Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY

MNRAS **458,** L118–L122 (2016) doi:10.1093/mnrasl/slw029
Advance Access publication 2016 February 19

Probing O-enrichment in C-rich dust planetary nebulae

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Accepted 2016 February 16. Received 2016 February 16; in original form 2015 December 22

ABSTRACT

The abundance of O in planetary nebulae (PNe) has been historically used as a metallicity indicator of the interstellar medium (ISM), where they originated; e.g. it has been widely used to study metallicity gradients in our Galaxy and beyond. However, clear observational evidence for O self-enrichment in low-metallicity Galactic PNe with C-rich dust has been recently reported. Here, we report asymptotic giant branch (AGB) nucleosynthesis predictions for the abundances of the CNO elements and helium in the metallicity range $Z_{\odot}/4 < Z < 2\,Z_{\odot}$. Our AGB models, with diffusive overshooting from all the convective borders, predict that O is overproduced in low-Z low-mass ($\sim$1–3 $M_{\odot}$) AGB stars and nicely reproduce the recent O overabundances observed in C-rich dust PNe. This confirms that O is not always a good proxy of the original ISM metallicity and other chemical elements such as Cl or Ar should be used instead. The production of oxygen by low-mass stars should be thus considered in galactic-evolution models.

Key words: nuclear reactions, nucleosynthesis, abundances – ISM: abundances – H II regions – planetary nebulae: general – Galaxy: abundances.

1 INTRODUCTION

Stars in the mass range $1\,M_{\odot} < M < 8\,M_{\odot}$ evolve through the asymptotic giant branch (AGB), just before they form planetary nebulae (PNe) and end their lives as white dwarfs. AGB stars are supported by H burning, which is periodically interrupted by shell He burning above the degenerate core, where 3α nucleosynthesis takes place; the so-called thermal pulses (e.g. Schwarzschild & Harm 1965). The main processes of nucleosynthesis take place during the thermally pulsing (TP) AGB phase. The H and He burning shell products are transported to the stars' surface via the third dredge-up (TDU) during the TP-AGB, converting originally O-rich stars into C-rich ones. Also, the stellar outer layers can be enriched in products of the so-called hot bottom burning (HBB, e.g. Sackmann & Boothroyd 1992; Mazzitelli, D'Antona & Ventura 1999) process for the more massive ($M > 3$–$4\,M_{\odot}$) AGB stars (e.g. García-Hernández et al. 2007), which avoids the formation of C-rich stars. At the end of the AGB phase, low-mass ($\sim$1.5–3.4 $M_{\odot}$) stars are predicted to be C-rich (C/O > 1), while more massive stars, because of HBB activation, would remain O-rich (C/O < 1) during the entire AGB evolution.

The theoretical modelling of AGB stars has been significantly improved in the last years; the last generation of AGB models even including dust formation (e.g. Nanni et al. 2013; Ventura et al. 2014b). There exist, however, important differences among the results obtained from different AGB models. This is mainly due to our poor knowledge of stellar convection and mass-loss, which profoundly affects the nucleosynthesis results obtained (Ventura & D'Antona 2005a,b; Doherty et al. 2014a,b). We are still far from a self-consistent and physically sound treatment of both processes. The only way to make a significant progress is to compare theoretical expectations with the observational evidence.

The chemical composition of PNe proves an extremely useful and valuable tool to constrain AGB models (Marigo et al. 2003, 2011; Stanghellini et al. 2009; Ventura et al. 2015); the chemistry of PNe is the outcome of the combination of the different processes that contribute to alter the surface chemical composition during the whole AGB life. In addition, PNe – because of their emission-line nature – are easily observed at very large distances, and the gas chemical composition can be derived. Some chemical elements (e.g. Ar and Cl) may remain practically unchanged in PNe, reflecting the primordial composition of the interstellar medium (ISM) where their central stars were born. Other elements like C and N (to a lesser extent O), however, may be strongly modified during the previous AGB phase. The O abundance in PNe has been widely used as a metallicity indicator of the ISM where they originated;

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e.g. to derive metallicity gradients in our own Galaxy and other nearby galaxies (e.g. Perinotto & Morbidelli 2006; Maciel & Costa 2010; Stanghellini et al. 2014; Richer 2015). This is because 'standard' (with no extra-mixing processes) nucleosynthesis theoretical models of low- and intermediate-mass stars available in the literature (e.g. Karakas 2010) do not predict significant O-enrichment (or destruction) at near-solar metallicities during the AGB phase.

