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REVIEW

Post-AGB stars as tracers of the origin of elements in the universe

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Abstract. The chemical evolution of galaxies is governed by the chemical yields from stars, especially from Asymptotic Giant Branch (AGB) stars. This underlines the importance of understanding how AGB stars produce their elements by obtaining accurate stellar nucleosynthetic yields. Although AGB nucleosynthesis has general validity, critical uncertainties (such as the treatment of convective-driven mixing processes and mass loss) exist in current stellar models. Observations from post-Asymptotic Giant Branch (post-AGB) stars serve as excellent tools to quantify the strongest discrepancies, and eliminate crucial uncertainties that hamper stellar modelling. Our recent studies of post-AGB stars have shown an intriguing chemical diversity that ranges from stars that are extremely enriched in carbon and *s*-process elements to the discovery of the first post-AGB star with no traces of carbon nor *s*-process elements. Additionally, AGB nucleosynthesis is significantly affected by a binary companion. These results reflect the complexity that surrounds the element production in AGB stars. In this review, I will briefly present the intriguing chemical diversity observed in post-AGB stars and its implications on element/isotope production in AGB stars and stellar nucleosynthetic yields.

Keywords. Stars: AGB and post-AGB—stars: chemically peculiar—Magellanic clouds—galaxy: stellar content—stars: abundances—techniques: spectroscopic.

1. Introduction

Hydrogen and helium trace their lineage back to the Big Bang. Elements such as carbon, nitrogen, and about half of the elements heavier than iron, including barium and lead, are manufactured by low- and intermediate-mass (LIM) stars (i.e., ~ 0.8–$8M_{\odot}$). Stars more massive than $\sim 8M_{\odot}$, produce the elements ranging from oxygen to iron, while their explosive death creates the rarest and heaviest elements found in nature including gold and uranium.

It has been estimated that LIM stars produce $\sim 90\%$ of the material injected into interstellar medium because they vastly outnumber massive stars (Sloan *et al.* 2008), making them key contributors to the chemical enrichment of the Universe. In its early stages of life, a LIM star like our Sun produces energy by burning hydrogen into helium. Once the Sun or a Sun-like LIM star has consumed all the hydrogen in its core, the core contracts until it is hot enough to burn helium into carbon. When the helium in the centre has been converted into carbon (and some oxygen), the star expands several hundredfold and begins the Asymptotic Giant Branch (AGB) phase of its life, where it appears as an immense red giant with a distended outer envelope (Herwig 2005). During this phase, the elements and isotopes that are freshly synthesised within the star are brought to the surface through convection-driven mixing processes (Ventura Van Winckel *et al.* 2013; Karakas & Lattanzio 2014). These mixing processes also fuel the synthesis of about half of the elements heavier than iron (e.g., zirconium, barium, europium, lead) through a mechanism that occurs deep in the stellar interior, involving the addition of neutrons onto iron and other elements, i.e. the slow-neutron capture process (*s*-process). However, the enriched stellar

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surface of an AGB star is turbulent, cool and dominated by molecules rather than atoms which makes it difficult to model. The surface is also hidden by an optically thick envelope of circumstellar material. AGB stars are therefore, poor probes of their own nucleosynthesis.

Towards the very end of the AGB phase, stars lose mass via a powerful wind driven by stellar pulsations (Vassiliadis & Wood 1993) or by interaction with another star (for stars in binary systems, Nie *et al.* 2012; Kamath *et al.* 2016). This sheds the entire outer envelope and, for an astronomically brief moment (<10,000 years), the chemically enriched surface of the star is exposed. The star is referred to as a dying or post-Asymptotic Giant Branch (post-AGB) star (Van Winckel 2003). The surface of a post-AGB star retains the signatures of the rich nucleosynthesis during the AGB phase. This makes post-AGB stars formidable probes to examine the elements produced by the star and subsequently gain insight into how these elements are created (De Smedt *et al.* 2012; van Aarle *et al.* 2013; Kamath *et al.* 2014, 2015, 2017). Eventually, the post-AGB star gets hotter, losing trace of its original nucleosynthetic history. It ionizes or lights-up its surrounding gas and its legacy is a collection of spectacular objects, planetary nebulae (De Marco 2009). The chemical content of the Universe is enhanced when this enriched gas is recycled back into the stars' surroundings (Sloan *et al.* 2008).

