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Binary post-AGB stars and their Keplerian discs

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Abstract.
In this contribution we give a progress report on our systematic study of a large sample of post-AGB stars. The sample stars were selected on the basis of their infrared colours and the selection criteria were tuned to discover objects with hot dust in the system. We started a very extensive, multi-wavelength programme which includes the analysis of our radial velocity monitoring; our optical high-resolution spectra; our groundbased N-band spectral data as well as the Spitzer full spectral scans; the broad-band SED and the high spatial-resolution interferometric experiments with the VLTI. In this contribution we highlight the main results obtained so far and argue that all systems in our sample are indeed binaries, which are surrounded by dusty Keplerian circumbinary discs. The discs play a lead role in the evolution of the systems.

Key words. Stars: AGB and post-AGB – Stars: atmospheres – Stars: evolution (Stars:) binaries: spectroscopic Techniques: radial velocities Techniques: interferometric

1. Introduction

This conference highlighted once more that the processes which govern the final evolution of low and intermediate mass stars are still poorly understood. Fundamental uncertainties remain in our understanding of the internal structure, the (chemical) evolution and the mass-loss processes of AGB stars. Another well known challenge is the study of PN formation, where much research is devoted to trying to understand the origin of the remarkable morphological and kinematical differences between AGB circumstellar envelopes and their more evolved counterparts. During the transition time, the star and circumstellar envelope must undergo fundamental and rapid changes in structure, mass-loss mode and geometry which are still badly understood. The debate on which physical mechanisms are driving the morphology changes gained even more impetus after the finding that resolved cooler post-AGB stars or proto-planetary nebulae (PPNe) display a surprisingly wide variety in shapes and structure, very early in their evolution off the AGB (Sahai 2003).

Impressive kinematic information resulted from the extensive CO survey of Bujarrabal et al. (2001): a fundamental property of the omnipresent fast molecular outflow in PPNe appears to be that it carries a huge amount of linear momentum, up to a 1000 times the momentum available for a radiation driven wind.

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Clearly, other momentum sources have to be explored. Despite intense debate between proponents of binary models and advocates of single star models, this issue remains a mystery. The testing of binary scenarios remains elusive, also because of the lack of observational information on binarity in PNe and often very obscured PPNe.

To study late stellar evolution in binary systems, optically bright, less obscured post-AGB stars are ideal candidates and in recent years it became clear that binaries are not uncommon. It was realised that these binaries have distinct observational characteristics, which include broad IR excesses often starting already in H or K, pointing to the presence of both hot and cool dust around the system. It was postulated that this indicates the presence of gravitationally bound circumstellar material in the system (for a recent review we refer to Van Winckel (2003)). The most famous example of an evolved binary is the Red Rectangle for which the Keplerian kinematics of its circumstellar disc have been resolved recently by interferometric CO measurements (Bujarrabal et al. 2005).

While the first binary post-AGB stars were serendipitously discovered, the distinct characteristics of their broad-band SED allowed us to launch a more systematic search for evolved binaries. In total we selected 51 objects (De Ruyter et al. 2006a) which is a fair number compared to some 220 post-AGB stars known in the Galaxy (Szczerba et al. 2001). We started a very extensive multi-wavelength observational study of those systems. Although the program is far from finished, we give here an overview our main results obtained so far.

2. Spectral Energy Distribution (SED)

The total sample of 51 stars (De Ruyter et al. 2006a) was defined by uniting three different sub-groups: the serendipitously discovered binary post-AGB stars; those RV Tauri stars which show an infrared excess as detected by IRAS; and a new sample of stars (Lloyd Evans 1999), detected by IRAS and with infrared selection criteria tuned to discover new RV Tauri stars.

The RV Tauri stars form a rather heterogeneous group of classical pulsators, with defining light curves showing alternative deep and shallow minima. The pulsational periods are between 30 and 150 days. They are generally acknowledged to be evolving on a post-AGB track, after the detection of thermal infrared radiation of circumstellar dust around many of them (Jura 1986). Thanks to the discovery of RV Tauri stars in the LMC (Alcock et al. 1998), their location on the high luminosity end of the Population II Cepheid instability strip has been corroborated.

The main result of our systematic study of the broad-band energetics of the sample stars was that the SEDs of all programme stars are in fact very similar (see Fig. 1). Double peaked SEDs were not found and the dust excess starts at very high temperatures, irrespective of the effective temperature of the central star. In almost all systems, dust near sublimation temperature must be present to explain the very hot dust component. With the expected luminosities and the effective temperatures of the stars, sublimation temperature is less than 10 AU from the surface of the star. Moreover, when available, the long wavelength fluxes at 850 μm, are indicative of a component of large, mm-sized grains (De Ruyter et al. 2005).