However, by using high-quality optical spectra in conjunction with the best available ionization correction factors (ICFs), Delgado-Inglada et al. (2015) have very recently reported the first observational evidence of O self-enrichment (by ∼0.3 dex) in Galactic PNe with C-rich dust; the expected outcome of low-mass (∼1.5–3 $M_\odot$) stars. As we mentioned above, the AGB nucleosynthesis theoretical models with no extra-mixing processes do not predict such O-enrichment in low-mass stars. Models that include diffusive convective overshooting (e.g. Herwig et al. 1997; Marigo 2001)[1] predict a significant production of oxygen, even at solar metallicities. This mixing process (first introduced by Herwig et al. 1997) in combination with an efficient TDU, may produce an increase of the O abundance for low-mass (∼1.5–3 $M_\odot$) stars. Rotation, magnetic fields, and thermohaline mixing are other mechanisms, even less understood, that may cause extra-mixing (e.g. Karakas & Lattanzio 2014). Here, we report self-consistent AGB nucleosynthesis predictions (based on the ATON code) for the CNO elements and He in the metallicity range $Z_\odot/4 < Z < 2\,Z_\odot$. Our AGB models predict that O is overproduced in low-mass AGB stars and nicely reproduce the recent O overabundances observed in C-rich dust PNe by Delgado-Inglada et al. (2015).

2 THE AGB ATON MODELS

The AGB models presented here are computed with the stellar evolution ATON code (Mazzitelli 1989). The numerical structure of ATON is given by Ventura et al. (1998), while Ventura & D'Antona (2009) reported the most recent updates in the code. A detailed description (i.e. numerical and physical input) of these AGB ATON models and discussion in terms of the evolution of the surface chemistry during the AGB phase – the role of mass and metallicity, the evolution of CNO elements, etc. – will be presented in Ventura et al. (in preparation). Here, we concentrate on the abundances of He, CNO elements and Cl (taken as a metallicity indicator) at the end of the AGB phase and their comparison with the corresponding abundances observed in C-rich dust PNe (see Section 4).

Briefly, the AGB ATON models are calculated using the following physical ingredients: (i) convection is modelled according to the full spectrum of turbulence model (Canuto & Mazzitelli 1991). In regions unstable to convection, mixing of chemical and nuclear burning is coupled by a diffusion-like equation (Cloutman & Eoll 1976). Overshoot of convective eddies into radiatively stable regions follows an exponential decay of velocities from the border of the convective zones (which is fixed via the Schwarzschild criterion) with the e-folding distance of the decay given by $\zeta H_p = 0.002$ (Ventura et al. 2014b);[2] (ii) the Blöcker (1995) and Wachter et al. (2002) mass-loss prescriptions are used for O- and C-rich AGB stars, respectively; (iii) the molecular opacities at low temperatures ($<10^4$ K) are calculated with the AESOPUS tool (Marigo & Aringer 2009); this is especially important for the description of the C-rich phase (Ventura & Marigo 2010).

[1] We note that the Pignatari et al. (2013) models also seem to predict O production at the level observed in C-rich dust PNe but these models have not been accepted for publication yet.

[2] The use of $\zeta = 0.002$ mimics overshoot from the base of the convective envelope and from the borders of the convective shell forming at the ignition of each thermal pulse (see Ventura et al. 2014b, for more details).

Table 1. Chemical properties of AGB ATON models.

