




Research Article

s-process enriched post-AGB star J003643.94–723722.1 in the SMC with an extreme C/O ratio and the first precise detection of lead

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Abstract

Post-asymptotic giant branch (post-AGB) stars are exquisite tracers of *s*-process nucleosynthesis, preserving the surface chemical signatures of their AGB evolution. The increasing chemical diversity observed among them challenges current nucleosynthesis models and motivates detailed case studies. In this study, we present a comprehensive abundance analysis of J003643.94–723722.1 (J003643), a single post-AGB star in the Small Magellanic Cloud (SMC). High-resolution UVES/VLT spectra analysed with E-iSpec reveal a C/O ratio of 16.21 and an $[s/Fe] = 2.09 \pm 0.20$ dex. In this study, we also report the first direct detection of lead in a post-AGB star via the Pb II 5 608.853 Å line, with a derived $[Pb/Fe] = 3.18$ dex. Comparison with a comprehensive and appropriate sample of post-AGB stars across the Galaxy, Large Magellanic Cloud (LMC) and SMC shows that J003643 has a relatively high C/O ratio, far exceeding the typical range of ~ 1 –3. J003643's $[C/Fe]$ (1.33 ± 0.14 dex) and $[s/Fe]$ (2.09 ± 0.20 dex) are consistent with expectations from standard third dredge-up (TDU) enrichment. However, its $[O/Fe]$ (-0.08 ± 0.20 dex) is significantly lower than that of the comparative sample with similar $[C/Fe]$ and $[Fe/H]$, which typically show $[O/Fe]$ between 0.5 and 1.0 dex. This relatively low $[O/Fe]$, along with an $[\alpha/Fe] \approx 0$ dex of J003643, is consistent with the chemical evolution of the SMC at $[Fe/H] \approx -1$ dex, in contrast to the oxygen-enhanced Galactic and LMC trend at $[Fe/H] \approx -1$ dex. This indicates that J003643's high C/O ratio primarily results from its intrinsic oxygen deficiency rather than from an unusually high carbon enhancement. To better understand the CNO, alpha, Fe-peak, and heavy element nucleosynthesis, we compared J003643's abundance pattern with yields from three stellar evolutionary codes: ATON, MONASH, and FRUITY, the latter two incorporating post-processing nucleosynthesis. While these models reproduce the majority of elemental abundances, they significantly underpredict the Pb abundance, highlighting a persistent gap in our understanding of heavy element production in AGB stars. J003643 represents the second *s*-process enriched single post-AGB star known in the SMC, stressing the need for more such observations. Its photospheric chemistry reflects the growing chemical diversity among post-AGB stars and reinforces the complexity of AGB nucleosynthesis beyond current theoretical models.

Keywords: Stars: evolution; AGB and post-AGB; chemically peculiar; abundances; techniques: spectroscopic; galaxies: Magellanic Clouds

(Received 24 June 2025; revised 29 July 2025; accepted 21 August 2025)

1. Introduction

The origin of heavy elements beyond iron ($A > 60$) is primarily attributed to neutron-capture nucleosynthesis, with the slow neutron-capture process (*s*-process) playing a dominant role in low- and intermediate-mass stars (~ 0.8 – $8 M_{\odot}$). The *s*-process operates under lower neutron densities ($n \lesssim 10^{12} \text{ cm}^{-3}$) and over longer timescales, allowing unstable nuclei to undergo β -decay between successive neutron captures (see Iben 1974; Busso, Gallino, & Wasserburg 1999; Lugaro et al. 2023, references therein). Asymptotic giant branch (AGB) stars are well established

as the primary astrophysical site for the *s*-process (e.g. Gallino et al. 1998; Lugaro et al. 2003; Herwig 2005; Karakas & Lattanzio 2014). The detection of technetium (Tc), a short-lived radioactive element produced by the *s*-process, in the atmospheres of AGB stars provides compelling observational evidence of ongoing *s*-process nucleosynthesis during this phase (Merrill 1952; Werner et al. 2015; Shetye et al. 2020). The *s*-process proceeds along the valley of β -stability and is typically categorised into three components based on neutron exposure: the weak component synthesises light *s*-process (ls) elements (e.g. Sr, Y, Zr), the main component synthesises heavier *s*-process (hs) elements (e.g. Ba, La, Nd); and the strong component is responsible for the heaviest stable *s*-process elements, including Pb and Bi (e.g. Lugaro et al. 2012; Karakas & Lattanzio 2014). The $[hs/ls]$ ratio is widely used as a diagnostic of neutron exposure and *s*-process efficiency during AGB nucleosynthesis.

However, observationally constraining AGB nucleosynthesis remains challenging due to the extended, pulsating atmospheres,

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Cite this article: Menon M, Kamath D, Mohorian M, Amarsi AM, Vescovi D, Cristallo S, Karakas A, Van Winckel H and Ventura P. (2025) *s*-process enriched post-AGB star J003643.94–723722.1 in the SMC with an extreme C/O ratio and the first precise detection of lead. *Publications of the Astronomical Society of Australia* 42, e122, 1–21. <https://doi.org/10.1017/pasa.2025.10085>

strong mass loss, molecular opacities, and circumstellar dust envelopes of AGB stars (Abia, de Laverny, & Wahlin 2008; Pérez-Mesa *et al.* 2019). Post-asymptotic giant branch (post-AGB) stars offer a valuable alternative. These luminous, short-lived objects have recently departed the AGB and retain surface compositions reflective of their prior nucleosynthetic histories (see Van Winckel 2003; Kamath *et al.* 2022, 2023). Their relatively high photospheric temperatures ($T_{\text{eff}} \sim 3\,000\text{--}30\,000\text{ K}$) allows access to a wide range of atomic lines in the optical regime, enabling detailed chemical abundance analyses of elements from CNO to heavy *s*-process elements well beyond the Ba peak (e.g. Van Winckel & Reyniers 2000; van Aarle *et al.* 2011; De Smedt *et al.* 2012, 2015, 2016; Kamath *et al.* 2022). These properties make post-AGB stars exquisite targets for constraining stellar evolution and nucleosynthesis models (Kamath & Van Winckel 2022).

To date, ~ 18 single *s*-process enriched post-AGB stars have been well studied in the Galaxy (see Kamath *et al.* 2022, and references therein) ~ 1 in the Small Magellanic Cloud (SMC) (e.g. De Smedt *et al.* 2012) and ~ 6 in the Large Magellanic Cloud (LMC) (e.g. van Aarle *et al.* 2011; De Smedt *et al.* 2012, 2015). Analyses of these stars have uncovered significant discrepancies between observed surface abundances and those predicted by theoretical nucleosynthesis models. These discrepancies have sparked renewed interest in alternative neutron-capture processes. This has motivated the proposal of the intermediate neutron-capture process (*i*-process), which operates at neutron densities between those of the *s*-process and *r*-process ($n \sim 10^{13}\text{--}10^{15}\text{ cm}^{-3}$) (see Hampel *et al.* 2016; Choplin, Siess, & Goriely 2021; Choplin *et al.* 2024, references therein). These models show promising agreement for elements between the first and second *s*-process peaks. However, the success of such models often hinges on finely tuned parameters such as overshoot efficiencies or neutron exposures, limiting their general applicability. Notably, even in models that match the general abundance trends, significant discrepancies remain for lead (Pb), highlighting its role as a particularly sensitive diagnostic of neutron-capture processes – especially in metal-poor environments (Kamath & Van Winckel 2021).

Previous abundance studies of single *s*-process enriched post-AGB stars have been valuable but often piecemeal. A recent study by Kamath *et al.* (2022) analysed a larger, comprehensive Galactic sample of ~ 30 single post-AGB stars, with luminosities and initial masses derived from Gaia DR3 parallaxes. This study exemplifies the remarkable chemical diversity among stars with similar stellar parameters and luminosities, revealing both *s*-process enriched and non-enriched stars, and challenging existing paradigms of AGB nucleosynthesis. Furthermore, the discovery of *s*-process enriched post-AGB binaries in both the Galaxy and the MCs further complicates the picture (Menon *et al.* 2024). Together, these findings point to a more nuanced and diverse range of neutron-capture signatures than previously appreciated.

The growing body of observational and theoretical work on post-AGB stars highlights that each star may reflect a distinct nucleosynthetic history (see e.g. Kamath *et al.* 2022, 2023; Menon *et al.* 2024). While large-sample studies reveal population-wide trends, detailed studies of individual stars remain essential for decoding the complex interplay of processes that shape surface abundances.