In none of the stars there is evidence for a present-day dusty mass loss; simplified SED modelling showed that in all systems, gravitationally bound material must be present. The most natural geometry is that the dust is stored in a Keplerian disc. The large infrared-to-optical conversion ratios show that inner regions of the disc must be puffed-up to cover a large enough solid angle, as seen from the evolved star. In many cases, the large infrared luminosity is combined with a very small line-of-sight total reddening, which gives a useful handle on the likely viewing angle onto the disc.

3. Radial Velocity Monitoring

Since the presence of a Keplerian disc is probably a signature of the binary nature of the central object, we started a long-term radial velocity monitoring program to detect binary mo-

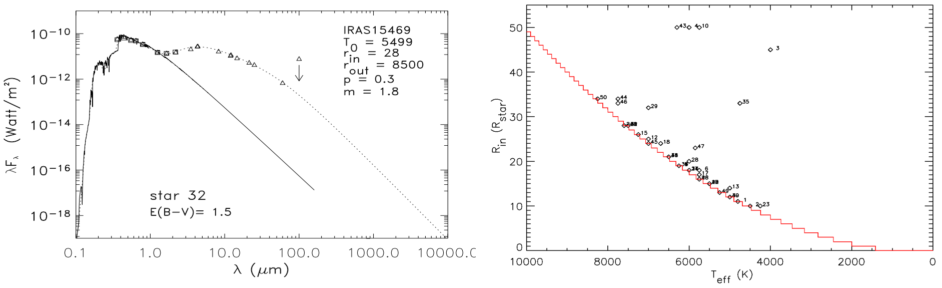

Fig. 1. The right panel gives an illustrative SED plot of one of the post-AGB stars (IRAS 15469-5311). The full line is an appropriate Kurucz model, the measurements are dereddened. Note the significant dust excess, which starts already at the H-band. In the right panel we show that for the whole sample and irrespective of the effective temperature of the central star (x-axis), the dust excess (R_{in} expressed in stellar radius) starts at or very near sublimation temperature (full line) (De Ruyter et al. 2006a).

tion and constrain the orbital parameters. We use a cross-correlation technique with spectral masks defined by the high signal-to-noise optical spectra obtained during our chemical analyses program. The photospheric motion of pulsationally unstable atmospheres, make the interpretation of radial velocity variabitily as due to orbital motion difficult. Results on individual stars can be found in Maas et al. (2002, 2003); Van Winckel (2004). Although the program is still running and the full statistics of our program are not yet determined, we can safely conclude we indeed found a very high binary rate. For objects with a small pulsational amplitude, this rate is even 100% on six stars (Van Winckel 2006).

In total and complemented with literature values, orbital parameters of 27/51 systems are now determined. The orbital periods are in the range of 100 to 2000 days. In Fig. 2, we show one of our new detections. The mass functions give the lower limit of the mass of the binary companion assuming a 0.6 $M_{\odot}$ primary and an edge-on orbital plane (Fig. 2). The masses of the companions cover a significant range, and in a few systems, the lower mass limit of the companion is superior to the Chandrasekhar limit of a white dwarf. In none of the systems is the companion detected or any symbiotic activity found. Given the orbital characteristics, it is likely that in most, if not all systems, the companions are non-evolved main-sequence stars. One of the surprising results is that the orbits are often not circularised (e.g. Van Winckel 2003).

The binaries are now not in contact, but all the orbits are too short to accommodate a full grown AGB star. The stars must have been subject to severe interaction in the past when the primary was at AGB dimensions. It is assumed that during the interaction, the rather massive circumbinary discs were formed.

4. Dust Processing

To study the chemico-physical characteristics of the circumstellar dust, the 10 micron N-band is ideally suited, since it samples resonances of the most dominant silicate minerals (olivines, pyroxenes and silica) as well as the SiC resonances expected to prevail in C-rich environments. Moreover, the resonance profiles are very sensitive to grain sizes from the typical 0.1 μm up to a few μm. We observed 22 stars from the sample with the TIMMI2 instrument mounted on the 3.6m telescope of ESO. Moreover, a wider wavelength range was observed for a limited sample during our explorative Spitzer program.