Z	Y	[α/*Fe*]	M_C	M_{HBB}	M_{up}
4×10^{-3}	0.25	+0.2	1.1	3.5	6.0
8×10^{-3}	0.26	+0.2	1.2	3.5	6.0
0.018	0.28	0.0	1.4	3.5	5.5
0.04	0.30	0.0	–	4.0	4.0

Table 1 summarizes the initial chemical composition of the AGB ATON models. They cover all progenitor masses (i.e. $1\,M_\odot \leq M \leq 8\,M_\odot$) of stars evolving through the AGB phase from subsolar to supersolar metallicity ($Z = 4 \times 10^{-3}$, 8×10^{-3}, 0.018 and 0.04). The low-Z models presented here, including the discussion of the evolutionary sequences, are extensively illustrated in Ventura et al. (2014a) ($Z = 4 \times 10^{-3}$), Ventura et al. (2013) ($Z = 8 \times 10^{-3}$; $M \geq 3\,M_\odot$) and Ventura et al. (2014b) ($Z = 8 \times 10^{-3}$; $M \leq 3\,M_\odot$). The solar/supersolar metallicity models have been calculated appositely for the present analysis (see Ventura et al. in preparation, for more details). An α-enhancement [α/Fe] = +0.2 is used for the two lower metallicities, while the chemical mixture for the $Z = 0.018$ and 0.04 models is solar-scaled. The solar composition from Grevesse & Sauval (1998) is assumed. We note that the He abundance and the abundance ratios studied here are consistent with similar models calculated with more recent solar abundances (e.g. Asplund et al. 2009).

3 BRIEF OVERVIEW OF THE AGB ATON MODEL PREDICTIONS

3.1 Changes in the AGB chemistry: TDU and HBB

The surface abundances of AGB stars are altered by TDU and HBB (see e.g. Karakas & Lattanzio 2014). The TDU is the mixing of nuclearly processed matter with the external regions and mainly increases the surface C abundance (also O but to a lesser extent). The HBB, however, is activated at the base of the convective envelope for $T_{bce} \gtrsim 30$ MK and favours CN nucleosynthesis (N production); for $T_{bce} \gtrsim 80$ MK, full CNO cycling is activated, which further produces N at the expenses of C and O. The efficiency of TDU and HBB mainly depends on the initial stellar mass and metallicity although the model results are highly sensitive to the treatment of the convective borders and to the adopted model for convection.

Both TDU and HBB mechanisms are more efficient at lower metallicity (e.g. the HBB temperatures decrease with increasing metallicity and the high-Z models experience less extended nucleosynthesis). We may distinguish three main cases depending on the progenitor masses: (i) stars with progenitor masses higher than M_{up} experience strong HBB at $T_{bce} \gtrsim 80$ MK and limited TDU; He (mostly due to the second dredge-up, SDU) and N are enhanced with C and O being destroyed. The threshold mass, M_{up}, increases with decreasing metallicity (Table 1); (ii) stars with progenitor mass between M_{HBB} and M_{up} also experience HBB but TDU is more efficient than in their higher mass counterparts; the lower metallicity models experience a few late TDU episodes that may convert the star into C-rich. In all models N is enhanced together with some He enrichment (again from the SDU) but C and O may be created or destroyed depending on the dominant mechanism (TDU or HBB).

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The mass limit for HBB activation, $M_{\rm HBB}$, increases with increasing metallicity (Table 1); (iii) stars with progenitor mass lower than $M_{\rm HBB}$ do not experience HBB because $T_{\rm bce} < 30$ MK and TDU dominates their chemistry, mainly increasing the surface C content (and O at a smaller extent). The minimum mass to form C-rich stars,[3] $M_{\rm C}$, decreases with decreasing metallicity (Table 1) because at lower metallicity, TDU is more efficient and less carbon is needed to attain the C-star stage.

3.2 Surface chemistry at the end of the AGB

The temporal evolution of the surface chemistry of the AGB ATON models allows us to calculate the yields of the different chemical elements (see Ventura et al. in preparation, for a full discussion on this). However, the interpretation of nebular abundances in PNe requires the surface mass fractions (or surface abundances) of the various chemical elements at the end of the AGB phase.

The final HeCNOCl surface abundances of the AGB ATON models used in the present analysis are shown in the four panels of Fig. 1. We show also the chlorine abundance together with He and the CNO elements because Cl is taken as a good metallicity indicator by Delgado-Inglada et al. (2015). Chlorine is not expected to undergo any processing during the AGB evolution, remaining constant during the whole life of the star. The surface Cl abundance is therefore representative of the gas from which the star was formed. It is to be noted here that for consistency with the AGB ATON models, we consider the solar Cl abundance of $12 + \log(Cl/H) = 5.50$ (Grevesse & Sauval 1998),[4] while Delgado-Inglada et al. (2015) considered a lower solar Cl abundance of $12 + \log(Cl/H) = 5.26$, as recommended by Lodders (2003). This means that all C-rich dust PNe in their sample are of subsolar metallicity here,[5] while Delgado-Inglada et al. (2015) considered the few most Cl-rich objects as near-solar metallicity PNe.

