not fully confirmed. Our VLTI/MIDI spectra show that a part of the strong PAH emission arises from the central source. About a third of the integrated flux from the 7.8 and 8.6 micron PAH features are recovered from the VLTI/MIDI spectrum, but only about 1/4 of the 11–14-micron plateau, and the 11.2 feature is almost absent from the VLTI/MIDI spectrum. Part of the difference may arise if the PAHs in the central object are ionised. The observed features are mostly C-H modes, and therefore the central PAHs are hydrogenated even though the star is hydrogen poor. The oxygen-rich material is not seen, but we note that this dust is too cold to emit at 10 microns. Our model of the infrared spectrum indicates that the disc extends outwards to perhaps 1000 AU: the ob-

served core corresponds to the inner edge of this disc. This suggests a model where the PAHs are located at the inner rim of an otherwise oxygen-rich disc that could be flared. The PAHs may form at the turbulent, shocked interface between the carbon-rich, H-poor wind from the star, and the disc.

He2-113 shows a more regular morphology (Lagadec et al. 2006). Figure 4 shows a three-colour image with indication of a large torus (~ 1500 AU) and a bipolar outflow. But there is again an infrared source located at the centre, with a diameter of ~ 150 mas, surrounded by a void. VLTI data did not show any more compact structure. The inner rim seen in CPD-56°8032 appears to lack a counterpart in He2-113, and neither does the PAH emission show an obvious central source. The large disc does appear to be present.

## Binarity

All four objects show evidence for the compact disc required by the ISW model. These discs indicate likely binary companions, evolving through either scenario 1 or 2 above. But in none of these cases do we find direct evidence for a stellar companion. This may be understandable, in view of the large luminosity difference between an AGB star and a main-sequence or white-dwarf companion, but it leaves a weak link in the argument. (One could argue that we don't find direct evidence for the primary star either.)

The IR-[WC] stars also show the disc morphology, and binarity is likely for these objects. However, the strong relation between emission-line central stars and the IR-bright, dual-chemistry nebulae remains unexplained. The late thermal pulse scenario for the [WC] stars (Hajduk et al. 2005) does not predict any link between the unusual star and the unusual nebula. Binary coalescence may be considered, removing the hydrogen envelope in the process. Otherwise, accretion from the circumstellar disc on the post-AGB star or a white-dwarf companion may be involved.

The results show the power of the new, high-angular-resolution observing modes available at the VLT. The origin of the structures seen in these objects are found within 100 AU of the star. Adaptive optics and optical interferometry are uniquely able to trace these size scales.

Now, if only we could detect the binary companions!

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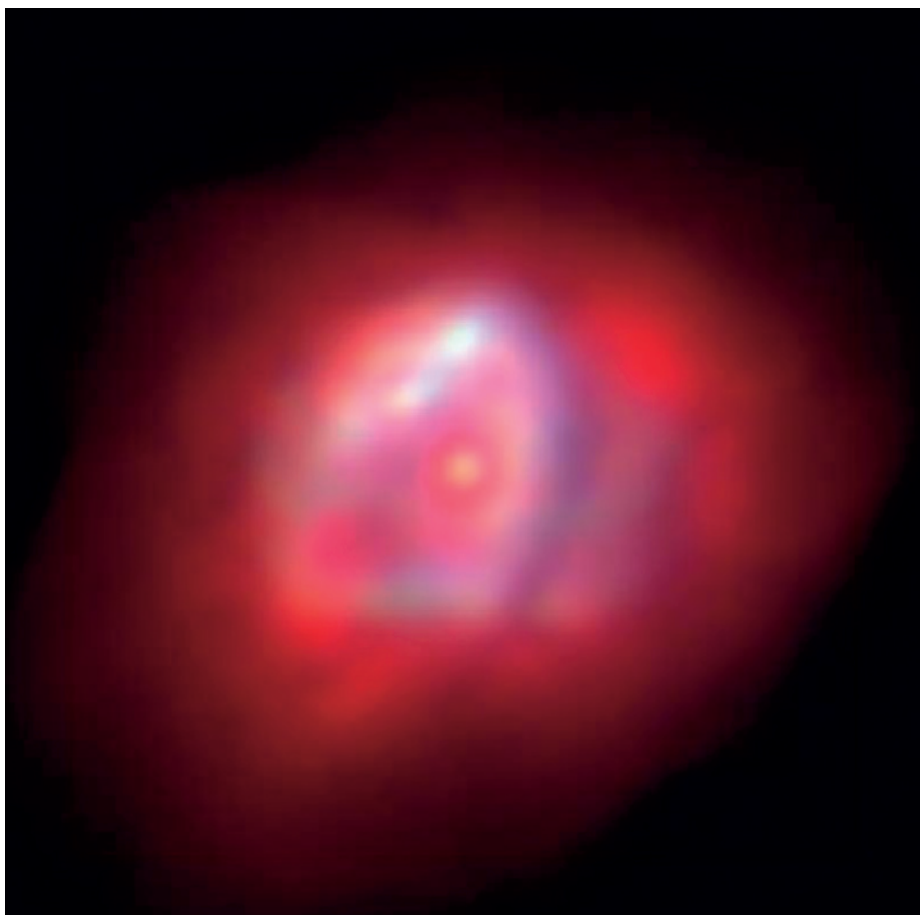Zijlstra A. A. et al. 2001, MNRAS 322, 280

Figure 4: Three-colour image of He2-113, combining HST Hα (coded as red), NACO L' (green) and M' (blue). The bright ring is approximately 1.5 arcsec across.