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SHARP VLTI VIEW OF SECOND-GENERATION PROTOPLANETARY DISKS AROUND EVOLVED BINARIES

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Abstract. At the end of their life some binary stars (post-AGB binaries) form Keplerian disks of gas and dust from the ejected matter of the primary star at the end of the AGB phase. Those disks are similar to the planet-forming disks around young stars in many aspects. The orbital properties of these evolved binaries are not understood and the circumbinary disks are possibly playing a major role by pumping up the orbital eccentricity via Lindblad resonances. However, the disk structure, evolution and dispersal remain elusive. In this talk we will present the first reconstructed VLTI images of such systems revealing their building blocks: the inner disk rim, the central binary, an unexpected emission from the companion and an over-resolved component. We will also present the key findings of our VLTI snapshot survey pushing the comparison with protoplanetary disks much further. We will end by presenting our recently awarded VLTI large programme that aims to sharpen our view of these exciting objects.

Keywords: stellar evolution, post-AGB stars, binaries, high-angular resolution, infrared interferometry.

1 Introduction

Binarity is present in all kinds of stars (25% of low-mass stars and more than 80% of high-mass stars have at least one companion Duchêne & Kraus 2013). However, binary evolution is complex as it can give birth to diverse phenomena such as thermonuclear novae, supernovae type Ia, sub-luminous supernovae, gravitational waves and objects such as sub-dwarf B-stars, barium stars, cataclysmic variables, and asymmetric planetary nebulae (PNe). Understanding the impact of binarity in stellar evolution is therefore crucial but is, also, still poorly understood.

Here, we focus on the evolution of post-AGB (pAGB) binaries, that are surrounded by a circumbinary disk and that are in fast transition (10^5 years) between the AGB and the PNe stages. These pAGB systems are the remnants of strong binary interactions happening at the end of the AGB phase and, as they have now lost their envelope and are not obscured by a shell anymore, they are perfect to study the consequences of binary interaction.

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Disks around pAGBs were first postulated from the detection of infrared excesses in the spectral energy distributions (SED), that could not be attributed to expanding shells (e.g. de Ruyter et al. 2006). Almost all of the disk sources were then discovered to be binaries through radial velocity measurements (van Winckel 2003; Van Winckel 2007). Those observations led to the conclusion that pAGB disks originate from the evolved star's matter ejections via strong winds that happen at the end of the AGB phase for low- and intermediate-mass stars (0.8 - 8 $M_\odot$). The dynamical interaction between this strong wind and the companion star causes part of the mass loss to be trapped in a circumbinary disk. Millimetre observations of CO lines with the Plateau de Bure interferometer and ALMA showed that these disks appear to be stable, i.e. in Keplerian rotation (Bujarrabal et al. 2013, 2015, 2017, 2018). These observations also revealed a disk-wind component suggesting angular momentum transport in the disk. These disks are dusty with large size dust grains (de Ruyter et al. 2005; Gielen et al. 2011; Hillen et al. 2015) and large crystallinity fraction (Gielen et al. 2008, 2011). Radiative transfer models of protoplanetary disks (PPDs) around young stellar objects (YSOs) are able to reproduce both the SED and infrared interferometric measurements on a few targets (Hillen et al. 2014, 2015, 2017; Kluska et al. 2018). The dust masses found in these disks are of the order of 10^{-4}-10^{-3} $M_\odot$ (Sahai et al. 2011; Hillen et al. 2014). In general, despite very different forming processes, pAGB disks are in many ways (infrared excess, Keplerian rotation, winds, jets, dust mass, dust mineralogy and grain sizes) similar to PPDs around YSOs. As the PPDs are well studied both observationally and theoretically, the very close similarity with the disks around pAGB binaries rises the question of the universality of physical processes in dusty circumstellar disks and more specifically of their planet formation efficiency. Circumbinary disks around pAGBs can therefore be second generation planet forming disks, especially as several planets are candidates of being formed in such disks (e.g. NN Ser Völschow et al. 2014; Marsh et al. 2014).

