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Stable discs around Galactic and LMC post-AGB binaries

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Abstract. In this work we present the results of our study on a particular class of Galactic and extragalactic evolved stars, which are part of a binary system, and surrounded by a stable dusty disc. By combining spectroscopic, photometric and interferometric observations with detailed models describing dust properties and disc structure, we investigate the exact disc composition and structure. With this study we hope to trace the evolution of these evolved binaries and their disc, and determine the impact of the disc on the entire system.

Keywords. Planetary Nebulae – Stars: AGB and post-AGB – Binaries

1. Late phases of stellar evolution

One of the major questions in current research is whether the predominantly symmetrical outflows during the AGB phase can produce the observed wide variety in proto-PNe (PPNe) and PNe shapes and structures, including spherical, point symmetric, axisymmetric and bipolar nebulae. During this short transition time, the star and its circumstellar envelope must be subject to fundamental and rapid changes in structure, mass loss and geometry (765; 779).

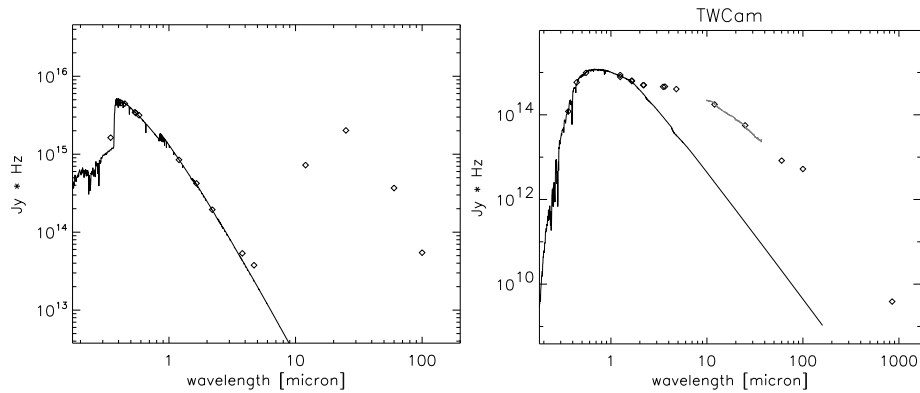


Figure 1. Spectral energy distributions of a typical outflow source (HD 187885, left) and a disc source (TW Cam, right). The outflow source is characterised by a double-peaked SED, dominated by cool dust, which resides at larger distances from the central star. The disc source shows a very broad infrared excess, showing the presence of both hot and cool dust.

There is now growing evidence that the processes in the strongly bipolar PPNe and PNe occur because of strong interactions in a binary system (e.g. 767). Many of these PNe have structures, such as bipolar lobes, jets, rings, dusty discs and tori, which are often explained by common envelope binary interactions, which is a badly understood process by itself.

Direct evidence for the suspected high binary rate in PNe however is still lacking, but this is no longer the case for post-AGB stars (780). Optically-bright post-AGB stars are thus invaluable to study the transition region between the AGB and the PNe phase.

2. Binary post-AGB stars

With the discovery of the first binary post-AGB stars, it became clear that these evolved stars have common observational characteristics, such as a broad infrared excess.

The observed broad IR excess in these binary post-AGB stars points to the presence of both hot and cool dust around the star (Fig. 1). De Ruyter et al. (769) showed that, for all stars, the hot dust is close to sublimation temperature (~ 1500 K). An outflow model is not adequate to explain the presence of such hot dust, since the near-infrared excess is expected to disappear within years after the cessation of the dusty mass loss. Also, the post-AGB stars are currently too hot to produce a strong dusty outflow. The dust must thus reside in a long-lived, stable reservoir close to the star. This leads us to suspect that these objects are surrounded by a stable Keplerian disc.

The specific observational characteristics allowed for systematic search for these visually bright objects and, so far, more than 70 Galactic objects have been discovered (769). For these stars our group started an extensive multi-wavelength study, including radial velocity monitoring, high-spectral resolution optical and infrared studies, sub-millimetre observations, and high-spatial resolution interferometric studies.

The formation of the disc is still a badly understood process, probably a result of non-conservative Roche Lobe overflow during the evolution in a binary system (see Verhoelst et al., these proceedings). To detect this binary motion, we started an extensive radial velocity monitoring programme, which confirmed the binary hypothesis and gave a typical semi-major axis for the orbit of around 1 AU (780). Given the effective temperature of the central star and its high luminosity, all the discs must be circumbinary, since the orbits all lie well within the sublimation radius of the dust. The mass functions calculated from the orbit indicate that the companion is likely a main-sequence star.