In this work, we present a detailed chemical abundance analysis of J003643.94–723722.1 (hereafter J003643), the most carbon-rich and one of the most *s*-process enriched post-AGB stars identified in the Small Magellanic Cloud (SMC). We compare the

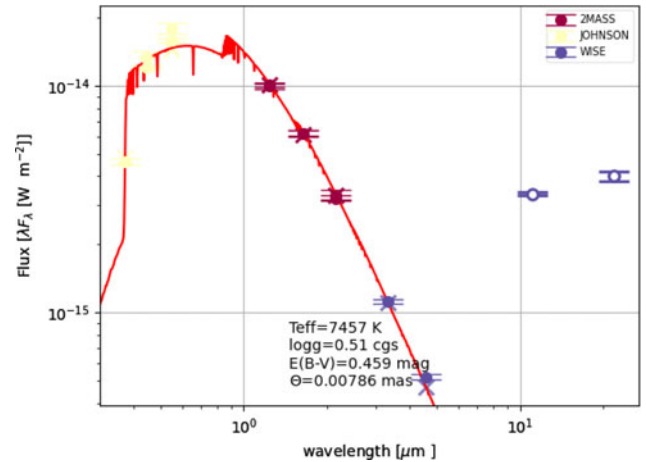


Figure 1. SED of J003643. The data points represent dereddened photometry, while the red line corresponds to the best-fitting scaled model atmosphere. See Section 4 for details on the SED fitting.

derived abundances with predictions from a range of theoretical stellar evolutionary models to investigate the underlying enrichment processes. J003643’s well-constrained luminosity and initial mass, coupled with its unique chemical fingerprint, provide fresh insight into *s*-process nucleosynthesis in post-AGB stars. To better understand the chemical diversity observed in post-AGB stars, we compare some of the key abundance ratios of J003643 with a broader sample of post-AGB stars, including single *s*-process enriched, non-*s*-process enriched, and binary *s*-process enriched post-AGB stars. In addition, we aim to investigate Pb abundances in post-AGB stars using both local thermodynamic equilibrium (LTE) and a toy model to make a preliminary estimate of non-local thermodynamic equilibrium (NLTE) effects, thereby refining Pb abundance estimates and addressing longstanding discrepancies between observational data and theoretical nucleosynthesis predictions.

This paper is organised as follows: Section 2 presents an overview of the target and describes the photometric and spectroscopic datasets. Section 3 outlines the derivation of atmospheric parameters and chemical abundances. Section 4 describes the luminosity derivation. Section 5 introduces the stellar evolutionary models used in this study. Section 6 compares J003643 to the comparative sample of post-AGB stars and explores its nucleosynthetic origin by comparing with theoretical model predictions. We also assess the Pb discrepancy using both LTE and NLTE techniques. Section 7 summarises the main findings and implications of this study.

2. Target details

The primary target of this study, J003643, was first identified as a post-AGB candidate in the SMC through a comprehensive low-resolution spectroscopic survey by Kamath, Wood, & Van Winckel (2014). In the same study, J003643 was classified as a shell-source based on its characteristic double-peaked spectral energy distribution (SED; see Figure 1). Shell-sources are typically thought to be single post-AGB stars that exhibit a distinct double-peaked SED, where the first peak in the near-IR corresponds to the stellar photosphere, while the second peak in the mid-infrared is attributed to thermal emission from a detached, expanding shell of cold

Table 1. Photometric data used for the SED of J003643. See text for full details.

Photometry band	Survey	Magnitude
U	JOHNSON	16.308
B	JOHNSON	15.908
V	JOHNSON	15.257
I	DENIS	14.395
J	2MASS	13.942
H	2MASS	13.707
KS	2MASS	13.612
W1	WISE	13.465
W2	WISE	13.317
W3	WISE	8.331
W4	WISE	6.115
[3.6]	IRAC	13.373
[4.5]	IRAC	13.285
[5.8]	IRAC	11.464
[8.0]	IRAC	9.515
	MIPS	6.139

Notes: A standard error of 0.05 mag is adopted for the SED fitting. IRAC and MIPS are instruments aboard the Spitzer satellite.

circumstellar dust material ejected during the AGB phase (Van Winckel 2003; Gezer et al. 2015).

2.1 Photometric data

Photometric data for J003643 were retrieved from the VizieR database (Ochsenbein, Bauer, & Marcout 2000) to construct its SED (see Figure 1). The optical and near-IR photometry characterises the photospheric emission of the post-AGB star, while mid- and far-IR photometry provides insight into the properties of the circumstellar environment.

For the optical and near-IR regime, we utilised data from the UBVR Johnson-Cousins photometric system (Bessell 1990). Mid- and far-IR fluxes were obtained from the 2MASS All-Sky Catalog of Point Sources (Cutri et al. 2003) and the WISE All-Sky Data Catalog (Cutri et al. 2012). The full set of photometric magnitudes for J003643 is presented in Table 1. A comprehensive list of commonly used photometric catalogues can be found in Appendix A of Oomen et al. (2018).

The resulting SED of J003643 is shown in Figure 1. Details of the SED fitting procedure are described in Section 4.

2.2 Spectroscopic observations and data reduction

High-resolution optical spectra of J003643 were obtained using the Ultraviolet and Visual Echelle Spectrograph (UVES) (Dekker et al. 2000), mounted on the 8 m UT2 Kueyen Telescope of the Very Large Telescope (VLT) array at the European Southern Observatory's (ESO) Paranal Observatory in Chile (Program ID: 092.D-0485). These observations were part of a broader effort to obtain high-quality spectroscopic data for post-AGB stars. To maximise wavelength coverage, the dichroic beam-splitter was employed, yielding spectra that span 3 280–4 560 Å for the blue arm and 4 726–5 800 Å and 5 817–6 810 Å for the lower and upper regions of the red arm CCD chip, respectively. Due to the

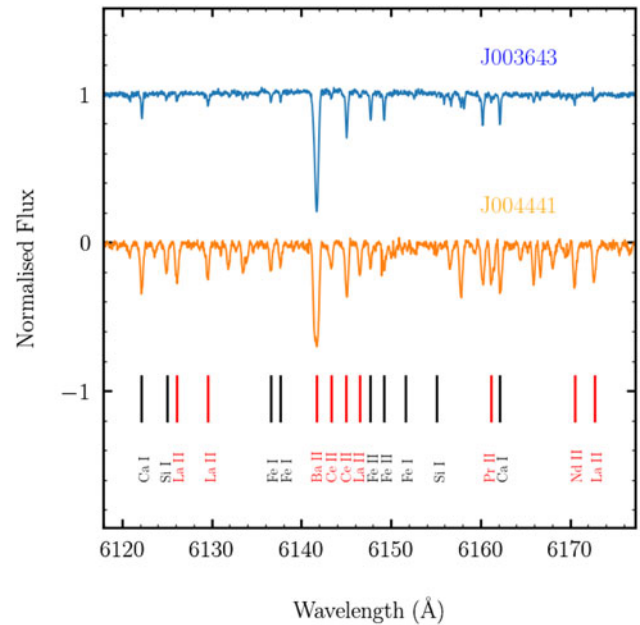


Figure 2. Normalised spectra of the target star J003643 (upper) and one of the most s-process enriched post-AGB stars, J004441 (lower), from De Smedt et al. (2012) for comparison. The spectra have been normalised and shifted to zero velocity for illustrative purposes. The red and black vertical lines mark the positions of selected s-process and non-s-process elements, respectively.

physical separation between the three UVES CCDs, small spectral gaps exist between 4 560–4 726 Å and 5 800–5 817 Å. Each spectral range was observed separately with a consistent exposure time. The resolving power of UVES for these observations ranges between $\sim 60\,000$ and $\sim 65\,000$.

Figure 2 presents a spectral region of the target star J003643 (upper) alongside J004441 (lower), one of the most s-process enriched post-AGB stars from De Smedt et al. (2012), for comparison. This figure illustrates the quality of the UVES spectra and highlights the detection of specific s-process elements in J003643.

The observational details, including spectral coverage and signal-to-noise (S/N) ratios per observation, are provided in Table 2. The S/N ratio is lower at blue wavelengths due to increased atmospheric extinction, reddening effect and reduced detector sensitivity. Additionally, the echelle spectra exhibit non-uniform S/N owing to the blaze function, which results in a higher S/N near blaze wavelengths where the spectrograph operates most efficiently. The final weighted mean spectrum has an S/N of 30 in the blue region and 55 in the red region.

The pre-reduced UVES spectra of J003643 were retrieved from the ESO Archive Science Portal. The normalisation of the reduced spectrum was performed by fitting fifth-order polynomials within small spectral windows using interactively selected continuum points. This step is particularly crucial in the blue spectral region, where significant line crowding makes continuum placement challenging. The primary source of measurement uncertainty in abundance determinations for lines in this region arises from continuum placement errors.

The radial velocity of J003643 was determined by measuring the central wavelengths of several well-identified atomic lines using Gaussian profile fitting. The Doppler shift equation was then applied to derive a heliocentric radial velocity of $v = 133.9 \pm 0.26 \text{ km s}^{-1}$, which is consistent with SMC membership, given

Table 2. Observational logs of the J003643.

Date (YYYY-MM-DD)	UTC start (hh:mm:ss)	Exp time (s)	Wavelength coverage (Å)	S/N
2013-10-19	02:03:19	2 730	3 282–4 563	15
2013-10-19	02:53:07	2 700	3 282–4 563	15
2013-10-19	03:46:18	3 000	3 282–4 563	18
2013-10-19	01:09:29	2 900	3 282–4 563	14
2013-10-19	02:03:11	2 730	4 726–6 835	52
2013-10-19	02:53:03	2 700	4 726–6 835	52
2013-10-19	03:46:15	3 000	4 726–6 835	60
2013-10-19	01:09:25	2 900	4 726–6 835	52

Notes: The final S/N after the weighted mean merging of similar observations is approximately 30 in the blue region and 55 in the red region of the spectrum.

the mean heliocentric velocity of the SMC being $\sim 160 \text{ km s}^{-1}$ (Richter, Tammann, & Huchtmeier 1987).

