Binarity, planets, and disks

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Post-RGB and Post-AGB stars as tracers of binary evolution

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Abstract. Binary interactions can alter the intrinsic properties of stars (such as: pulsation, mass-loss, photospheric chemistry, dust-formation, circumstellar envelope morphology etc.) and can even play a dominant role in determining its ultimate fate. While past studies have shown that binarity can end the AGB life of a star, recent studies have revealed that in specific cases binarity also pre-maturely terminate the RGB evolution. A characteristic feature of evolved binaries is the presence of a Keplerian circumbinary disc of gas and dust which plays a lead role in the evolution of the systems. In this article, I will review our advances in the research landscape of post-RGB and post-AGB binary stars, focussing on their observational properties, spectral energy distribution, photospheric chemistry, the evolution of their stable circumbinary discs, and the evolutionary connection between the enigmatic post-AGB/post-RGB binaries, and other systems whose primary component is a white dwarf.

Keywords. stars: AGB and post-AGB, stars: binaries, stars: evolution, stars: fundamental parameters, stars: chemically peculiar, Galaxy: stellar content, galaxies: Magellanic Clouds.

1. Introduction

It is known that ∼60% of low- and intermediate-mass (LIM) stars evolve in binary systems. It is also established that mass transfer in binary systems result in a range of objects; from energetic systems such as thermonuclear novae, supernovae type Ia, sub-luminous supernovae, gravitational wave sources, to less energetic systems such as sub-dwarf B stars, barium stars, bipolar planetary nebulae, etc. While this brings to light that binarity can alter the ultimate fate of stellar systems, the exact binary interaction mechanisms, and the evolutionary connection between these systems, remain unknown. Therefore, an in-depth study on poorly understood binary interaction processes is essential to constrain stellar (especially binary) evolution as well as the chemical evolution of the Universe. In this article, I will focus on binary stars that have evolved off the giant branches: post-Asymptotic Giant Branch (post-AGB) and post-Red Giant Branch (post-RGB) stars.

2. Post-AGB and Post-RGB binaries

For red giants in binary systems, the binary interaction process is governed by the balance between the Roche-lobe and the stellar radius of the red giant. Binaries with a main sequence separation of less than about two giant radii at the AGB tip will be tidally captured somewhere on the RGB or AGB. Population synthesis models (e.g., Nie *et al.* 2012) predict that a possible outcome of such a binary interaction is stable mass transfer, resulting in the formation of binaries through the following channels: the

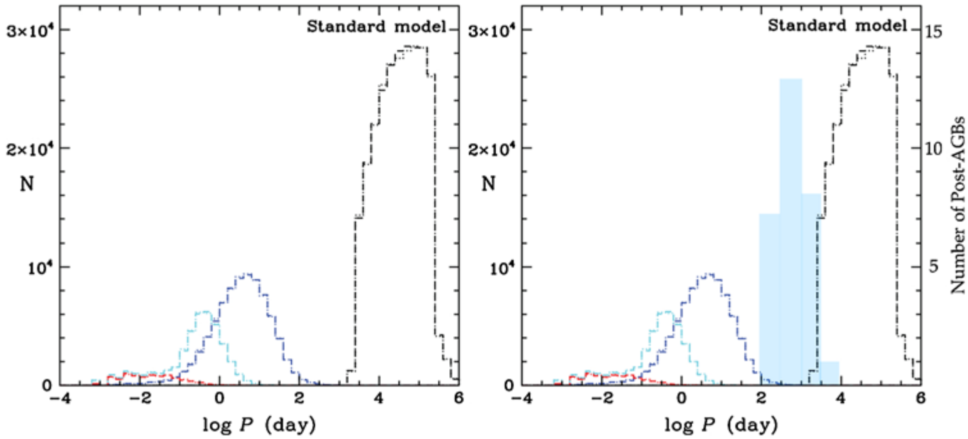

Figure 1. The discrepancy between the observed periods of the Galactic post-AGB and/or post- RGB binaries and the predictions from population synthesis models. Left: The results of the population synthesis models which were normalised to the sequence E (ellipsoidal) variables in the LMC. (The distribution of intermediate period binary post-AGB systems is given in black, the close binary post-AGB stars in blue, the post-RGB and post-EAGB binaries in cyan/grey and the double degenerate secondaries in red. Figure adapted from Nie *et al.* (2012). Right: The histogram shows the distribution of observed orbits for the Galactic systems (e.g., Van Winckel *et al.* 2009; Gorlova *et al.* 2014). All orbits fall in the period range NOT predicted by the models. The observed large eccentricities are also not predicted.