Although these scenarios for the creation of the elements have general validity, there are several crucial missing pieces and unsolved questions that prevent our advancement in the basic understanding of production of elements and isotopes in LIM stars. Critical uncertainties exist in the theoretical modelling of processes, especially convection, convective-driven mixing processes, and mass loss, that govern the chemically-rich AGB phase for these stars and affect the predicted stellar yields of elements and isotopes. Accurately derived observational parameters using post-AGB stars allow us to constrain crucial uncertainties that plague stellar evolution and nucleosynthesis models, thereby providing a gateway for understanding the production of elements and isotopes in LIM stars.

2. Asymptotic Giant Branch (AGB) nucleosynthesis

During the AGB phase, element production is governed by poorly understood convection-driven mixing processes responsible for: (1) *'third dredge-ups'* wherein material from the hydrogen-exhausted core is mixed into the envelope of the star resulting in an increase of the surface abundance of C and other elements (Karakas & Lattanzio 2014); and (2) *'s-process'* or slow-neutron capture process wherein protons are mixed into the inner layers of the star creating a neutron source which facilitates the production of the slow-neutron capture or *s*-process elements (Busso *et al.* 2001). Stars with initial masses $>2.5M_{\odot}$ (depending on the metallicity) are thought to be sensitive to an additional process; *'hot bottom burning'*, wherein the base of the convective envelope becomes hot enough for proton-capture nucleosynthesis, thereby preventing the formation of C and promoting the production of N and elements such as lithium (Boothroyd *et al.* 1993; Karakas & Lattanzio 2007; Ventura *et al.* 2015).

3. The best tracers of AGB nucleosynthesis

Post-AGB stars, the progeny of AGB stars, contain the products of AGB nucleosynthesis. During the brief post-AGB phase, the warm stellar photosphere makes it possible to quantify photospheric abundances for a very wide range of elements from CNO up to the heaviest *s*-process elements (Reyniers & Van Winckel 2003) that are brought to the stellar surface during the AGB phase. This is not possible with AGB stars since molecular veiling dominates their spectra (Abia *et al.* 2008).

Until 2018, the poorly constrained distances (and hence luminosities and initial masses) to the Galactic post-AGBs has made it difficult to exploit the known Galactic sample. The Magellanic clouds (with accurate distances and hence luminosities and initial masses) make ideal test beds to investigate the AGB evolution and nucleosynthesis as a function of initial mass and metallicity. Our recent extensive low-resolution optical spectral surveys of optically visible post-AGB stars in the LMC (Kamath *et al.* 2015) and SMC (Kamath *et al.* (2014)), with the AAOmega multi-fibre spectrograph mounted on the Anglo Australian telescope resulted in a clean and complete census of well characterized single and binary post-AGBs with spectroscopically determined stellar parameters spanning a wide range in luminosities and hence initial masses. Therefore, these LMC/SMC post-AGB objects provide direct and stringent constraints on the parameters governing single and binary stellar evolution and nucleosynthesis, especially during the chemically-rich AGB phase.

In our recent study (Kamath *et al.* 2020 in-prep), we have capitalised on the *Gaia* DR2 data release (Luri *et al.* 2018) and exploited the Galactic sample of the single post-AGB stars. Though *Gaia* DR2 has provided parallaxes to many of the post-AGB stars in our Galaxy, the parallaxes are derived assuming a single star evolutionary nature. Therefore, the obtained parallaxes from *Gaia* DR2 cannot, as of yet, be used to directly derive distances and hence luminosities to the Galactic post-AGB binaries.

Our current combined sample of Galactic, LMC, and SMC post-AGB stars has allowed us to study element production in single and binary stars as a function of initial mass (the entire low- and intermediate-mass range) and composition (over a wide range of compositions, from the early Universe to the present).

4. The intriguing chemical diversity observed in post-AGB stars

Our pilot studies have shown an interesting chemical diversity (see Figure 1) that ranges from stars that are extremely enriched in carbon and *s*-process elements (De Smedt *et al.* 2012, 2015; van Aarle *et al.* 2013) to the discovery of the first luminous post-AGB star with no traces of carbon nor *s*-process elements (Kamath *et al.* 2017). Additionally, our studies show that stellar nucleosynthesis is significantly affected by a binary companion, resulting in a *depleted* photosphere devoid