After normalisation and radial velocity correction of all the spectra (blue and red), a weighted mean merging was performed to obtain a single final spectrum, which was subsequently used for a detailed spectroscopic analysis of J003643. A significant portion of the blue spectrum (3 280–4 560 Å) exhibits an S/N too low (< 30) for reliable abundance determination. Consequently, these wavelength ranges were excluded from the spectroscopic analysis of J003643.

3. Spectroscopic analysis of J003643

The spectroscopic analysis of J003643, including the determination of accurate atmospheric parameters and the derivation of chemical abundances for all identifiable elements, was conducted using E-iSpec (Mohorian et al. 2024), a custom Python wrapper for iSpec (Blanco-Cuaresma et al. 2014; Blanco-Cuaresma 2019). E-iSpec interfaces with the LTE spectrum synthesis tool MOOG (Snedden 1973). A detailed description of E-iSpec and the spectroscopic analysis methodology is provided in Mohorian et al. (2024). Our approach closely follows the methods outlined in Menon et al. (2024) and Mohorian et al. (2024).

The atmospheric parameters and elemental abundances were determined using carefully selected spectral lines that are isolated, unblended, and non-saturated. To minimise spectral noise, we included only lines with equivalent widths (EW) greater than 5 mÅ, while excluding those exceeding 150 mÅ to avoid saturation effects.

A summary of the atmospheric parameter determination and chemical abundance derivation is presented in Sections 3.1 and 3.2, respectively.

3.1 Atmospheric parameter determination

The atmospheric parameters of J003643 were determined using Fe I and Fe II lines, following the approach described in Mohorian et al. (2024) and Menon et al. (2024). The EWs for each line were computed iteratively by comparing the theoretical EWs with the observed values.

The effective temperature (T_{eff}) was derived through excitation equilibrium, ensuring that Fe I abundances remain independent of excitation potential (EP). The surface gravity ($\log g$) was determined via ionisation equilibrium, enforcing consistency between Fe I and Fe II abundances. The microturbulent velocity (ξ_t) was

Table 3. Spectroscopically derived atmospheric parameters of J003643.

Stellar parameters	This study	Kamath et al. (2014)
T_{eff} (K)	$7\,552 \pm 91$	$7\,458 \pm 250$
$\log g$ (dex)	1.04 ± 0.16	0.50 ± 0.50
[Fe/H] (dex)	-0.92 ± 0.11	-0.63 ± 0.50
ξ_t (km/s)	4.02 ± 0.13	3.00 ± 0.50

Notes: Atmospheric parameters from Kamath et al. (2014) were derived using low-resolution AAOmega spectra.

obtained by requiring that the derived Fe abundances are independent of the reduced equivalent width (RW) of individual lines. Uncertainties in the atmospheric parameters were estimated using the covariance matrix from the non-linear least-squares fitting algorithm in E-iSpec.

The results of the atmospheric parameter analysis for J003643 are presented in Table 3 and discussed in Section 3.3. The values in the last column of Table 3 correspond to the atmospheric parameters derived from low-resolution AAOmega spectra by Kamath et al. (2014).

3.2 Derivation of chemical abundances

The chemical abundances of different elements of J003643 were derived using both the EW method and spectral synthesis fitting (SSF), both implemented in E-iSpec, following a similar approach to Menon et al. (2024). In the EW method, the observed EWs were compared with theoretical EWs based on synthetic spectra from a model atmosphere (ATLAS9; Castelli & Kurucz 2003). The assumed abundances were iteratively adjusted until the observed and predicted EWs converged, yielding the best-fit values.

The SSF method involved comparing the observed spectra with synthetic spectra generated from model atmospheres, using a chi-square fitting procedure to iteratively refine the model parameters and determine precise chemical abundances. Instrumental and macroturbulent broadening were incorporated through Gaussian convolution, consistent with the UVES resolving power ($R \approx 60\,000$) and with macroturbulent velocities expected in cool, low-gravity stellar atmospheres. Examples of SSF applied to the spectral lines of four elements are shown in Figure 3: O I at 6 155.971 Å, 6 156.755 Å, and 6 158.187 Å, Y II at 6 613.731 Å, Eu II at 6 437.640 Å and Pb II at 5 608.853 Å. These illustrate the sensitivity of the derived abundances to both line strength and local continuum placement. SSF was performed alongside the EW method for these elements to ensure consistency and to validate the robustness of the derived abundances.

The lines used for abundance derivation were selected based on the line selection criteria outlined in Section 3. The linelist used for the spectroscopic analysis of J003643 is provided in Table A1.

The uncertainties in the derived abundances were estimated using the method outlined in Deroo et al. (2005). E-iSpec calculates the errors as standard deviations ($\sigma_{|121|}$) for each line, while the total error (σ_{tot}) is computed as the quadratic sum of $\sigma_{|121|}$, uncertainties due to atmospheric parameters, and the [Fe/H] error. To assess the sensitivity of the abundances to stellar parameters, we recomputed the abundances by varying T_{eff} , $\log g$, and ξ_t within their respective uncertainties (see Table 3). A $\sigma_{|121|}$ of 0.20 dex was adopted for species with only a single measurable line, reflecting the expected line-to-line scatter.

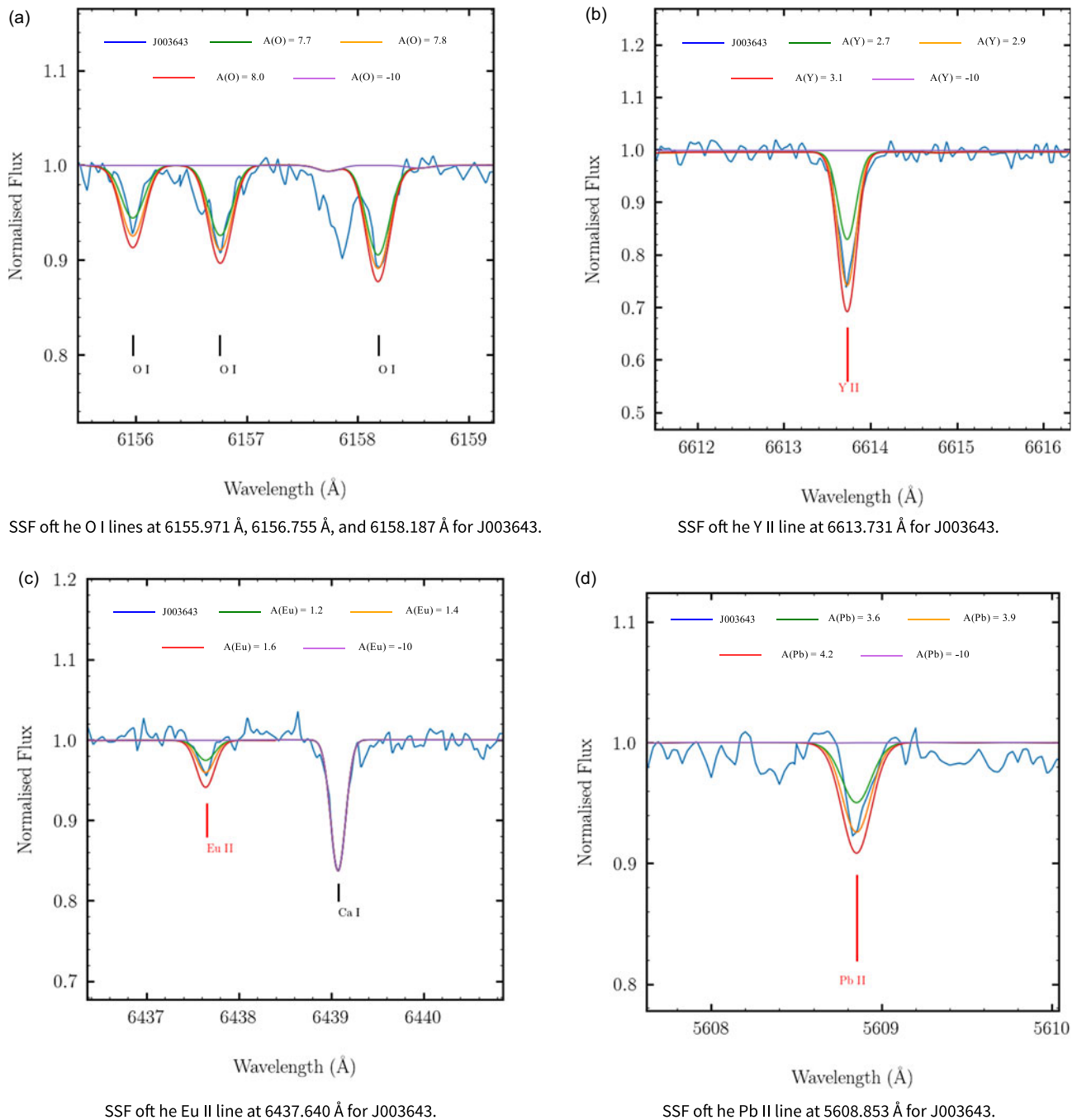


Figure 3. SSF of the O I lines at 6155.971, 6156.755, and 6158.187 Å (top left), Y II line at 6613.731 Å (top right), Eu II line at 6437.640 Å (bottom left), and Pb II line at 5608.853 Å (bottom right) for J003643. Here, $A(X)$ denotes the logarithmic absolute abundance $\log \epsilon(X)$ of the respective element, and $A(X) = -10$ indicates a synthetic spectrum computed with zero abundance of that element.