common-envelope (CE) channel and the wind accretion channel. The CE channel results in short-period binaries ($P \approx 1$ day) and the wind accretion channel results in wider systems ($P > 1000$ days), see Fig 1. However, our ongoing large radial velocity monitoring campaign on Galactic post-AGB stars, using the HERMES spectrograph (Raskin *et al.* 2011) mounted on the Flemish 1.2m Mercator telescope, has resulted in the discovery of many evolved binaries with unexpected periods between 100 and 2000 days (see Fig 1, Van Winckel *et al.* 2009; Gorlova *et al.* 2014). These systems are now far from Roche Lobe-filling, but the periods are too short to have previously accommodated a RGB or AGB star. Furthermore, these systems did not suffer dramatic spiral in and therefore the common envelope was either very rapidly expelled or somehow avoided.

The discrepancy between the observations and the predictions are linked to both theoretical and observational limitations. From the theoretical point of view, a wide range of binary interactions are not understood from first principles. Theoretical models have several uncertainties, such as, the increase of the mass-loss prior to contact (e.g., Chen *et al.* 2011; Abate *et al.* 2013), the common-envelope phase (e.g., Izzard *et al.* 2012; Ivanova *et al.* 2013), the efficiency of envelope ejection (e.g., Toonen & Nelemans 2013), the impact of radiation pressure on the shape of the classical Roche potential (e.g., Dermine *et al.* 2009), the impact of eccentricity pumping mechanisms (e.g., Izzard *et al.* 2010; Dermine *et al.* 2013), the assumed mass transfer efficiency and its orbital phase dependency, etc. (referenced here are only the most recent literature on the subject). From the observational point of view, the challenge persists as many parameters involved in predicting the outcome of the binary evolution channels are not well constrained by observations. Additionally, the difficulty in fully interpreting this Galactic sample is that we have no good distances and hence neither luminosities nor core masses (see Sect. 3).

A discrepancy also exists with respect to the observed eccentricities of these systems. Over 70 % of post-AGB binaries (ranging all orbital periods) have significant non-zero eccentricity (Oomen *et al.*, 2018, submitted). This indicates that circularisation has not happened, even though the Roche-lobe radii are smaller than the maximum size of a

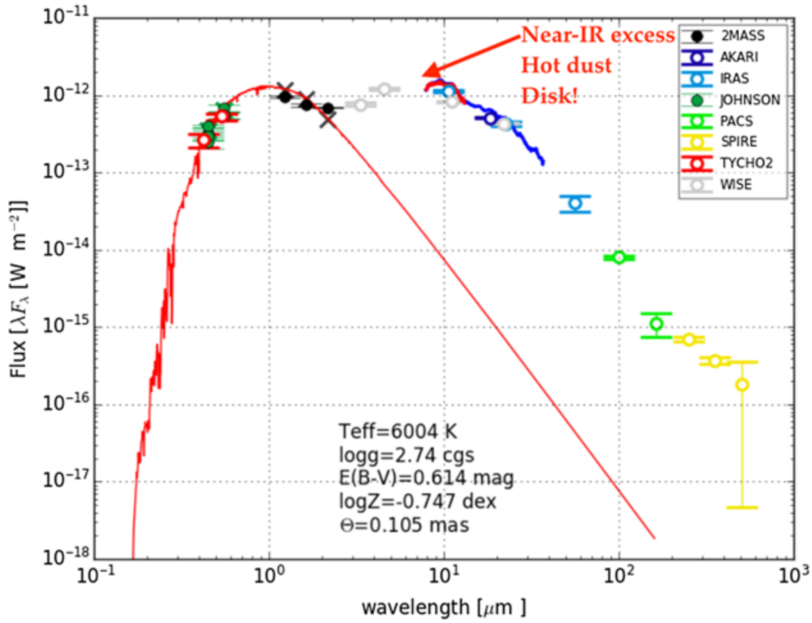

Figure 2. Disc-type SED of a post-AGB binary showing the presence of near-IR excess indicative of a circumbinary disc. The symbols represent the photometric points shown in the legend. The red solid line (in the optical part of te SED) represents the model that best fits the SED. The blue solid line (in the IR part of the SED) represents the IR spectrum of the star from the Spitzer Space Telescope Survey.

typical AGB star and tidal circularisation should have been strong when the objects were on the AGB.