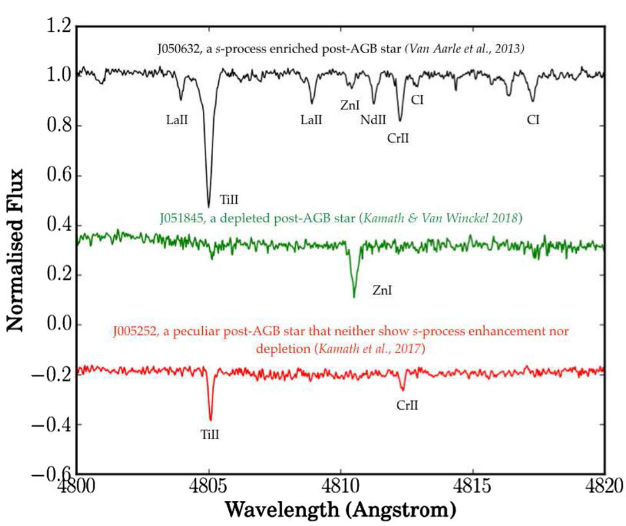

Figure 1. Spectra of three of our post-AGB stars. These spectra are representative of the chemical diversity observed in the current small sample of low-mass post-AGB stars. The spectra of J050632 and J051845 are from UVES/VLT. The spectra of J005252 is from MIKE/Magellan.

of refractory elements (Reyniers & van Winckel 2007; Kamath & Van Winckel 2019). Understanding this chemical diversity remains a challenge since our current sample of well-studied post-AGB stars is small, and targets only a very narrow range in luminosities and hence initial masses ($\sim 1.5 M_{\odot}$), and metallicities ($[Fe/H] \approx -1.5$).

4.1 *Carbon and s-process enrichment in post-AGB stars*

As mentioned in Section 2, owing to the TDU process that occurs during the AGB phase, the AGB phase is considered to house the production of elements such as ^{12}C, ^{14}N and Fe-peak. In-fact, AGB stars are the main contributors to the total ^{12}C and ^{14}N enrichment of galaxies (Romano *et al.* 2010; Kobayashi & Nakasato 2011). The TDU also brings to the stellar surface freshly synthesised products from the slow-neutron capture process (or *s*-process). Standard theories predict that the *s*-process relies on the ^{13}C-pocket which is produced by transport of protons from the convective envelope into the He-rich intershell. The $^{13}C(\alpha, n)^{16}O$ reaction then acts as the main neutron source in low-mass AGB stars, i.e. 1–3$M_{\odot}$, depending on the metallicity (Straniero *et al.* 1995; Gallino *et al.* 1998; Mowlavi *et al.* 1998; Abia *et al.* 2002; Karakas & Lattanzio 2014; Neyskens *et al.* 2015).

Several observational studies of post-AGB stars in the Galaxy and the Magellanic clouds have revealed some of the most C-rich and *s*-process enhanced objects (e.g., Reddy *et al.* 2002; Van Winckel 2003; De Smedt *et al.* 2012; van Aarle *et al.* 2013; De Smedt *et al.* 2015 and references therein.) The majority of these objects also show the 21-micron feature, hence giving them the name '21-micron sources'. The true nature and composition of the 21-micron feature is still unclear.

Although observations confirm that heavy elements can indeed be created by AGB stars, AGB internal nucleosynthesis and associated dredge-up processes are poorly understood. For instance, as shown in Reyniers & van Winckel (2007), De Smedt *et al.* (2014) and De Smedt *et al.* (2015), we find that a low Pb abundance seems to be a common feature in *s*-process rich low mass ($\sim$1–1.5$M_{\odot}$) and low metallicity ($[Fe/H] < -0.7$ dex) post-AGB stars in the Magellanic clouds. This is in contrast to the predicted large overabundances (with respect to other *s*-elements in metal-poor conditions, i.e. [Fe/H] smaller than –1.0 dex) expected from the doubly magic ^{208}Pb

isotope – which is the end product of the *s*-process nucleosynthesis (Gallino *et al.* 1998; Goriely & Mowlavi 2000; Lugaro *et al.* 2012 and references therein). For all Galactic post-AGB stars (with $[Fe/H] > -0.7$ dex), the model predictions are consistent with the deduced upper limits on the Pb abundances (De Smedt *et al.* 2015).