The period distribution of the post-AGB binaries was predicted to follow a bimodal distribution where short period binaries are post-common envelope systems that spiraled-in and long period binaries are binaries that evolved through wind interaction and have therefore widen their orbits (Nie et al. 2012). However, the observed period distribution falls between the two peaks of the predicted distribution showing that an important element of binary interaction is still not understood in these systems. Moreover, the orbits are predicted to be circular given the circularisation that happen at the common envelope phase. Again the observed orbits can have eccentricities around 0.3 (Oomen et al. 2018). Here, we present high angular observations of these systems that aim to understand the disk-binary interactions and characterise the inner disk parts in these intriguing systems.

2 A VLTI/PIONIER snapshot survey

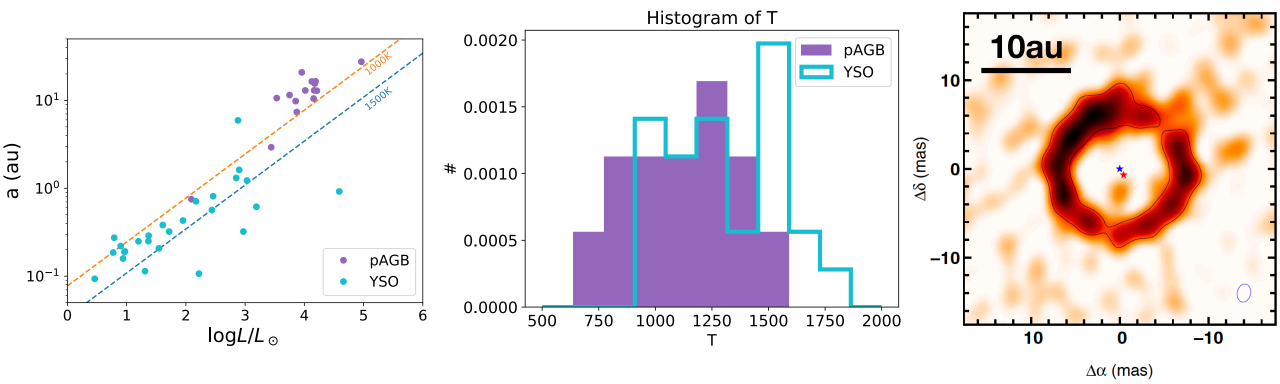

Fig. 1. Left: Near-infrared circumstellar size versus the stellar luminosity for both YSOs and pAGB binaries. The pAGB circumbinary scales with stellar luminosity but the relation is shifted towards larger sizes. **Center:** Histogram of temperatures for the circumstellar (or circumbinary for pAGBs) environments as measured from VLTI/PIONIER data. The environment of pAGB binaries appear to be colder. **Right:** The image reconstruction of the circumbinary environment of IRAS08544-4431 as reconstructed with the SPARCO approach (here the central binary was modelled as two point sources and do not appear in the image reconstruction).

We have conducted a VLTI snapshot survey (Kluska et al. subm.) in the near-infrared with the PIONIER instrument, that is a four beam combiner observing in the H-band (1.55-1.8μm). The aim of this snapshot survey was to uncover the disk morphology (e.g. radius, width, azimuthal brightness distribution), temperature and deduce interesting properties about the physical properties of its inner parts, such as its mineralogy or density. We have observed 23 targets in a snapshot mode, meaning that most of the targets were observed once or twice on two or three configurations. The resulting (u, v)-plane is not optimised for image reconstruction but is enough to recover basic properties of the observed targets. We have therefore fitted different models to the dataset with increasing complexity, starting from a two-parameter model of a point source and a background to a 17 parameters model of a double point source, an azimuthally modulated Gaussian ring and a background. We then have used the Bayesian Information Criterion to select the most likely model that fits the data. From this we could infer that the complexity of the targets is high given that 14 out of 23 targets need to be fitted by models with 11 or more parameters. We could also derive the size of the circumbinary Gaussian ring and place it in a size-luminosity diagram that is used for young stars (Monnier & Millan-Gabet 2002; Monnier et al. 2005; Lazareff et al. 2017). We can see that the sizes of the near-infrared extended emission in pAGB targets (that have a higher luminosity that YSOs) extend the size-luminosity relation that holds for YSOs where the near-infrared size is proportional to the square root of the luminosity. This can be explained by the fact that the near-infrared emission is ruled by dust sublimation physics. There is however a slight off set to higher sizes. We can also see that the distribution of the temperatures of the circumstellar emission in pAGBs is lower that around YSOs. Those two results point towards either the absence of refractory dust grains at the disk inner rim or lower gas density in the dust sublimation region.