While the binary interaction mechanisms that govern the evolution of post-AGB binaries is unknown, observational studies using photometric, spectroscopic, and interferometric techniques have provided a gateway to investigate these objects.

2.1. *Stable, long-lived circumbinary discs around post-AGB binaries*

Extensive studies of post-AGB stars in our Galaxy and the Magellanic Clouds have shown a group of objects that displayed spectral energy distributions (SEDs) with the onset of a near-IR excess, indicative of hot dust. This indicates that the circumstellar dust must be close to the central star, near sublimation temperature, typically in the form of a disc surrounding the central system (see Fig. 2). Such SEDs are referred to as disc-type SEDs (e.g., Van Winckel 2003; de Ruyter *et al.* 2006; Bujarrabal *et al.* 2013). The evolution of the (binary) star and the formation and evolution of the disc are closely coupled: the primary's AGB phase was abruptly terminated due to mass loss induced by a poorly understood binary interaction process. Part of the ejected material was forced into a circumbinary disc. Stable Keplerian discs are commonly detected towards post-AGB binaries with binary orbital time scales of the order of 100 to 2000 days (see Van Winckel 2017, and references therein). The dust in these discs are processed crystalline and relatively large grains ranging up to 1 μm, typically traced at longer wavelengths. A long life time of the discs is supported by the high degree of dust processing (grain growth, crystallisation Gielen *et al.* 2011; Hillen *et al.* 2016).

While the majority of the post-AGB binaries with circumbinary discs can be recognised by their disc-type SEDs (with an onset of an excess flux at near-IR wavelengths), in

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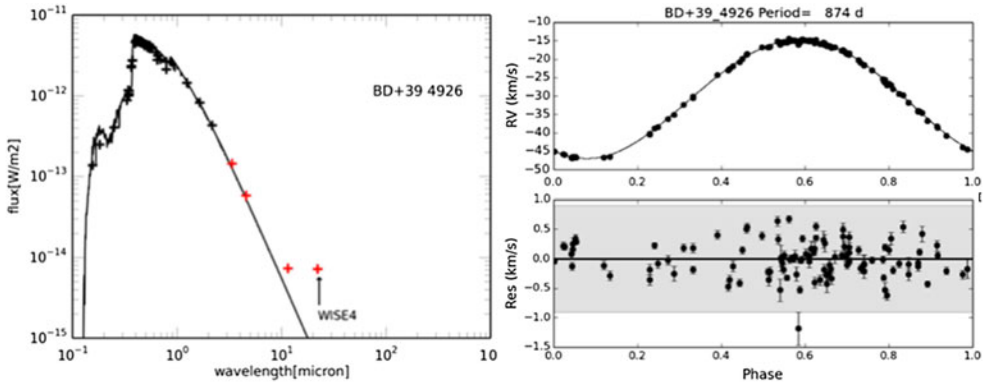

Figure 3. Left: SED of BD+394926, a Galactic post-AGB binary. Right: Radial velocity curve of BD+394926, confirming its binary nature. Figure adapted from Gezer *et al.* (2015).

somes cases, SEDs of post-AGB binaries can have only a mild IR-excess. For example, BD+39492 is a confirmed post-AGB binary with an orbital period of 874^{d} (see Fig. 3). Thus, we expect this star to have a circumbinary disc. However, its SED does not conform to typical disc-type SED but instead shows only a mild IR-excess, indicative of an evolved disc. This is because, just like the central star, the circumbinary disc also evolves. The evolution of the SED depends more on the disc dissipation rather than the evolution of the star. While the exact evolution of the circumstellar disc is uncertain, it is widely accepted that there is more complex physics involved than just expansion and dissipation of the circumbinary disc.