The derived chemical abundances for J003643 are presented in Table 4, and the result of the analysis is discussed in Section 3.3. The elements in Table 4 are arranged by atomic number (Z), with the corresponding solar abundances ($\log \epsilon_{\odot}$) taken from Asplund et al. (2009). The table also includes the number of identified lines per element (N), the element-to-iron ratio ($[X/Fe]$), the total uncertainty on $[X/Fe]$ (σ_{tot}), the absolute abundance ($\log \epsilon$), and the line-to-line scatter ($\sigma_{[121]}$). Despite the inability to determine the abundances of several key nucleosynthesis elements, Table 4

presents quantified abundances for a wide range of s -process elements.

Notably, this study presents the first direct measurement of the Pb abundance in a post-AGB star, derived from the Pb II line at 5608.853 Å, which was the only detectable Pb line in J003643 (further details on Pb are provided in Section 6.3). In contrast, previous studies of post-AGB stars have only been able to derive upper limits on Pb abundance using SSF (e.g. De Smedt et al. 2016), primarily due to the intrinsic weakness of Pb lines

Table 4. Spectroscopically determined abundance results for J003643.

Ion	Z	N	$\log \varepsilon_{\odot}$	$\log \varepsilon$	$[X/Fe]_{\text{LTE}}$	σ_{tot}	$[X/Fe]_{\text{NLTE}}$	eNLTE	$\sigma_{|121|}$
C 1	6	14	8.43	8.90	1.39	0.14	1.33	0.14	0.12
O 1	8	3	8.69	7.80	0.03	0.20	−0.08	0.20	0.02
Mg 1	12	2	7.60	6.66	−0.01	0.13	−0.09	0.13	0.03
Ca 2	20	2	6.34	5.25	−0.16	0.11	−0.13	0.11	0.01
Sc 2	21	2	3.15	2.07	−0.16	0.10			0.13
Ti 2	22	14	4.95	3.84	−0.19	0.16			0.10
Cr 1	24	2	5.64	4.85	0.13	0.21			0.13
Cr 2	24	9	5.64	4.66	−0.06	0.17			0.14
Fe 1	26	46	7.50	6.56	−0.02	0.17			0.11
Fe 2	26	5	7.50	6.53	−0.04	0.16			0.15
Ni 1	28	1	6.22	5.28	−0.02	0.22			0.20
Y 2	39	14	2.21	2.89	1.60	0.19			0.17
Zr 2	40	3	2.58	3.45	1.79	0.17			0.15
La 2	57	18	1.10	2.62	2.44	0.17			0.15
Ce 2	58	27	1.58	2.88	2.22	0.17			0.10
Pr 2	59	6	0.72	2.18	2.38	0.15			0.12
Nd 2	60	40	1.42	2.88	2.39	0.16			0.13
Sm 2	62	5	0.96	2.16	2.12	0.12			0.04
Eu 2	63	2	0.52	1.41	1.81	0.11			0.09
Gd 2	64	2	1.07	2.05	1.90	0.18			0.07
Er 2	68	2	0.92	2.33	2.33	0.21			0.11
Yb 2	70	1	0.84	2.12	2.20	0.22			0.20
Lu 2	71	1	0.10	1.25	2.07	0.21			0.20
Hf 2	72	2	0.85	2.61	2.68	0.13			0.06
Pb 2	82	1	1.75	3.98	3.16	0.21			0.20

Notes: The ions that were detected and their corresponding atomic number (Z) are listed in columns 1 and 2, respectively. The solar abundances ($\log \varepsilon_{\odot}$) in column 3 are retrieved from Asplund *et al.* (2009). N represents the number of lines used for each ion, $[X/Fe]_{\text{LTE}}$ is the element-over-iron ratio derived considering LTE, σ_{tot} is the total uncertainty on $[X/Fe]$, $\log \varepsilon$ is the determined abundance, and $\sigma_{|121|}$ is the line-to-line scatter. We impose a $\sigma_{|121|}$ of 0.20 dex for all ions for which only one line is available for the abundance determination. $[X/Fe]_{\text{NLTE}}$ is the element-over-iron ratio derived considering NLTE along with uncertainty eNLTE (see Section 3.2.1 for details).

and line blending effects, which have hindered precise abundance measurements.

3.2.1 NLTE effects

Departures from LTE, if not accounted for, can introduce inaccuracies in spectroscopic analyses and lead to biased conclusions. To assess their impact, we tested possible NLTE effects on spectral lines of C I, O I, Mg I, and Ca I. Weak lines of Ti II (Mallinson *et al.* 2024) and Fe II (Lind, Bergemann, & Asplund 2012) are expected to show relatively mild departures from LTE. Therefore, we adopted $[Fe/H]$ derived from Fe II lines as the metallicity and applied NLTE corrections to the elemental abundances of C, O, Mg, and Ca accordingly. The results, including uncertainties, are presented in Table 4 under the column ' $[X/Fe]_{\text{NLTE}}$ '. To calculate the uncertainties of the NLTE abundances, we adopt the same systematic error as in the LTE analysis, the component that quantifies the sensitivity of the abundances to uncertainties in T_{eff} , $\log g$, and ξ_t by recomputing them within their quoted errors, since the NLTE corrections themselves are essentially invariant to these parameter shifts. We then compute the $\sigma_{|121|}$ of the NLTE abundances (eNLTE), which is found to be very similar to that

in LTE. Consequently, the total uncertainty σ_{tot} for the NLTE abundances matches the LTE value to two decimal places.

The NLTE calculations were performed using Balder (Amarsi *et al.* 2018b), which is based on Multi3D (Leenaarts & Carlsson 2009). These calculations were carried out using the same ATLAS model atmosphere of J003643 employed for LTE abundance determinations in this study. The abundances were computed for five values in steps of 0.5 dex around the 1D LTE value. The model atoms were adopted from Amarsi *et al.* (2019) for C I, Amarsi *et al.* (2018a) for O I, and Asplund *et al.* (2021) for Mg I and Ca I.

A caveat of this test is that the adopted model atoms were originally calibrated for stars with lower effective temperatures and higher atmospheric densities than J003643. Nevertheless, the results provide insight into the extent to which departures from LTE might affect our abundance determinations.

3.3 Results of spectroscopic analysis: Atmospheric parameters and chemical abundances

In this section, we present the results of the spectroscopic analysis of J003643.

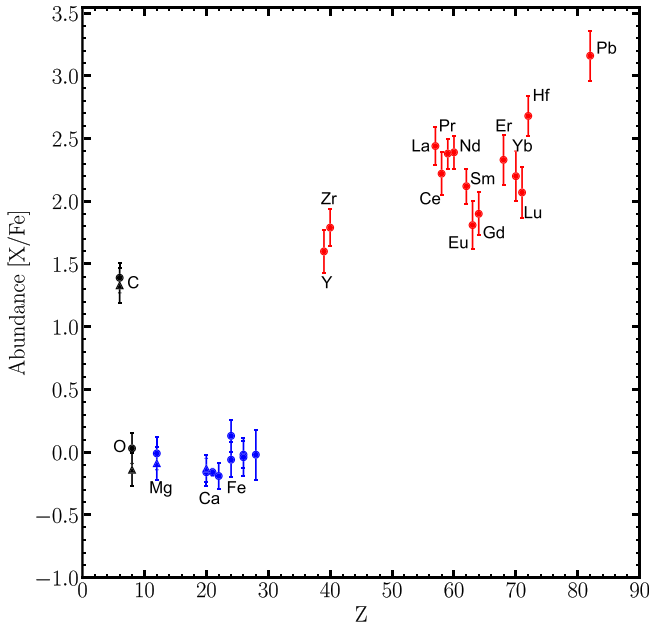


Figure 4. Spectroscopically derived abundances of J003643. The error bars represent the total uncertainties (σ_{tot}). The data points are colour-coded: black for CNO elements, blue for Fe-peak elements, and red for s-process elements. Circles represent LTE abundances, while triangles represent NLTE abundances (for details on NLTE, see Section 3.2.1). Some elements are labelled for reference.

The atmospheric parameters derived for J003643 are summarised in Table 3. Our analysis confirms that J003643 is an A-type post-AGB star with an effective temperature of $T_{\text{eff}} = 7552 \pm 91$ K. It has a low surface gravity ($\log g = 1.04 \pm 0.16$ dex) and an iron abundance of $[\text{Fe}/\text{H}] = -0.97 \pm 0.11$ dex. Although the iron abundance of J003643 is low, it is comparable to the mean metallicity of the SMC ($[\text{Fe}/\text{H}] = -0.7$ dex) (Luck et al. 1998).

The derived chemical abundances for J003643 are presented in Table 4. Figure 4 illustrates the abundance distribution ($[\text{X}/\text{Fe}]$) as a function of atomic number (Z).

In Figure 4, the circles represent LTE abundances, while the triangles correspond to NLTE abundances (for details on NLTE, see Section 3.2.1). The NLTE abundances, where available, generally agree with the LTE results within the uncertainties.