So far we have orbital parameters for about 30 sources, with orbital periods ranging from 100 to 2000 days and high eccentricities, up to 0.6 (see Gorlova et al., these proceedings). This is surprising, since theory predicts efficient circularisation by tidal forces on very short time scales.

All orbits discovered so far are too small to have accommodated a full-grown AGB star. This implies that the system must have been subject to severe binary interaction, while the evolved star was at giant dimension.

2.1. The circumbinary disc

The presence of the circumbinary disc has an impact on several observational characteristics of the post-AGB star:

- The strong infrared excess, $L_{IR}/L_* > 40\%$ for most stars, shows that significant amounts of circumstellar material are present, to reprocess the incoming stellar light. Surprisingly, a very low total reddening towards these stars is observed. This is clear evidence for a non-spherical circumstellar environment (CE).
- The binary disc sources are characterised by a depletion pattern in their photospheres (e.g. 781; 775). Generally, a lack of carbon or s-process enhancement is found. These stars apparently did not undergo a third dredge-up process on the AGB, even though they have initial masses which would theoretically make them evolve to carbon stars. The abundance pattern is the result of gas-dust separation in the CE, followed by a re-accretion of the gas component, which is now poor in refractory elements. Waters et al. (782) already proposed that the most likely circumstance for this process to occur is when the dust is trapped in a disc.
- Recent interferometric studies indeed confirm the very compact nature of the circumstellar material (770; 771). All disc sizes are very similar, with N-band sizes between 30 – 50 AU, although the geometrical location of different dust components can differ significantly. Some objects show crystalline dust species close to the inner rim, others show strong processing throughout the disc.
- Kinematical information of a few objects detected in CO shows typical rotation velocities instead of outflows (e.g. 766), again confirming the presence of a Keplerian disc.
- Submillimetre measurements (768, Gielen et al. in prep.) indicate the presence of large grains (> cm-size) in the CE. A disc is an ideal environment for grain growth, since it is a long-lived stable reservoir, with relatively high densities.

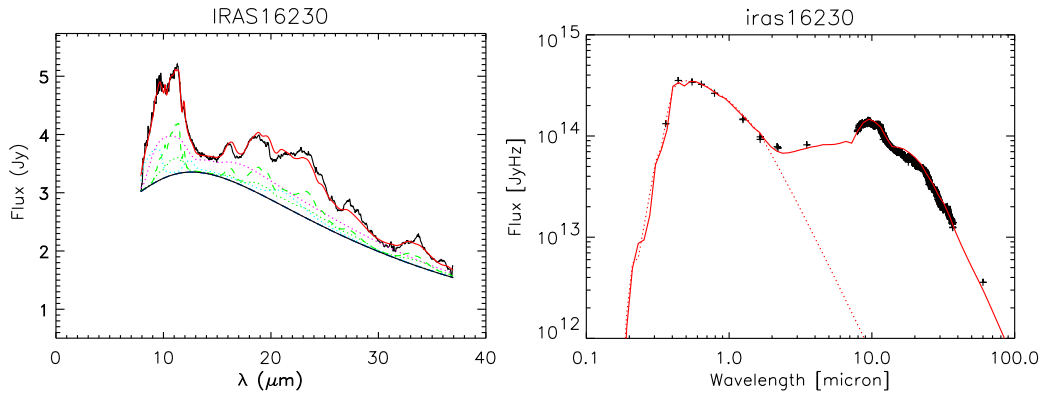


Figure 2. Left: Result from our full-spectrum fitting. The observed spectrum (black) is plotted together with the best model fit (red solid line) and the continuum (black solid line). Right: Result from our 2D disc modelling. Observations are represented by crosses; the underlying Kurucz model is given by the dotted line. The full line represents the SED of the disc model.

These large grains have smaller dust-settling times, causing the disc to be inhomogeneous, consisting of small hot grains in the surface layer of the disc and a cool mid-plane of mainly large grains.