2.2. *The discovery of dusty post-RGB stars*

Though the post-AGB stars in our Galaxy are observationally well studied, before the Gaia era, the exploitation of these objects has been a challenge owing to the lack of accurate distances (and hence luminosities and initial masses) to these systems (see Sect. 3). On the other hand, since the distances to the Magellanic Clouds are well known, so are the luminosities and initial masses of all the stars within these galaxies. Hence, we initiated a comprehensive survey for post-AGB candidates in the Magellanic Clouds. We performed an extensive low-resolution optical spectral survey with the AAOmega multi-fibre spectrograph mounted on the Anglo Australian telescope, which resulted in a clean and complete census of well-characterised post-AGB objects with spectroscopically determined stellar parameters spanning a wide range in luminosities in the Large Magellanic Cloud, LMC (Kamath *et al.* 2015) and SMC (Kamath *et al.* 2014). The known distances to the Magellanic clouds enabled luminosity estimates for all the objects which led to one of the most important results of this survey: the unexpected discovery of a group of low-luminosity, evolved, low-metallicity, dusty objects in the LMC (119 objects) and SMC (42 objects) (Kamath *et al.* 2016). These objects have mid-IR excesses and stellar parameters similar to those of post-AGB stars (G to A spectral types, low log g values between 0 and 2), and low metallicities (lower than the mean metallicity of young stars in their host galaxy). However, their luminosities are much lower (200 - 2500 $L_{\odot}$) than that expected for post-AGB stars. We therefore suspect they are 'post-RGB' stars, and these Magellanic Cloud objects are the first examples of such objects.

The $\sim$2:1 ratio of the number of optically visible post-AGBs to post-RGBs in the LMC and SMC proves that not all LIM stars evolve on to the AGB phase before their death. This presents dusty post-RGB stars as new building blocks in the archaeology of galaxies. It also underlines the need to determine the total fraction of these systems and

Table 1. Properties of post-AGB and Post-RGB binaries

Parameters	**Post-AGB binaries**	**Dusty post-RGB binaries**
Initial mass	$\sim 1-8\,M_{\odot}$	$\sim 1-2\,M_{\odot}$
Final mass[1]	$\sim 0.48-0.9\,M_{\odot}$	$\sim 0.28-0.48\,M_{\odot}$
Observed SED types	mostly disc-type	diverse SEDs[2]: disc-type, double-peaked, mild-IR excess
Orbital periods	100 to 1000 days	yet to be studied
Pulsation periods	$\gtrsim$20 days	$\lesssim$20 days
Metallicity	metal poor in comparison to the young stars in their host galaxy	likely to be metal-rich in comparison to their post-AGB counterparts
Luminosity[1]	$\gtrsim 2500\,L_{\odot}$	$\lesssim 2500\,L_{\odot}$
completion of core-He burning	yes	no (for the majority of the objects)
Photospheric chemical depletion	yes	yes
Dust Mass	$10^{-3}\,M_{\odot}$	yet to be estimated but likely to be greater than $10^{-3}\,M_{\odot}$

Notes:
[1]Depending upon the metallicity.
[2]This indicates that we do not fully understand the evolution, properties, and circumstellar environment of the dusty post-RGB stars (see Section 2.3)

fully understand their evolution and nucleosynthesis. Table 1 summarizes the properties of post-AGB and Post-RGB binaries.

2.3. *Likely evolution scenario and dust properties of post-RGB stars*

During the RGB phase (where luminosities are $\lesssim 2500\,L_{\odot}$), single-star mass loss is insufficient to remove the H-rich envelope and produce a dusty post-RGB star (Vassiliadis & Wood 1994). The only way large amounts of mass loss and premature evolution off the RGB can occur is via binary interaction (Han *et al.* 1995). As mentioned in Sect. 2.1, in the Galaxy, the binaries among the post-AGB stars all have a common property: their SEDs display a clear near-infrared excess. It is now well established that this feature in the SED indicates the presence of a stable compact circumbinary disc. We find that many of our new post-RGB candidates, in the LMC/SMC, also show similar disc-type SEDs (see Fig. 3) pointing to binarity in these objects.