4.2 *Photospheric chemical depletion in post-AGB binary stars*

Extensive observational studies of post-AGB stars has shown that many non-*s*-process enriched post-AGB objects show a characteristic chemical pattern of photospheric depletion of refractory elements in their photosphere whereby elements with a high dust-condensation temperature (such as Fe, Ti, Ca and Cr) are systematically under-abundant (Van Winckel *et al.* 1998; Giridhar *et al.* 2005; Deroo *et al.* 2005; Rao *et al.* 2012; Kamath & Van Winckel 2019). Several studies (e.g., Van Winckel 2003; de Ruyter *et al.* 2006; Gezer *et al.* 2015; Manick *et al.* 2017; Oomen *et al.* 2019) have shown that 'photospheric depletion' is associated with a binary evolution scenario and the best elements to trace depletion are volatile elements such as Zn and S (see Figure 1). The process to acquire this chemical anomaly involves that radiation pressure on the circumstellar dust grains results in a chemical fractionation of dust and gas in the circumstellar environment. The cleaned gas is then re-accreted onto the stellar surface making the photosphere devoid of refractory elements. As a result of this process, the stars display a peculiar photospheric composition similar to the interstellar gas. Waters *et al.* (1992) proposed that the most likely circumstance for the process to occur is when the dust is trapped in a circumstellar disc. In recent studies by Oomen *et al.* (2019, 2020), the authors concluded that accretion from the circumbinary disc accounts for the observed photospheric depletion. However, we are yet to fully understand the interactions between the circumbinary disc and the binary system and how this affects the evolution of post-AGB binary stars.

4.3 *The first observational evidence of star that failed the third dredge-up (TDU)*

In our recent study (Kamath *et al.* 2017), we presented a detailed chemical abundance analysis of J005252, using high-resolution optical spectra (spanning the spectral regions: 3280–4530 Å, 4780–5770 Å and 5800–6810 Å). Our study showed that J005252 is a A-type ($T_{eff} = 8250 \pm 250$ K) luminous ($8200 \pm 700 L_{\odot}$), metal-poor ($[Fe/H] = -1.18 \pm 0.10$), low-mass ($M_{initial} \approx 1.5$–$2.0 M_{\odot}$) post-AGB star in the SMC. Furthermore, our study revealed that J005252 shows an intriguing photospheric composition with no confirmed carbon-enhancement (upper limit of $[C/Fe] < 0.50$) nor enrichment of *s*-process elements (see Figure 1). We derived an oxygen abundance of $[O/Fe] = 0.29 \pm 0.1$. For Fe and O, we took into account the effects of non-local thermodynamic equilibrium (NLTE). We could not derive an upper limit for the nitrogen abundance as there are no useful nitrogen lines within our existing spectral coverage. J005252 does not show signs of photospheric depletion either (see Figure 1).

Based on the derived stellar parameters and inferred evolutionary state of J005252, single star nucleosynthesis models (Fishlock *et al.* 2014; Ventura *et al.* 2015; Cristallo *et al.* 2015) predict that this star should have undergone TDU episodes while on the AGB and be C-enriched. However, our observations are in contrast with these predictions. Therefore, as concluded in (Kamath *et al.* 2017), J005252 very likely reveals a new stellar evolutionary channel whereby a star evolves without any of the chemical enrichments associated with third dredge-up episodes.

4.4 *s-process rich versus non s-process rich single post-AGB stars*

The Galactic sample of single post-AGB stars in our Galaxy has shown that they can be classified into two groups: those with enhanced *s*-process elements (with an average [S/Fe] of around 1.5 dex), as expected from third dredge-up on the AGB and those without *s*-process enhancements (Van Winckel 2003). The average [C/Fe] values of the *s*-process enhnaced group of stars is around 0.9 dex. The non *s*-process enhanced stars show an average [C/Fe] or around 0.3 dex. Both groups cover a range in metallicities with $-1.4 < [Fe/H] < -0.2$. For over two and a half decades, the bimodal *s*-process abundance distribution observed in Galactic single post-AGB stars remained a mystery due to the unknown distances (and hence luminosities and initial masses) of the Galactic sample. In our recent study (Kamath *et al.* 2020 in-prep),