Fig. 1 shows the final N and O abundances and the C/O and N/O ratios versus Cl and/or He in our AGB ATON models compared with the observations of C-rich dust PNe by Delgado-Inglada et al. (2015).[6] Lower metallicity models cover a wider range of N and O compared to their solar and supersolar counterparts (see the top panels in Fig. 1). The reason for this is twofold: (a) in the massive AGB domain, lower-Z models experience a stronger HBB, which favours lower O and higher N; (b) in the low-mass regime the efficiency of TDU is higher, the lower is the metallicity, which favours the O increase and the production of primary N (see also Section 3.1). In the ATON models, the individual C and O abundances are extremely sensitive to the metallicity, but the C/O ratio is similar for the four metallicities; the highest C/O ratio (over a factor of 10 higher than in the initial mixture) is found in the $Z = 4 \times 10^{-3}$ models, as expected. The interpretation of the N/O versus He plane (right-bottom panel of Fig. 1) is less straightforward. The N/O ratio is generally used as an HBB strength indicator, while He is connected to the inwards penetration of the convective envelope during the SDU. The SDU efficiency (which increases He at the stellar surface) mainly increases with increasing stellar mass (Ventura 2010). Thus, the model predictions are distributed dychotomically in the N/O versus He plane. Low-mass AGB stars define an approximately vertical sequence at constant He (no SDU is expected below $\sim 4\,M_\odot$ and variable N/O ($\lesssim 0.3$)), while higher mass HBB stars are spread in the high N/O and He region.

4 UNDERSTANDING O-ENRICHMENT IN C-RICH DUST PNE

The C-rich dust PNe sample (seven objects) of Delgado-Inglada et al. (2015) span a range of metallicities, as traced by the Cl content, extending over one order of magnitude. Most C-rich dust PNe (five sources), however, display subsolar Cl abundances of $12 + \log(\rm Cl/H) \sim 4.9$–$5.0$ dex. The other two objects are Hu 2−1 ($12 + \log(\rm Cl/H) = 4.68$ dex) and NGC 6826 ($12 + \log(\rm Cl/H) = 5.19$ dex). The more metal-rich PN (NGC 6826) is suspected to have a binary companion (Méndez 1989), which might produce its carbon enrichment, and we do not consider it in the subsequent discussion.

Fig. 1 shows that the chemical composition of five out of the six low-metallicity C-rich dust PNe is nicely reproduced by our low-mass ($\sim$1–3 $M_\odot$) models of metallicity $Z = 8 \times 10^{-3}$. The theoretical predictions account for the slight O enhancement (by $\sim$0.2–0.3 dex) observed in these PNe, but also for the N and He abundances as well as for the C/O and N/O ratios. The chemical composition of the lowest metallicity PN (Hu 2−1) is also nicely reproduced by our lowest metallicity models ($Z = 4 \times 10^{-3}$), with the exception of He that is more abundant than predicted. Higher mass ($M > 3\,M_\odot$) models experience HBB (marked with open symbols in Fig. 1) with the consequent decrease of C, leading to C/O<1. These models do not predict the observed O-enrichment neither the N/Cl and N/O ratios (and He abundances). Therefore, we do not expect C-rich dust PNe arise from high-mass progenitors. As far as we know, our models are the first ones giving a self-consistent explanation for the O-enrichment observed in C-rich dust PNe. Also, our AGB models, when coupled with dust formation, predict these objects to be rich in C dust (see e.g. Ventura et al. 2015), as observed.