Figure 4 shows that J003643 has a $[\text{C}/\text{Fe}]$ of 1.33 ± 0.14 dex and an $[\text{O}/\text{Fe}]$ of -0.08 ± 0.20 dex. Notably, it has a C/O ratio of 12.58 ± 0.25 based on LTE abundances and 16.21 ± 0.22 from NLTE-corrected abundances. This is relatively higher than the typical C/O ratios of s-process enriched post-AGB stars ($\approx 1-3$), primarily driven by J003643's low oxygen abundance, relative to typical post-AGB stars (see Section 6.1 for details).

Additionally, Figure 4 also shows that J003643 is enriched in s-process elements. The s-process distributions and overabundances of LIM stars are commonly described using four observational indices: $[\text{ls}/\text{Fe}]$, $[\text{hs}/\text{Fe}]$, $[\text{s}/\text{Fe}]$, and $[\text{hs}/\text{ls}]$. To maintain consistency, we use the same elemental abundances as in De Smedt et al. (2016) for calculating these indices. We define the hs index as the average of La, Ce, Nd, and Sm; the ls index as the average of Y and Zr; and the overall $[\text{s}/\text{Fe}]$ index as the mean of all six s-process elements. For J003643, we derive $[\text{ls}/\text{Fe}] = 1.72 \pm 0.17$ dex, $[\text{hs}/\text{Fe}] = 2.19 \pm 0.11$ dex, $[\text{hs}/\text{ls}] = 0.48 \pm 0.12$ dex and $[\text{s}/\text{Fe}] = 2.09 \pm 0.20$ dex.

Furthermore, while previous studies of s-process enriched post-AGB stars have only reported upper limits for Pb abundances based on SSF (e.g. De Smedt et al. 2016), this study provides the first direct Pb abundance measurement in a post-AGB star using both EW and SSF methods. The clearly detected Pb II line at 5608.853 Å yields a consistent Pb abundance of $[\text{Pb}/\text{Fe}] = 3.16$ dex from EW fitting and $[\text{Pb}/\text{Fe}] = 3.20$ dex from SSF (see Figure 3d), enabling a more robust comparison with theoretical nucleosynthesis predictions.

4. Luminosity determination through SED fitting

Accurately determining the luminosity of a post-AGB star and combining it with its derived atmospheric parameters and elemental abundances provides valuable insights into its evolutionary stage and facilitates the estimation of its initial mass. However, deriving the luminosities of post-AGB stars remains challenging due to several factors, including the effects of circumstellar and interstellar reddening on observational photometry (see e.g. Kamath et al. 2022, 2023).

To determine the luminosity of J003643, we utilised its SED fitting parameters, following the approach outlined in Kluska et al. (2022) and Kamath et al. (2022). In summary, the total line-of-sight reddening or extinction parameter ($E(B - V)$) was determined by minimising the difference between the observed optical fluxes and the reddened photospheric models. This total reddening accounts for both interstellar and circumstellar extinction. We assumed that the total reddening follows the wavelength dependency of the interstellar extinction law (Cardelli, Clayton, & Mathis 1989) with $R_V = 3.1$. While the extinction law in the circumstellar environment likely differs from the interstellar law, investigating this aspect is beyond the scope of this study.

For the atmospheric models, we adopted the Kurucz models (Castelli & Kurucz 2003) with parameters derived from the spectroscopic analysis in Section 3.1 (see Table 3). The SED fitting was performed by interpolating within the χ^2 landscape, using models centred on the spectroscopically determined parameters and applying variations of $\Delta T_{\text{eff}} \pm 500$ K, $\Delta \log g \pm 0.5$ dex, and $\Delta [\text{Fe}/\text{H}] \pm 0.5$ dex (see Section 3.1). The resulting SED of J003643 is shown in Figure 1.

The bolometric luminosity or SED luminosity (L_{SED}) of J003643 was derived by integrating the flux under the dereddened photospheric SED model, assuming an average distance of 62.1 ± 1.9 kpc to the SMC (Graczyk et al. 2012). The derived SED luminosity (L_{SED}) and its corresponding upper and lower limits for J003643 are $7.623^{+0.606}_{-0.761} L_{\odot}$. To estimate the uncertainties in luminosity, we incorporated the upper and lower limits of the reddening values, as outlined in Table 5.

5. Stellar evolutionary models: ATON, MONASH and FRUITY

Comparing the derived chemical abundances of a star with stellar evolutionary models is key to understanding its evolution and nucleosynthesis. In this section, we compare the spectroscopically derived abundances of J003643 with predictions from three independent stellar evolutionary models: ATON (Section 5.1), MONASH (Section 5.2) and FRUITY (Section 5.3), to assess nucleosynthetic efficiency and constrain parameters such as initial mass and mixing.

Table 5. Overview of the effective temperature, metallicity, C/O ratio, s-process indices, derived luminosity and initial mass estimate of J003643.

Parameter	Value
T_{eff} (K)	$7\,552 \pm 91$
[Fe/H] (dex)	-0.97 ± 0.11
C/O _{LTE}	12.58 ± 0.25
C/O _{NLTE}	16.21 ± 0.22
[s/Fe]	2.09 ± 0.20
[ls/Fe]	1.72 ± 0.17
[hs/Fe]	2.19 ± 0.11
[hs/ls]	0.48 ± 0.12
[Pb/Fe]	3.16 ± 0.18
[Pb/ls]	1.39 ± 0.16
[Pb/hs]	1.86 ± 0.15
$L_{\text{SED}} (L_{\odot})$	$7\,623^{+606}_{-5761}$
$E(B - V)$ (mag)	$0.46^{+0.50}_{-0.36}$

Notes: See Section 3.2 for details on chemical abundances presented here. See Section 4 for details on luminosity derivation.

5.1 ATON

To facilitate meaningful comparison with theoretical stellar evolutionary models, we first estimated the initial mass of J003643, a key parameter that governs stellar evolution and chemical yields. For this, we utilised evolutionary tracks computed with the ATON stellar evolution code (Ventura *et al.* 1998).

ATON stellar evolution code models the structure and nucleosynthesis of LIM stars, employing the Full Spectrum of Turbulence (FST) model for convective mixing (Ventura *et al.* 1998; Ventura, D’Antona, & Mazzitelli 2008; Ventura *et al.* 2018). It includes treatments of mass loss, convective boundary mixing, and thermal pulses during the AGB phase. The code tracks the evolution of light-element surface abundances, particularly C, N, and O, shaped by internal mixing processes. Although it does not compute detailed heavy-element nucleosynthesis, ATON provides robust predictions for CNO enrichment and structural evolution relevant to AGB modelling (see e.g. Kamath *et al.* 2023).

In this study, we adopt an initial metallicity of $Z = 0.0014$, and use ATON to model the stellar evolution of J003643 based on its spectroscopically derived luminosity, atmospheric parameters, and surface carbon and oxygen abundances, following the methodology of Kamath *et al.* (2023).

Figures 5 and 6 illustrate the luminosity evolution and surface [C/Fe] abundance variation as functions of the AGB lifetime (normalised to the total duration of the AGB phase) for stars with initial masses of $2M_{\odot}$ (black), $2.5M_{\odot}$ (red), and $3M_{\odot}$ (green). In Figure 5, the blue horizontal line represents the SED-derived luminosity of J003643 (see Section 4), while in Figure 6, the grey-shaded region indicates the spectroscopically derived carbon abundance of J003643 with its uncertainty (see Section 3.2). We use [C/Fe] rather than [O/Fe] to constrain AGB evolution because carbon is gradually enhanced through third dredge-up (TDU) episodes, making it highly sensitive to the progenitor mass and internal nucleosynthesis. In contrast, oxygen shows little surface variation during the AGB phase for low-mass stars ($<3M_{\odot}$) and primarily reflects the composition of the progenitor gas. This

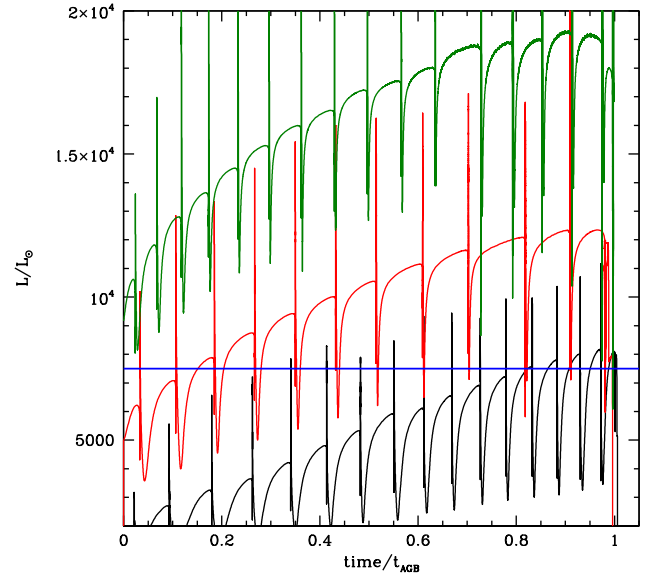


Figure 5. Luminosity evolution as a function of AGB lifetime for stars with an initial metallicity of $Z = 0.0014$. The models correspond to initial masses of $2M_{\odot}$ (black), $2.5M_{\odot}$ (red), and $3M_{\odot}$ (green). The blue horizontal line represents the derived SED luminosity of J003643 (see Section 4). See text for more details.