2.2. Similar sources in the LMC

The first extragalactic RV Tauri stars, pulsating post-AGB stars with alternating deep and shallow minima in their lightcurves, in the LMC were discovered by the MACHO experiment (764). Recent chemical studies on a few RV Tauri stars (778; 773), selected from those reported by Alcock et al. (764), show that, like in the Galaxy, the disc candidates display the depletion pattern in their photospheres.

More recently the SAGE (Surveying the Agents of Galaxy Evolution) Spitzer LMC survey (776) observed the LMC, using all photometric bands of Spitzer IRAC/MIPS instruments. Thanks to the release of this database we found that the LMC post-AGB objects have infrared excesses similar to the Galactic sources. Also, a search for other post-AGB disc sources in this survey, based on their location in colour-colour diagrams, resulted in a list of about 650 disc candidates (van Aarle et al., these proceedings). Thanks to the follow-up SAGE-Spec programme we also have Spitzer IRS spectra for the LMC objects (774).

3. Disc composition

To study the mineralogy of the disc, we used Spitzer mid-infrared spectra. So far, we have spectra for 33 Galactic and 24 extragalactic LMC sources. Using a full-spectral fit routine (see Fig.2), we determined the parameters, such as composition and temperature, of the dust responsible for the observed spectra (772).

All sample stars show signatures of oxygen-rich dust species in their infrared spectra, more specifically amorphous and crystalline silicates. Only four stars display evidence for polycyclic aromatic hydrocarbons (PAHs).

The magnesium-rich end members of crystalline silicates seem to prevail in the spectra, with strong emission due to forsterite, and to lesser extent enstatite. From our full spectral fitting we also find that the amorphous dust might be Mg-rich. Detailed chemical studies of these stars (e.g. 775; 773) have shown that the stellar photospheres are devoid of iron, with the iron instead being locked up in the dust of the disc. If no iron is detected in the observed dust species, this could imply that iron is stored in the form of metallic iron or iron oxide, which have no distinct observable dust signatures.

We find that the discs are the ideal environment for strong dust grain processing to occur, both in grain growth and crystallinity. For our sample stars, the mass fraction in crystalline grains ranges from 10 to 70%, which is much higher than what is observed in outflow sources. The observed peak-to-continuum ratio shows that, on average, grain sizes above $0.1 \mu\text{m}$ prevail. There thus seems to be a removal of the smallest grains in the disc surface layers. Several sources show strong crystalline emission features at longer wavelengths, coming from rather cool crystalline dust grains in the disc. Crystalline dust is typically formed close to the inner rim, where temperatures are high enough for crystallinisation to occur. The presence of cool crystalline grains shows that either radial mixing must be very efficient or that the grains have a crystallinisation process which is already efficient at low temperatures.

So far, no clear difference is found in the disc composition of the Galactic and extragalactic sources. Also, no correlation is found between the observed dust parameters and other characteristics, such as the central star or binary orbit.

4. Disc geometry

To determine the structure of the discs, we performed 2D disc modelling on the observed photometry and spectroscopy of the Galactic and LMC disc sources (see Fig. 2), using the MCMMax radiative transfer code (777). We found that a good fit is obtained with a passively irradiated, self-shadowed disc with a puffed-up inner rim. The inner radius of the disc is found slightly below the dust sublimation radius, but the outer radius is unfortunately less-well constrained. Typical values for the inner and outer radius are 2-20 AU and 100-500 AU, respectively. Dust masses range from 10^{-6} - $10^{-4}M_{\odot}$, with a surface density powerlaw > -2 , using a gas-to-dust ratio of 100.

5. Conclusions

Our studies show that, both in our Galaxy and beyond, circumbinary discs around evolved stars are clearly present, and are a common by-product of binary evolution.

Both from our mineralogy study and from our disc modelling, we found that the chemical and physical properties of these discs around evolved binaries are very similar to those seen in proto-planetary discs around young stars, which is remarkable since these discs have very different formation histories. All discs are oxygen rich, and thus formed when the star was oxygen rich. In both disc types, dust processing is very

effective: large grain sizes prevail and the crystallinity is very high. The observed correlation between the evolutionary phase and the disc parameters found for young stars, is not yet observed in our limited sample of evolved binary stars.

Clearly, many open questions still remain on the formation, structure and evolution of these circumbinary discs around evolved stars, and the impact the disc has on the evolution of the central binary system. The interaction in the binary system is fundamental in trapping part of the dust in a stable circumbinary environment, and determines the further evolution of the binary star and the disc.

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