In short, the main difference between the ATON models and another published AGB models[7] is that ATON assumes extra-mixing (diffusive overshooting) from all the convective borders, including the bottom of the convective shell, while other models use only overshoot from the base of the convective envelope. When the extra-mixing from the convective shell is used, the pulse is stronger (which also leads to a more penetrating TDU) and convection reaches more internal layers, where the oxygen content is higher. Herwig et al. (1997) also assume a tiny overshoot (comparable to ATON) at the base of the pulse-driven convective zone but their overshoot from the base of the convective zone is much higher than in ATON. Unfortunately, Herwig et al. (1997) did not report the final O surface abundances predicted by their 3 $M_\odot$ solar metallicity AGB models. Their treatment of boundaries of convective regions leads to intershell abundances of typically (^{4}He/^{12}C/^{16}O) = (23/50/25) [compared to (70/26/1) in the standard treatment], while intershell abundances of (50/37/6) are obtained in our ATON model (2 $M_\odot$,

[3] Stars with initial mass lower than $M_{\rm C}$ are not converted to C-rich (C/O > 1) because their chemistry is only affected by the first dredge-up during the red giant branch.

[4] This also corresponds to the most recent solar Cl abundance as determined by Asplund et al. (2009).

[5] This is in perfect agreement with García-Hernández & Górny (2014), who derived homogeneously the Cl and Ar abundances in a large sample of C-rich dust Galactic PNe.

[6] The abundances of C, Cl, He and O were obtained using the ICFs derived by Delgado-Inglada, Morisset & Stasińska (2014) for PNe. The N abundances were computed using the classical expression $\rm N/O = N^+/O^+$ that seems to work better (see the discussion in Delgado-Inglada et al. 2015).

[7] The Marigo (2001) AGB models are based on synthetic computations, which renders difficult a straight comparison with our ATON results, rather based on a self-consistent description of the whole stellar structure.

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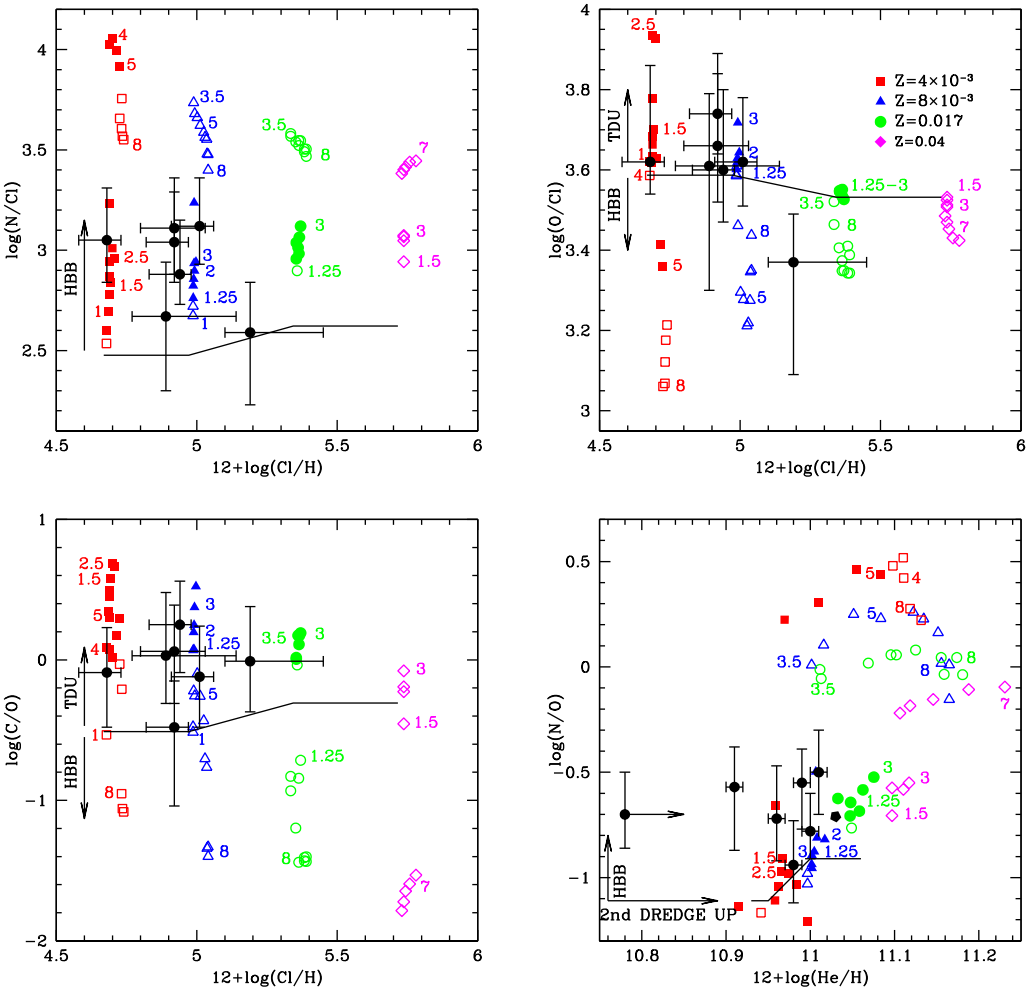