For a fraction of the LMC/SMC post-RGB stars, their SEDs are not representative of the expected disc-type SEDs. (see Kamath *et al.* 2016). Since we expect these dusty post-RGB stars to be in binary systems, a possible explanation for these diverse SEDs is the evolution of the disc, as mentioned in Sect. 2.1.

2.4. *The first radial velocity monitoring studies of post-RGBs in the Magellanic Clouds*

While the likely presence of a circumbinary disc, which points to the binary nature of these systems, can be inferred from the SEDs of the LMC/SMC post-RGB stars, a true test of binarity comes the detection of radial velocity changes.

In our recent studies, we have initiated a radial velocity monitoring program carried out with the X-shooter spectrograph on ESO's Very large Telescope (VLT). The targets selected for this study are representative of the entire post-RGB SMC/LMC sample (i.e., objects covering a range of spectral-types and SED-types). The data available so far comes from 4 epochs of observations and covers a period of ~ 370 days. A detailed radial velocity (RV) analysis of all the data obtained so far revealed significant RV changes in two out of 10 objects, see Fig. 4. While these observations provide a breakthrough result: the first evidence of binarity in two dusty post-RGB stars in the Magellanic Clouds, it is also puzzling since for the remaining objects no significant RV changes were detected. Binary interaction is the only known mechanism for stars to leave the

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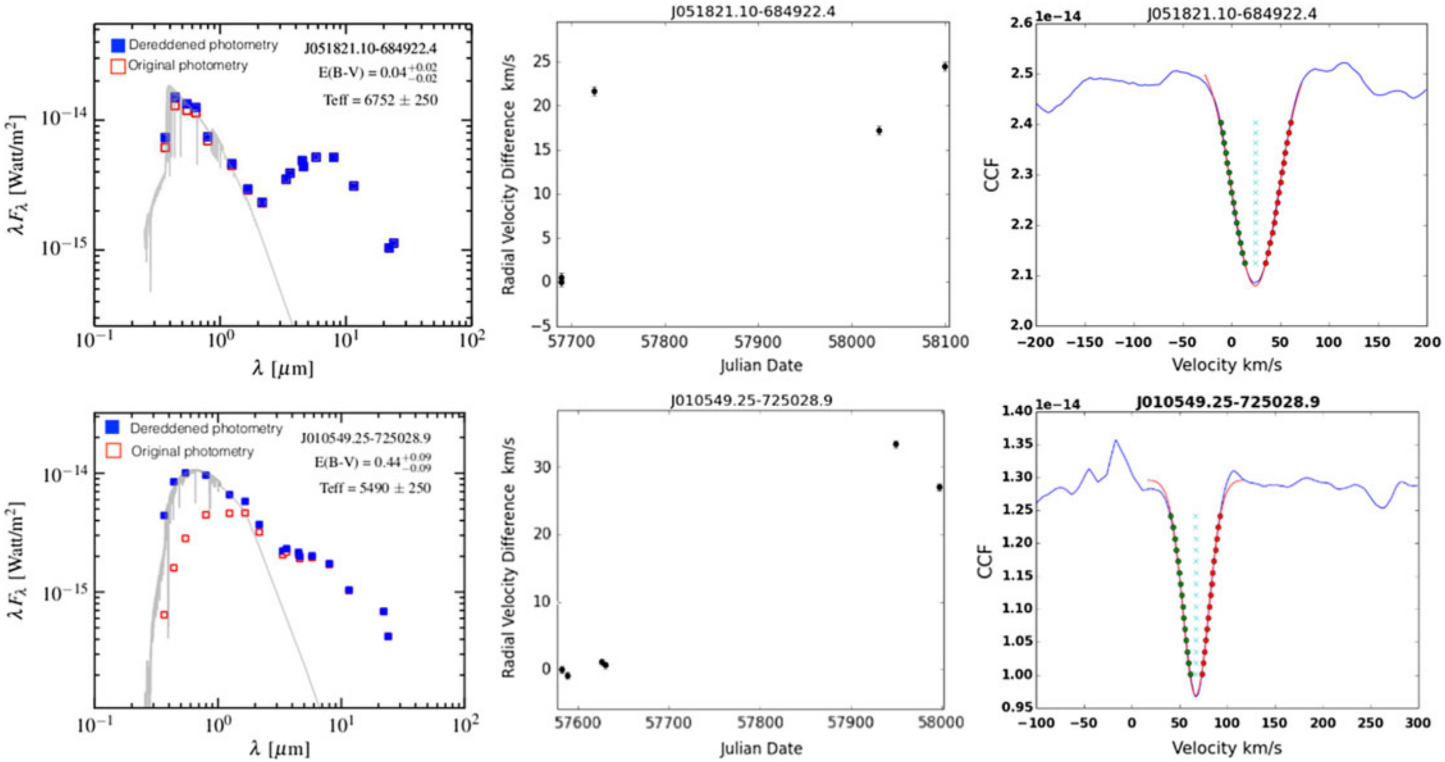