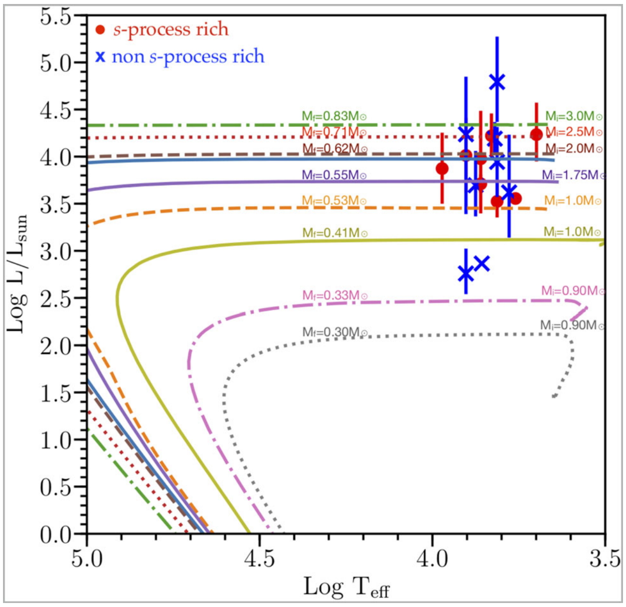

Figure 2. HR diagram for the Galactic sample of single post-AGB stars. The plot shows the position of the *s*-process enhanced group of stars (in red) and the non *s*-process enhnaced group of stars (in blue). Shown are the evolutionary tracks of Miller Bertolami (2016) for post-AGB stars and Driebe *et al.* (1998) for post-RGB stars, along with initial and final masses.

we capitalised on the *Gaia* DR2 distances to the Galactic sample of single post-AGB stars and estimated accurate luminosities and hence intial masses.

Our study (Kamath *et al.* 2020 in-prep) has revealed a spectacular result: there is no significant luminosity (and hence initial mass) difference between the *s*-process rich and the non *s*-process rich post-AGBs, as is shown in the HR diagram (see Figure 2). This shows that the compositional differences between the two groups does not depend on initial or final mass, which is contrary to expectations. This points to a more complex third dredge-up and *s*-process nucleosynthesis.

5. Discrepancies between the observed and predicted abundances of post-AGB stars

In our past studies (De Smedt *et al.* 2014, 2015), we compared abundances derived from a small group of post-AGB stars (which were of 1 to 1.5 solar masses) to a dedicated suite of theoretical stellar models. We found that while the predicted ^{12}C abundance is compatible with the observations, the predicted ^{16}O abundance is significantly lower, resulting in a predicted carbon over oxygen ratio (C/O) of $\sim$18 to 20, which is significantly higher than the observed C/O $\sim$ 2. The discovery of stars that have failed the TDU (Kamath *et al.* 2017) and also stars that are non *s*-process enriched (Kamath *et al.* 2020 in-prep) have raised several intriguing questions regarding the efficiency of the TDU and the *s*-process. These discrepancies indicate that there is a critical gap in the treatment of mixing in both the envelope and the deeper interior, as well as the neutron capture nucleosynthesis.

Additionally, our studies also showed that the predicted abundance of lead (Pb), which is double magic and the end product of the *s*-process nucleosynthesis, is significantly higher than the observed one. This motivated Lugaro *et al.* (2015) to explore modifications to the current scenario of *s*-process in these stars. They concluded that a delayed neutron capture nucleosynthetic process occurring during the post-AGB phase of evolution (Herwig *et al.* 2011), is likely to be responsible for the observed abundances of lead and other s-process elements. To test this delayed nucleosynthesis scenario and identify other discrepancies, a systematic confrontation of the models with a comprehensive observational dataset is crucial.

6. Conclusion

Understanding the production of elements from LIM stars, especially during the AGB phase, is crucial to reconstruct the processes that lead to the formation and chemical evolution of our and other galaxies.

Current studies of post-AGB stars have shown an intriguing chemical diversity that ranges from stars that are extremely enriched in carbon and *s*-process elements to the discovery of the first post-AGB star with no traces of carbon nor *s*-process elements. Additionally, stellar nucleosynthesis is significantly affected by a binary companion. These results reflect the complexity that surrounds the element production in these stars.

To understand AGB nucleosynthesis, demystify the star-to-star variation, and quantify the effect of binarity on nucleosynthesis, a systematic and statistically-relevant chemical abundance study of post-AGB stars covering a wide range of initial masses and metallicity environments (e.g., LMC, SMC, and our Galaxy) is critical.

Through our current on-going studies we are aiming to systematically increase the observational sample of post-AGB stars so as to obtain observationally derived abundances of C, N, Fe-peak, and *s*-process elements, and feasible isotopic ratios, as a function of a wide range of initial masses and metallicites. By specifically studying intermediate-mass post-AGB stars, we are also targeting a very specific and vital missing piece in the AGB nucleosynthesis puzzle: the minimum mass required for Hot Bottom Burning to come alive in AGB stars. Such a dataset will also allow us to make advances in unifying the treatment of crucial processes (e.g., convection, mixing processes, mass loss) that govern the element production in the suite of stellar models that currently exists.

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