Figure 1. Chemical abundances in Galactic C-rich dust PNe (black dots, Delgado-Inglada et al. 2015) versus the ATON AGB model predictions for different masses (a few relevant masses are marked) and metallicities: Cl versus N/Cl (top, left), Cl versus O/Cl (top, right), Cl versus C/O (bottom, left), He versus N/O (bottom, right). The thin, solid lines indicate the assumed initial abundances, while the arrows indicate the qualitative effect of HBB, SDU and TDU. Filled and open symbols correspond to C- and O-rich stars, respectively. The black pentagon (bottom-right panel) is the median abundance of Galactic C-rich dust PNe measured by García-Hernández & Górny (2014).

$Z = 0.004$) undergoing the largest O-enrichment. Thus, we would expect the Herwig et al. (1997) models to predict more surface O than observed in C-rich dust PNe.

The characterization of the formation epoch and of the progenitor masses is hampered by uncertainties associated with the individual abundances, particularly of the C/O ratio. In addition, the formation epoch estimates are model dependent; e.g. the ATON evolutionary time-scales are generally much shorter than the Karakas (2010) models. We may conclude, conservatively and according to ATON, that these C-rich dust PNe descend from stars of initial mass in the range $1.5\,M_{\odot} < M < 3\,M_{\odot}$, formed between ∼400 Myr and 2 Gyr ago. If we assume the recommended C/O values given by Delgado-Inglada et al. (2015), we may rule out progenitors more massive than $2\,M_{\odot}$; indeed models of mass $M \geq 2.5\,M_{\odot}$ undergo the most noticeable variation in the surface chemical composition, reaching C/O∼3, which is significantly higher than the maximum C/O observed in these C-rich dust PNe (i.e. C/O∼1.8 in PN IC 418). This upper limit to the observed C/O in C-rich dust PNe, if confirmed, would suggest an even narrower range of progenitor masses, namely $1.5\,M_{\odot} \leq M \leq 2\,M_{\odot}$, with formation epochs extending from ∼1 to 2 Gyr ago. This finding is in agreement with recent results on similar low-metallicity C-rich dust PNe in the Large Magellanic Cloud (Ventura et al. 2015), which show C/O ratios below 2 and identical C-rich dust features in their mid-IR Spitzer spectra (Stanghellini et al. 2007).

In summary, our AGB models with extra-mixing (diffusive overshooting) from all the convective borders (including the bottom of the convective shell) predict that O is overproduced in low-Z low-mass (∼1–3 $M_{\odot}$) AGB stars and nicely reproduce the O overabundances observed in C-rich dust PNe as well as their N and He abundances and CNO abundance ratios. This shows that O is not always a good proxy of the original ISM metallicity and other chemical elements such as Cl or Ar should be used instead. Oxygen production by low-mass stars should be thus considered in galactic chemical evolution models.

ACKNOWLEDGEMENTS

DAGH was funded by the Ramón y Cajal fellowship number RYC−2013−14182 and he acknowledges support provided by the Spanish Ministry of Economy and Competitiveness (MINECO) under grant AYA−2014−58082-P. PV was supported by PRIN

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MIUR 2011 'The Chemical and Dynamical Evolution of the Milky Way and Local Group Galaxies' (PI: F. Matteucci), prot. 2010LY5N2T. GDI acknowledges support from the Mexican CONACYT grant CB−2014−241732.

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