Figure 4. Top-left panel: SED of J051821, an LMC post-RGB source that is representative of the target sample. The SED show a clear near-IR excess, indicative of hot dust in the form of a disc. The grey solid line represents the synthetic spectrum (Munari *et al.* 2005) with the best fit to the observed spectra of the object. Top-center panel: The radial velocity (RV) plot for J051821 (see text for more details). The plot clearly shows the RV changes. Top-right panel: The corresponding cross correlation function (CCF) of the radial velocity measurements. Bottom panels: Same as top panels but for J010549, an SMC post-RGB source.

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RGB prematurely. While the proof of binarity is limited to only two of the 10 post-RGBs, our RV monitoring is too sparse to conclude on the nature of these systems. Furthermore, population synthesis models (Nie *et al.* 2012) normalised to the LMC binary red-giants (the likely progeny of these dusty post-RGB objects), predict that our systems are likely to have orbital periods in the range of ∼25 to 500 days. Therefore, we are continuing our RV monitoring to obtained an orbital period sampling of $\gtrsim$500 days, which covers the full range of predicted orbital periods for these systems. We have also increased the number of epochs so that we will be able to identify the orbital period for the stars that showed RV variations and look for RV variations in the remaining objects.

As mentioned before, over the last decades, the lack of accurate distances to the objects in our Galaxy has stymied the derivation of luminosities of the Galactic sources. Since luminosity is the only key to disentangling the likely post-RGB stars amongst the Galactic post-AGBs, we are yet to identify the Galactic post-RGB stars. In the following section, we present the progress in this field owing to the recent Gaia DR2 data release (Luri *et al.* 2018).

3. Galactic Post-RGB/Post-AGB binaries and GAIA DR2

The recent release of the Gaia DR2 parallaxes (Luri *et al.* 2018) to many of the Galactic objects, provides a possibility to exploiting these systems. For the single post-AGB stars, the Gaia DR2 parallaxes have provided the opportunity to derive distances and luminosities (Kamath *et al.*, 2018, in-prep). However, care must be taken when using the parallaxes of the binary stars because the parallaxes presented in Gaia DR2 come from astrometric solutions assuming a single star evolutionary nature. Furthermore, for the Galactic post-AGB binaries, the orbital motion amplitude is similar to the parallaxes (1 AU orbit in a period of 1-3 years). Thus for binaries with orbital periods of the order of 1.5 to 2 years (such as post-AGB binaries), the proper motions or parallaxes listed in Gaia DR2 may be quite far from the true values for the system.

4. Nucleosynthesis in binary post-RGB/post-AGB stars

Stellar nucleosynthesis is directly linked and influenced by stellar evolution. Post-AGB binaries commonly show a chemical anomaly in which the photosphere is devoid of refractory elements (e.g., Van Winckel 2003; Venn *et al.* 2014; Gezer *et al.* 2015, and references therein). Although the mechanism to acquire the chemically depleted anomaly is not yet completely understood, the commonly accepted scenario is that, when the circumstellar dust is trapped in a circumbinary disc, the gas, devoid of refractory elements, can be segregated from the dust and be re-accreted onto the photosphere (Waters *et al.* 1992; Van Winckel *et al.* 1998).