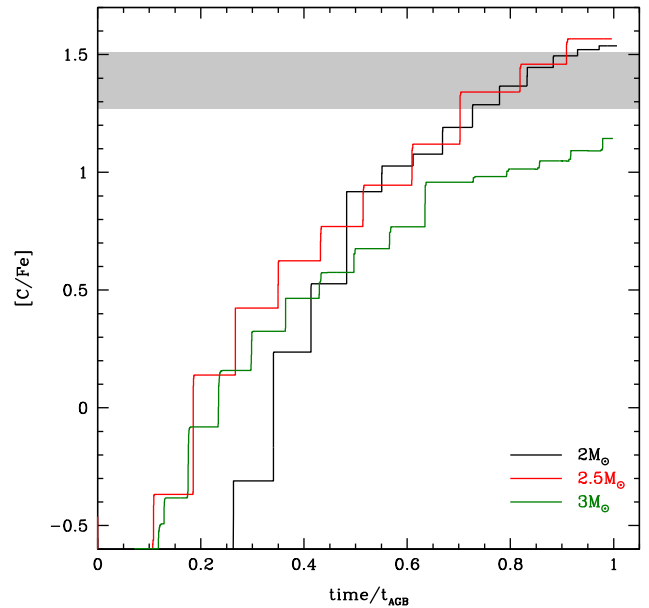


Figure 6. Surface [C/Fe] abundance evolution as a function of AGB lifetime for stars with an initial metallicity of $Z = 0.0014$. The models correspond to initial masses of $2M_{\odot}$ (black), $2.5M_{\odot}$ (red), and $3M_{\odot}$ (green). The grey-shaded region indicates the spectroscopically derived carbon abundance of J003643 with its uncertainty (see Section 3.2). See text for more details.

distinction is confirmed by Kamath *et al.* (2023), demonstrating that [C/Fe] correlates more tightly with stellar mass and TDU efficiency, while [O/Fe] remains largely unaffected in the mass range relevant to post-AGB stars. Nevertheless, the [O/Fe] predicted by the $2M_{\odot}$ model assuming no α -enhancement is ~ 0.2 dex, which is slightly higher but still consistent within uncertainties with the spectroscopically derived oxygen abundance of J003643 ([O/Fe] = -0.08 ± 0.20 dex).

The evolutionary tracks show that all three models cross evolutionary phases consistent with the estimated luminosity of J003643. Specifically, in the $2M_{\odot}$ model, the observed luminosity is reached toward the end of the AGB phase. In the $2.5M_{\odot}$ model, it occurs in the first half of the AGB lifetime and in the $3M_{\odot}$ model, the luminosity is attained at the beginning of the AGB phase. However, within the ATON grid, higher masses ($\geq 3M_{\odot}$) can be ruled out, as hot-bottom burning (HBB) would prevent carbon enrichment, which contradicts the observed high $[C/Fe]$ in J003643. Similarly, within the ATON grid, lower masses ($< 2M_{\odot}$) are also excluded, as they fail to reach the derived luminosity of J003643 (indicated by the blue line in Figure 5) (Dell’Agli et al. 2015).

Furthermore, examining the surface carbon abundance evolution in Figure 6, we find that the observed carbon abundance of J003643 aligns best with the final phases of the AGB. This suggests that J003643 most likely originated from a star with an initial mass of about $2M_{\odot}$, corresponding to a formation epoch of approximately 1 billion years ago. We note that the initial mass estimated here refers to the mass at the ZAMS, before the star evolved into its post-AGB phase.

5.2 MONASH

The MONASH stellar evolution code (Lattanzio 1986; Karakas 2014) was used to construct detailed stellar evolution models of J003643. The stellar evolutionary sequences allow us to calculate the detailed nucleosynthesis, including s -process elements, using a post-processing nucleosynthesis code. We refer to Karakas & Lugaro (2016) for further details. For this study, we used the same version of the code and input physics described in Karakas et al. (2018). The main uncertainties that we examined include the amount of TDU, which we can change by including convective overshoot at the base of the convective envelope (e.g. see Kamath, Karakas, & Wood 2012), and the size of the partially mixed zone (PMZ) in the post-processing calculations. In our post-processing calculations, the ^{13}C pocket is formed by inserting protons into the top layers of the He-intershell during the deepest extent of each TDU event. The extent of the protons in the He-shell is called the PMZ. Observations of barium stars show a range of s -process abundances which likely indicate some natural variation in the size of ^{13}C pockets (e.g. Cseh et al. 2018). For this reason, we experiment with calculating models with different size PMZ (we refer to Buntain et al. (2017) for a detailed study of ^{13}C pockets in our models, including a comparison to other studies).

We experiment with models with initial masses between 1.5 to $2M_{\odot}$ with $Z = 0.001$ and find that the best match to the luminosity of J003643 near the end of the TP-AGB phase occurs in a $1.7M_{\odot}$ model. This is similar to the result from the ATON code ($2M_{\odot}$, see Section 5.1), given that these are two independent stellar evolution codes and there is a slight difference in metallicity. We note that a $0.3M_{\odot}$ offset is well within the typical systematic uncertainties of TP-AGB modelling. For the nucleosynthesis predictions (Figure 11, green line), we adopt a PMZ mass of $0.006M_{\odot}$, which provides the best overall match to the observed s -process enrichment.

The results and the interpretation of our comparison between the spectroscopically derived abundances of J003643 and the MONASH models, including the impact of PMZ on s -process abundances, are discussed in Section 6.2.

5.3 FRUITY

To explore the impact of differences in input physics and numerical treatments across stellar evolution codes, we also utilised the stellar evolution and nucleosynthesis framework: FRUITY (Full-Network Repository of Updated Isotopic Tables and Yields) (Cristallo et al. 2011). FRUITY is designed to simulate the evolution and chemical enrichment of LIM stars, with a particular focus on s -process nucleosynthesis. These models span a range of initial masses ($1.3\text{--}6.0M_{\odot}$) and metallicities ($Z = 0.00002$ to $Z = 0.03$), making them well-suited for comparisons with stars observed in different galactic environments.

For this study, we use the s -process distribution from the latest FRUITY models, which incorporate the effects of mixing triggered by magnetic fields (Vescovi et al. 2020), to compare with the spectroscopically derived abundances of J003643. These updated FRUITY models incorporate a magnetic mixing mechanism as a new driver for the formation of the ^{13}C pocket, the primary neutron source for s -process nucleosynthesis. Unlike previous versions (Cristallo et al. 2011; Piersanti, Cristallo, & Straniero 2013; Cristallo et al. 2015), where the ^{13}C pocket was formed via convective overshoot, this new approach accounts for buoyancy-driven magnetic instabilities, which naturally induce mixing within the He-intershell. This results in a self-consistent ^{13}C pocket formation, influencing both neutron exposure and the overall efficiency of the s -process.

In addition to this revised mixing mechanism, several other updates have been implemented in the latest FRUITY models, including the equation of state (EOS) and the nuclear reaction network (see Vescovi et al. 2021, for more details). For the models presented in this work, an updated initial chemical composition from Lodders (2021) and revised values for C, N, O, and Ne from Magg et al. (2022) were used. Additionally, mass-loss prescriptions were updated using a revised period-mass-loss relation calibrated to the latest Galactic O- and C-rich giant data (Höfner & Olofsson 2018), with pulsation periods derived from the period-mass-radius relation of Trabucchi & Mowlavi (2022). The updated mass-loss rate is less efficient than that previously adopted in Vescovi et al. (2020, 2021), further enhancing predictions of carbon and heavy-element abundances.

We tested models with initial masses between 1.5 and $2M_{\odot}$ at $Z = 0.001$ and found that the $2M_{\odot}$ magnetic-mixing FRUITY model provides the best match to the observed heavy-element abundances (see Figure 12, black line). We also explore the magnetic-mixing FRUITY model with an initially r -process enhanced composition, adopting a solar r -process distribution prescribed by Prantzos et al. (2020) scaled by +2 dex ($[r/Fe] = +2$ dex) from Ga to Bi (see Figure 12, magenta line).

The results and the interpretation of our comparison between the spectroscopically derived abundances of J003643 and the magnetic mixing FRUITY models are discussed in Section 6.2.

6. Discussion

In this section, we place the photospheric chemical composition of J003643 in a broader astrophysical context. We first compare its CNO and s -process abundance ratios with a relevant and comprehensive sample of post-AGB stars to investigate chemical trends and diversity (Section 6.1). We then explore the origin of its chemical enrichment by comparing its abundance pattern against predictions from various stellar evolutionary models

(Section 6.2). Finally, we assess the longstanding Pb abundance discrepancy, including a first exploration of possible NLTE effects on Pb (Section 6.3).

6.1 Comparative analysis of key abundance ratios in post-AGB stars

The detailed spectroscopic analysis of J003643 revealed a relatively high C/O ratio (16.21) compared to other post-AGB stars ($\sim 1-3$). To investigate this anomaly, we compared some of the key abundance ratios of J003643 (C/O, [C/Fe], [O/Fe], [s/Fe], [hs/ls]) with a comprehensive sample of post-AGB stars, including single *s*-process enriched stars, single non-*s*-process enriched stars, and binary *s*-process enriched stars, spanning different galactic environments, the LMC, SMC and Galaxy. The full post-AGB sample (referred to hereafter as the ‘comparative sample’) considered in this study, including their references, is summarised in Table B1.