In all objects studied so far, the dust emission is oxygen rich. The dust signatures are, however, very different from what is observed in outflow sources (Fig. 3). The narrow resonances of the crystalline lattices make unique identification possible and crystalline features are indeed very prominent in the spectra.

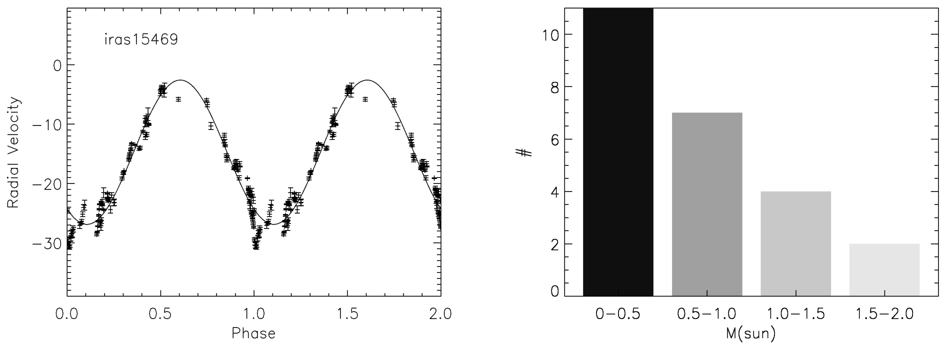

Fig. 2. The left panel shows the orbital solution of one of the programme stars (IRAS 15469-5311). The orbital elements are: Period = 387d ± 1d, amplitude = 12.1±0.3 km s^{-1}, system velocity = -14.8 ± 0.2 km s^{-1}. This star is circularised (Van Winckel 2006). The right panel shows the distribution of systems with respect to the lower mass limit of the companion star assuming a 0.6 M$_\odot$ primary and an inclination of 90°.

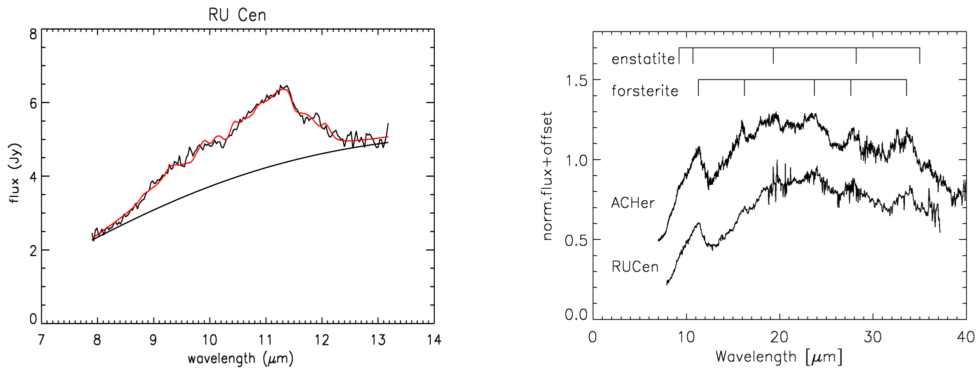

Fig. 3. The N-band spectrum of one of the program stars (RU Cen). The full thick line represents the model in which we used several components (amorphous silicates, forsterite, enstatite) and different grain sizes. The contributing continuum is also shown (De Ruyter et al. 2006b). Our Spitzer high-resolution IRS spectra show that RU Cen is a spectral analogue to another RV Tauri star AC Her (Molster et al. 1999) which was observed by ISO: the silicates are very strongly processed both in grain size and certainly in crystallinity rate. This again is indicative of processing in gravitationally-bound material.

Moreover, the width and contrast of the solid state emission profiles are good tracers of the grain size (e.g. Min et al. (2004)), while the temperature structure can be traced by the features' flux ratios. The main conclusions of our preliminary analyses of the TIMMI2 and Spitzer spectra obtained so far (Gielen et al. (2006); De Ruyter et al. (2006b), Fig. 3), are that the Mg-rich end members of the crystalline olivine and pyroxenes (forsterite and enstatite) prevail. For some sources the silicate emission is over 80% crystalline ! The strong crystalline signature and the lack of both amorphous and crystalline small grains, imply that the grain population is highly processed (De Ruyter et al. 2006b) both in crystallinity and in average grain size.