Oomen *et al.* (2018, subm.) have shown that post-AGB stars with a high effective temperature (>5500 K) in a wide orbit show depletion, suggesting that re-accretion of material from a circumbinary disc is an ongoing process. It seems, however, that depletion is inefficient for the smaller orbits irrespective of the actual surface temperature.

Kamath & Van Winckel (2018, in prep.) find that photospheric depletion is not only active in luminous post-AGB stars but also in lower luminosity post-RGB stars. This reflects on similar binary properties amongst post-AGB binaries and post-RGB binaries. Figure 5 shows the efficiency of depletion (expressed in terms of the [Zn/Ti] abundance) for both the Galactic and LMC depleted post-AGB/post-RGB sources. The LMC sources (black circles in Fig. 5) have luminosities in the range 2000 $L_\odot$ to 5000 $L_\odot$. This shows that the spread in the efficiency of depletion is independent of luminosity.

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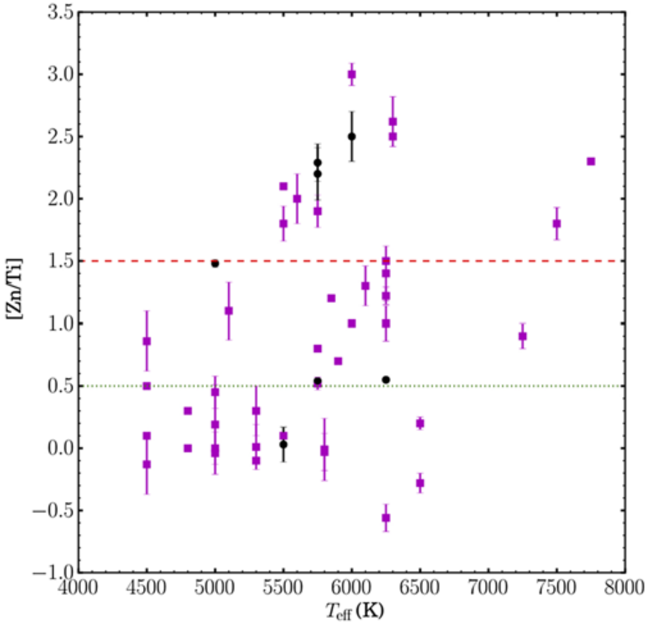

Figure 5. The [Zn/Ti] abundance as a function of $T_{\rm eff}$ for the depleted post-AGB stars in the LMC (black filled circles) and their Galactic analogues (magenta filled squares). The dashed line represent the limit of what we call 'strongly depleted' while the dotted line marks our definition of 'mild depletion'. Figure adapted from Kamath & Van Winckel (2018, in prep.).

Disentangling the likely complex dependence of the efficiency of chemical depletion on a suite of factors such as the effective temperature, luminosity, and the orbital properties of the binary system remains a challenge.

5. The structure and dynamics of the circumstellar environment around post-AGB binaries: the circumbinary disc, jets, and outflows

A review of the state-of-the-art of the studies involving the structure and dynamics of the circumstellar environment around post-AGB binaries is presented in Van Winckel (2017). In this section, I present a few highlights.

IRAS 08544–4431 is a well-studied binary post-AGB star, surrounded by a dusty disc that shows Keplerian rotation. Interferometric studies (Hillen *et al.* 2016; Kluska *et al.* 2018) of IRAS 08544–4431 have imaged the sublimation rim of the circumbinary disc, which has an angular diameter of 15 mas (see attached figure) and is seen at an inclination of 20°. Bujarrabal *et al.* (2018) have identified the rotation of the disc, which has an angular momentum comparable to that of the central binary system. Surprisingly, the system also shows a continuum flux contribution of 4% at 1.65 micron at the location of the secondary component.

Since the photosphere of the secondary is too faint to produce this flux contribution, the exact emitting source remains unknown. Due to the confirmed presence of a high-velocity outflow or jet originating from the secondary component the likely source for the contribution is a circum-companion accretion disc. On-going studies are in place to investigate this.

Ertel *et al.* (2018, in prep.) has resolved the edge-on disc, in the optical, for the post-AGB binary star AR Pup using SPHERE ZIMPOL and IRDIS. This is the second post-AGB disc to be directly imaged after the Red Rectangle.