Given the complexity of the targets it was difficult to deduce the binary separation and to study in detail the disk morphology and disk/binary interactions. An interferometric imaging survey is needed to reveal the disk complexity and link the disk morphology to the position of the two components of the binary.

3 A first near-infrared image of a post-AGB system

We have also led an interferometric imaging campaign on one post-AGB binary target, IRAS08544-4431. We have obtained a (u, v)-coverage that is suitable for image reconstruction. The visibility has a strong dependency on the observed wavelength channel. This is the so-called chromatic effect that is due to the temperature difference between one unresolved component (here the main star) and its resolve environment (here the circumbinary disk). One needs to take this chromatic effect into account when performing image reconstruction and this is done by using the SPARCO approach (Kluska et al. 2014) that consists in modelling the star and reconstructing its environment only by taking the difference of temperature into account. The first reconstruction have revealed the circumbinary disk but also a point source close to the primary star location (Hillen et al. 2016). This point source is likely the circum-secondary accretion disk (as the main-sequence secondary is too faint to be detected by our observations.) When subtracting this second point source emission the image reconstruction have revealed the complex circumbinary disk morpohology. We have then modelled this dataset (Kluska et al. 2018) with a radiative transfer model of a protoplanetary disk using MCMax (Min et al. 2009). The model treats the vertical disk scale-height self-consistently assuming hydrostatic equilibrium. The dust composition is of interstellar silicates with a power-law distribution of sizes between 0.1μm to 1 mm. The surface density follows a double power-law with radius where in the inner disk index is positive (1.5) and in the outer part it is negative (-1). The inner rim is found to be at 8.25 AU, the outer rim is fixed at 100 AU and the surface density changes at 24.75 AU. We then add a point source to the model to represent the circum-secondary accretion disk. We also found out that the model cannot reproduce the amount of extended flux detected in the interferometric observations. We have therefore add a background component of 8.1%.

This model reproduces well both the SED and the interferometric squared visibilities but is not able to reproduce the closure phases and the azimuthal disk brightness modulations. Those modulations could be due to spirals due to the disk-binary interactions and is a topic of research.

4 INSPIRING: A VLTI Imaging Large Programme

To have a better view of the interaction between the binary and its circumbinary disk we have launched a 250 h long VLTI Large Programme using two near-infrared interferometric instruments (PIONIER and GRAVITY) to observe 11 targets. The programme is entitled INSPIRING (INterferometric Survey of Post-AGB binary Interaction with their RING, PI: Kluska). The aim is to perform image reconstruction (as for IRAS08544-4431) in the continuum with PIONIER and locate any line emission with GRAVITY. The goals are to uncover the complex structure of the circumbinary disk inner rim, look for direct signs of accretion from the circumbinary disk but also for circum-secondary accretion disks and possibly build an evolutionary sequence for these disks.

5 Conclusion

Post-AGB binaries are intriguing objects that are tracing binary evolution and that could be surrounded by second-generation planet forming disks. The brightness and angular size of these targets is ideal to be observed by current infrared interferometric facilities. We have conducted a snapshot survey of these targets using the VLTI/PIONIER instrument and have revealed the complexity of the targets and that the inner disk rims are ruled by dust sublimation physics as it is the case in protoplanetary disks around young stars. The first near-infrared interferometric image of such a system has revealed a prototype of such a system with a post-AGB primary, a main-sequence secondary surrounded by an accretion disk, a circumbinary disk inner rim that has azimuthal brightness modulations probably due to disk-binary interactions and the presence of a strong extended component that is not reproduced by the radiative transfer model. In order to progress on the knowledge of these disks an interferometric imaging survey is needed to study the disk brightness distribution w.r.t. the inner binary. Also observations at larger wavelengths will help to study the disk structure and the disk physical conditions to push the comparison with protoplanetary disks further and look for the possibility of second generation planet formation mechanisms.

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