Neither in the recently obtained N-band spectra nor in our Spitzer data, are carbon-rich dust or gas signatures found. This despite the dynamical evidence from the orbits, that at least some objects must have had initial masses which are theoretically thought to evolve to carbon stars on the AGB (Fig. 2). This lack of third dredge-up enrichment is further evidenced by the CO_2 gas emission detected in our Spitzer spectra in one source. The $^{12}C/^{13}C$ is < 10, which illustrates again that ^{12}C was not enriched during AGB evolution. Mixed chemistry, which is observed in a few well studied binaries like HR 4049 and HD 44179 (e.g Van Winckel 2003) seems to be an exception rather than the rule.

Note that our photospheric chemical studies reveal no evidence for successful 3rd dredge-up enrichment in any of the stars. The study of possible AGB enrichment is made difficult by the fact that in the total sample, depletion abundance patterns are frequently detected (Van Winckel 2003; Giridhar et al. 2005; Maas et al. 2005). The basic scenario of the badly understood depletion process involves a chemical fractionation due to dust formation in the circumstellar environment followed by a decoupling of the gas and the dust. The "cleaned" gas is then reaccreted on the stellar photosphere, which becomes depleted of the refractory elements. Waters et al. (1992) showed that the most favourable circumstance for this process to occur is, if the circumstellar dust is trapped in a disc. Possible AGB enrichment could be masked by this process. S-process elements are refractory, but in all systems of our sample, the s-process elements show similar abundances to intermediate-mass elements with similar condensation temperature.

The photospheric chemical composition as well as the chemical information of the dust indicate that stellar evolution was shortcut on the AGB, prior to efficient dredge-up episodes.

5. Resolving the disc: Interferometry

Single telescope infrared spectra are of limited diagnostic value to probe the actual structure and dimension of the circumstellar environment. The MIDI instrument – producing spectrally dispersed fringes in the N-band – is ideally suited, not only to resolve the compact discs, but also to obtain spatial information of the different dust components. We therefore started an interferometric program on our sample stars. With the data available now on only a few objects, the interferometric measurements prove that the circumstellar emission originates indeed from a very compact region. Deroo et al. (2006) showed that one of the objects, SX Cen is not even resolved with a 45m baseline, implying an upper limit of some 18 A.U. for the diameter of the dust emission. Most sample stars are, however, well resolved giving unprecedented constraints on the spatial dimensions of the infrared emitting surface.

The added value of the MIDI instrument are the dispersed fringes allowing us to probe distribution differences between the minerals. The inner disc reaches temperatures above the glass temperatures causing the grains to anneal on very short timescales. Therefore, the innermost disc regions are expected to be strongly crystalline. In some objects, this radial gradient in crystallinity is indeed observed (Deroo et al. 2006). Other objects, however, show evidence that the whole disc is processed since amorphous and crystalline grains show the same distribution. The cool crystalline silicates detected in our Spitzer data, as well as by the interferometric data, show either that radial mixing was very efficient or that the thermal history of the grains implied significant processing during the formation process of the grains themselves.

6. Conclusion

Although our analysis of all data is not complete yet, it is clear that all experiments till now confirm that the stars are indeed surrounded by stable dusty reservoirs in a Keplerian discs.

The global picture that emerges is that a binary star evolved in a system which is too small to accommodate a full grown AGB star. The AGB evolution was cut short and during a badly understood phase of strong interaction, a circumbinary dusty disc was formed, while the binary system did not suffer dramatic spiral in. What we observe now is a F-G supergiant in a binary system, which is surrounded by a circumbinary dusty disc in a bound orbit. In all observed cases, the dust in the disc is oxygen rich. Since all systems have orbits well within the sublimation temperature of dust grains, the dust discs must be circumbinary.

Formation scenarios of the discs include a wind capture scenario, in which the dusty wind of the primary is accreted by the companion, or a scenario in which the disc is formed through a non-conservative mass transfer in an interacting binary. Given the orbits detected till now, the second scenario is more likely, but unfortunately it is theoretically poorly explored. The thermal history of the grains may have been very different from that in normal AGB winds, which could lead to very different chemo-physical properties of the grains during dust formation. On the other hand, in the limited sample for which we have the full Spitzer spectrum, several do show evidence of much less processed material, while the global binary characteristics (orbit, SED) are not very different. This would suggest also an effect of processing and radial mixing during the storage time in the disc.

In the limited sample observed till now, there is no clear connection between the quantified properties of the dust spectra, and other characteristics of the stars like the binary orbit, effective temperature of the central star and/or SED characteristics. Clearly many questions remain.

The formation structure and evolution of the Keplerian disc is far from being understood, but it does appear to be a key ingredient in our understanding of the late evolution of a very significant binary population.

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