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Our long-term radial velocity monitoring of evolved stars has revealed that the presence of a high-velocity outflow, or jet, is a common feature in post-AGB binaries. Bollen *et al.* (2017) provides a good illustration and geometric models for the jet found in BD+46 442, a post-AGB binary system. Both simulations and model fitting of the observations show that these jets are not strongly collimated, but are rather wide with half-opening angles >40° (Bollen *et al.* 2017). These high-velocity outflows or jets have a great impact on their surrounding environment and are believed to be the key components for the shaping of bipolar and irregular planetary nebulae.

Though our understanding of the geometry and kinematics of the jet has gained progress, the exact source that feeds the accretion disc around the secondary component, from which the jet is launched remains unknown. Furthermore, the jets around post-AGB stars are rather diverse in nature and understanding the nature of jets in different post-AGB stars and obtaining a physical model for the jet, is a part of our on-going study.

While jets around psost-AGB stars are commonly observed, jets around post-RGB systems are yet to be observed and studied, owing to observational limitations.

6. Evolutionary connection between evolved binaries

Standard theories of stellar evolution predict that PNe are the progeny of post-AGB stars. Low-luminosity PNe, such as the Boomerang Nebula, are considered to be the progeny of post-RGB stars (Sahai *et al.* 2017). However, except for a small sample of PNe that house central stars with periods of the order of a few years (Jones *et al.* 2017), spiralled-in systems are commonly observed in central stars of PNe (Miszalski *et al.* 2011). Moreover, post-AGB stars with discs seem to avoid spiral-in. The exact physical mechanism(s) responsible for spiral-in or avoiding a spiral-in remains unknown.

The evolutionary connection between the enigmatic post-AGB and post-RGB binaries, and other systems whose primary component is a white dwarf (WD) is not straight forward. The latter not only include cataclysmic variables and narrow binaries among central stars of PNe (e.g., Miszalski *et al.* 2011) which did suffer a spiral-in phase, but also wide systems such as symbiotic stars, barium stars, CH-stars, and the more extreme CEMP-s stars (Jorissen 2003; Aoki *et al.* 2007). These wide systems show similar observed period distributions as the post-AGB binaries. The former evolution of the current WD in these systems is unknown making them fossils of unidentified binary interaction processes. Additionally, it is generally accepted that Type Ia supernovae are exploding CO WDs. The formation channels are not very well understood but some are thought to be formed by single degenerate explosions which occur when the massive WD accretes material from a companion (see Maoz *et al.* 2014, and references therein).

Piecing together the evolutionary connection between the zoo of evolved binaries is a major obstacle in the domain of binary stellar evolution.

7. Summary

Post-AGB and Post-RGB binary stars are a class of objects that have evolved off the AGB and RGB, respectively, due to binary interactions. These objects have been discovered in our Galaxy and the Magellanic Clouds. They are a significant population of evolved binaries and hence are ideal tracers of the binary evolution. So far, the binary interaction mechanism to form these objects remains uncertain. However, it can be concluded the circumbinary disc plays a key role in the binary interaction process, and the loss of angular momentum is powered by circumbinary disc. The evidence for disc-star interaction is seen in the observed photospheric properties (chemical depletion), orbital properties (intermediate-range periods, high eccentricities), and the structure and kinematics of their circumstellar environment (e.g., jets, outflows). Furthermore, using interferometric and direct imaging techniques, the circumbinary discs are now resolvable and likely to be second generation proto-planetary discs. The evolutionary connection between the post-AGB/post-RGB binaries and their precursors and progeny remains a long-standing astrophysical puzzle.

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Discussion

Kaminski: What are the masses of stars and circumstellar discs in the post-RGB systems?

Kamath: The dusty post-RGB stars have luminosities below the RGB tip. Depending on the metallicity, their luminosities (while on the post-RGB) range between 500 $L_\odot$ to 2500 $L_\odot$. This typically translates into post-RGB masses of 0.2 to 0.45 $M_\odot$. The disc (circumbinary) mass for post-AGB binaries are about 10^{-3} to 10^{-2} $M_\odot$. We expect that post-RGB circumbinary discs will have similar masses.

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