Figure 7a shows the spectroscopically derived C/O ratios versus [s/Fe] for the comparative sample of post-AGB stars. The data points are symbol- and colour-coded to distinguish between different groups (see caption for details). J003643 stands out as an outlier, displaying the highest C/O ratio (16.21) in the comparative sample, making it the first spectroscopically confirmed post-AGB star with such a high C/O ratio.

To investigate the high C/O ratio of J003643, we compared its [C/Fe]–[s/Fe], [O/Fe]–[C/Fe] and [O/Fe]–[Fe/H] distributions with the comparative sample (Figures 7b, c and d respectively). Figure 7b reveals a strong positive correlation with an increase of [C/Fe] with [s/Fe] consistent with expectations from TDU during the AGB phase. J003643 clearly falls along this correlation, indicating its carbon enhancement scales with its *s*-process enrichment, similar to other *s*-process enriched post-AGB stars. This suggests a typical TDU history and implies that the high C/O ratio of J003643 is not due to an unusually high carbon abundance.

Figure 7c reveals a positive correlation between [O/Fe] and [C/Fe], where stars with higher [C/Fe] generally also exhibit higher [O/Fe]. Similarly, Figure 7d shows a negative correlation between [O/Fe] and [Fe/H], indicating that [O/Fe] tends to increase with decreasing metallicity. J003643 stands out as a distinct outlier in both figures, exhibiting a relatively low [O/Fe] = -0.08 ± 0.20 dex compared to stars with similar [C/Fe] and [Fe/H]. Given that oxygen is not substantially altered during the RGB or AGB phases (e.g. Karakas & Lattanzio 2014), this oxygen deficit is likely a reflection of the initial chemical composition of its natal gas.

To investigate the oxygen abundance of J003643 and the comparative sample, we examined the chemical evolution trends of the Galaxy and the MCs. Chemical evolution studies of Galactic field giant stars show that [O/Fe] generally increases with decreasing metallicity, reaching values up to ~ 1 dex at [Fe/H] $\lesssim -1.5$ dex (see, e.g. Bensby *et al.* 2005; Reddy, Lambert, & Prieto 2006; Mucciarelli *et al.* 2023a). This trend is reflected in our Galactic comparative sample, where metal-poor stars show similarly enhanced oxygen abundances and consequently C/O ratios within the typical range of $\sim 1-3$. In the LMC, [O/Fe] is as low as 0 dex at [Fe/H] ≈ -0.5 dex and rises to ~ 0.5 dex at [Fe/H] ≈ -1.5 dex (e.g. Van der Swaelmen *et al.* 2013). Our LMC comparative sample generally follows this trend at low metallicities, though some stars with [Fe/H] $\lesssim -1$ dex show high [O/Fe] values up to 0.8 dex (see Figure 7d). This may reflect observational biases due to the limited number of low-metallicity LMC field

giants available for comparison. In the SMC, field giant stars at [Fe/H] ≈ -1.0 dex exhibit [O/Fe] values ranging from -0.1 to $+0.4$ dex with a mean of $\approx +0.2$ dex, although with a scatter (see Figure 8 of Mucciarelli *et al.* 2023a). At [Fe/H] ≈ -1.5 dex, the mean [O/Fe] rises to $\approx +0.8$ dex. Our SMC comparative sample, including J003643, generally follows this trend. Some stars with [Fe/H] $\lesssim -1.5$ dex exhibit elevated [O/Fe] up to 1 dex (see Figure 7d), which may again reflect observational biases from the limited number of low-metallicity SMC field giants available for comparison.

The relatively low [O/Fe] = -0.08 ± 0.2 dex, compared to the comparative sample of post-AGB stars at similar [Fe/H] and [C/Fe], together with $[\alpha/\text{Fe}] \approx 0$ dex of J003643 indicates that it likely formed from an interstellar medium (ISM) that was intrinsically oxygen-poor. Additionally, recent APOGEE observations of $\approx 3\,600$ RGB stars in the LMC and SMC by Nidever *et al.* (2020) further confirm both $[\alpha/\text{Fe}]$ and [O/Fe] remain essentially solar at [Fe/H] ≈ -1 , demonstrating that oxygen-poor, α -solar abundance patterns are indeed present in SMC star-forming regions. Therefore, the relatively high C/O ratio observed in J003643 primarily reflects formation from oxygen-poor gas, rather than resulting from an unusually high carbon abundance.

Having established the likely chemical origin of J003643’s high C/O ratio, we next examined its *s*-process efficiency in the context of the comparative sample, using the [hs/ls]–[s/Fe] plane. Figure 8 shows the spectroscopically derived [hs/ls] ratios plotted against [s/Fe] for the comparative sample. Previous studies (Van Winckel & Reyniers 2000; Reyniers *et al.* 2004; van Aarle *et al.* 2013) have reported a positive correlation between [s/Fe] and [hs/ls], where stars with higher [s/Fe] tend to exhibit higher [hs/ls] ratios, reflecting a shift in the *s*-process path toward heavier elements at higher neutron exposures. Our analysis confirms this correlation and supports the theoretical expectation that stronger *s*-process enrichment corresponds to a greater relative production of *h*s elements compared to *l*s elements, due to increased neutron flux per iron seed. However, there is a 2σ scatter. This is unlikely to arise from observational uncertainties, which are relatively well constrained, but may reflect variations in neutron exposure, the structure and extent of the ^{13}C pocket, initial stellar mass, or other processes not fully captured by current models. Additionally, J003643 fits well within the least-squares relation derived from the comparative sample. This indicates that its heavy-to-light *s*-process element production is typical for its overall [s/Fe] value. Furthermore, as in the C/O–[s/Fe] plane, no systematic trend is observed with galactic environment, as stars from the Galaxy, LMC, and SMC remain evenly distributed.

Lastly, to examine how neutron exposure varies with stellar metallicity, Figure 9 presents the spectroscopically derived [hs/ls] ratio as a function of [Fe/H] for the comparative sample. The colours and symbols follow the same scheme as in Figure 6, and the black and green dotted line shows the theoretical prediction from a $2\,M_{\odot}$ FRUITY model (Cristallo *et al.* 2015) and $1.5\,M_{\odot}$ MONASH model (see Karakas 2014; Karakas & Lugaro 2016; Karakas *et al.* 2018) respectively. Previous studies (e.g. De Smedt *et al.* 2016) did not report a clear correlation between [Fe/H] and [hs/ls], likely due to the limited number (~ 14) of well-characterised post-AGB stars. However, with the inclusion of a more comprehensive sample of *s*-process enriched stars (~ 29), we now find a negative correlation between [Fe/H] and [hs/ls]. To explore the significance of this correlation, we performed a Pearson correlation test. Although the test gives a

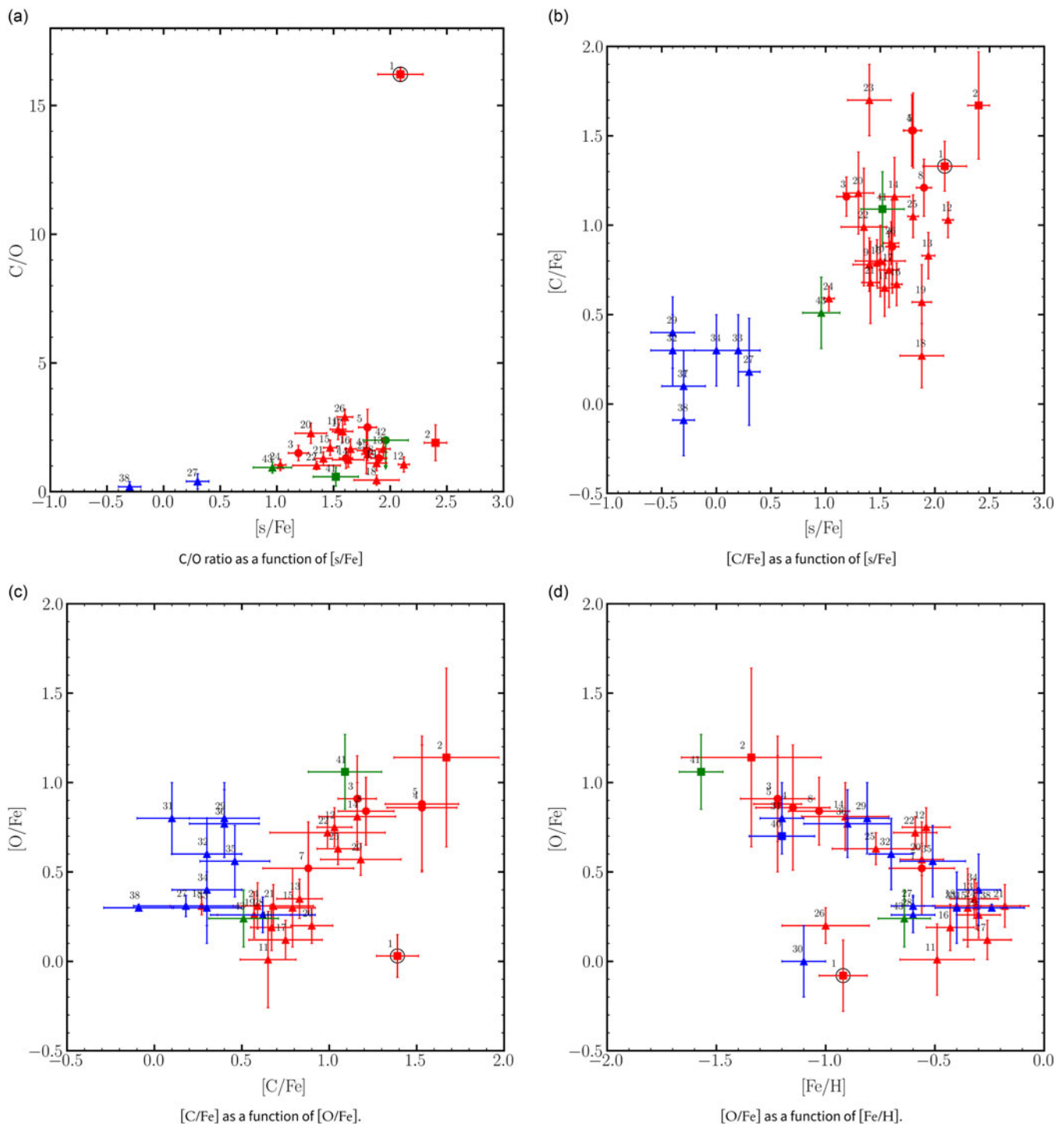


Figure 7. Comparison of key abundance ratios for the comparative sample of post-AGB stars. Red represents single s-process enriched post-AGB stars, blue corresponds to single non-s-process enriched post-AGB stars, and green denotes binary s-process enriched post-AGB stars. The target J003643 is highlighted with a black circle. LMC stars are shown as circles, SMC stars as squares, and Galactic stars as triangles. The numbers correspond to the index values listed in Table 8.

statistically significant negative correlation between $[\text{Fe}/\text{H}]$ and $[\text{hs}/\text{ls}]$ (slope = -0.35 , $r = -0.42$, $p = 0.024$), the object-to-object scatter is large, with objects 3, 4, and 29 falling outside the 2σ errors. Additionally, a significant fraction of the current sample does not match the model predictions. Although this trend supports theoretical predictions that lower-metallicity stars have

higher neutron-to-seed ratios, favouring the production of heavier s-process elements and yielding elevated $[\text{hs}/\text{ls}]$ ratios (see Gallino et al. 1998; Busso et al. 2001), a more complete sample is required to confirm the correlation. Additionally, J003643 agrees with the model prediction, further reinforcing that its s-process efficiency is consistent with expectations for its metallicity. However, the

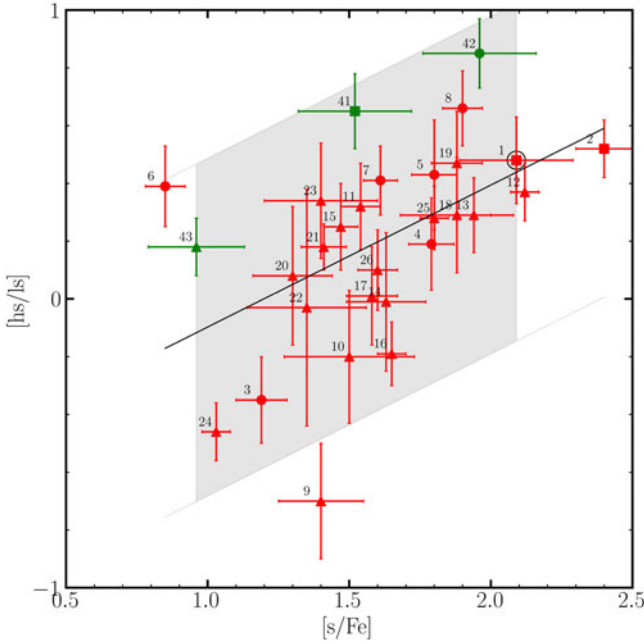


Figure 8. [hs/lr] as a function of [s/Fe] for the comparative sample of post-AGB stars. Colours, symbols and numbering remain the same as in Figure 6. The black line represents the least-squares fit, while the grey-shaded region indicates the 2σ standard deviation.

persistent disagreement between model predictions and observations for the majority of stars, especially at $[\text{Fe}/\text{H}] \lesssim -0.5$ dex, suggests that factors beyond metallicity, such as initial mass, TDU efficiency, dominant neutron source (^{13}C vs. ^{22}Ne), and mass-loss history, may significantly influence the resulting [hs/lr] ratios. This disagreement does not appear to depend on galactic environment, as stars from the Galaxy, LMC, and SMC are distributed uniformly in the [hs/lr]–[Fe/H] plane.

6.2 Understanding the nucleosynthetic origin of J003643 using predictions from different stellar evolutionary models

To investigate the nucleosynthetic origin of the heavy-element enrichment observed in J003643, we first assess whether its chemical composition could reflect pre-enrichment from its birth environment in the SMC. The SMC's chemical evolution is distinct from that of the Galaxy, characterised by low metallicities and modest enhancements in s -process elements. For example, Mucciarelli *et al.* (2023a) report that the average $[\text{Zr}/\text{Fe}]$, $[\text{Ba}/\text{Fe}]$, and $[\text{La}/\text{Fe}]$ abundances in SMC field giants remain below ~ 0.5 dex, even at low metallicities. In contrast, J003643 exhibits significantly higher values for these s -process indicators, pointing toward substantial intrinsic enrichment during its AGB phase. Additionally, studies of SMC field stars and clusters have revealed signs of enhanced r -process contributions, particularly in elements like europium (Eu), with $[\text{Eu}/\text{Fe}]$ often exceeding typical Galactic values at comparable metallicities (e.g. Reggiani *et al.* 2021; Mucciarelli *et al.* 2023b).

To further explore the intrinsic nucleosynthesis, we compared the spectroscopically derived abundances of J003643 with predictions from various stellar evolutionary models previously applied to the most s -process enriched post-AGB star, J004441 (see De

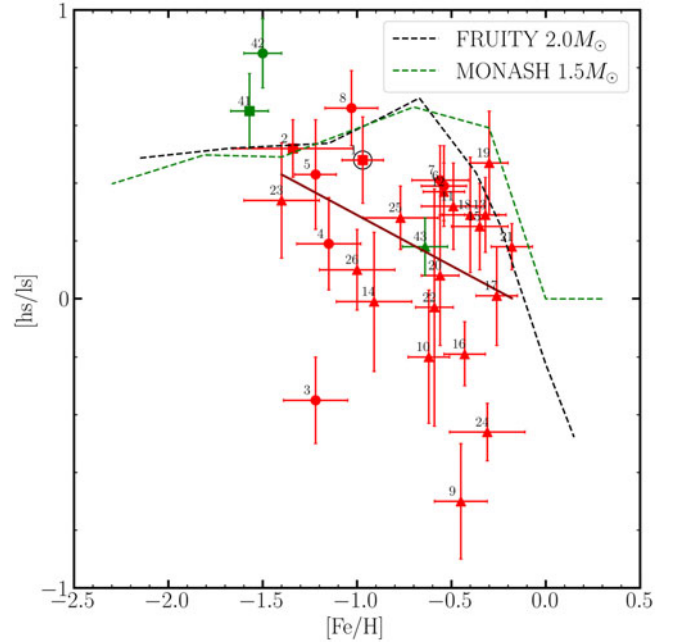


Figure 9. [hs/lr] ratio as a function of [Fe/H] for the comparative sample of post-AGB stars. Colours, symbols and numbering remain the same as in Figure 6. The black dotted line represents the theoretical prediction from a $2 M_{\odot}$ FRUITY model (Cristallo *et al.* 2015). The dark brown solid line represents the least-squares linear fit to the combined observational data.

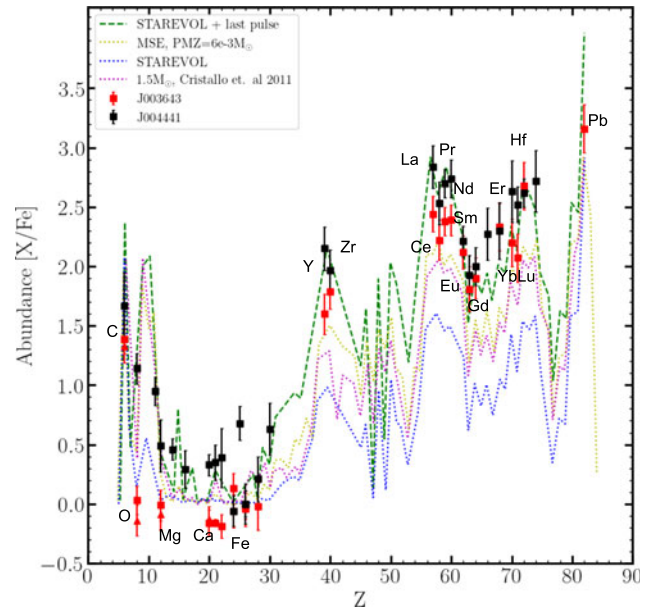


Figure 10. Comparison of the spectroscopically derived abundances of J003643 with stellar evolutionary model predictions reproduced from De Smedt *et al.* (2012), originally used for the post-AGB star J004441. Selected elements are labelled for reference. See text for details.

Smedt *et al.* 2012, references therein). As shown in Figure 10, adapted from De Smedt *et al.* (2012), the best-fitting model for J004441 is the STAREVOL model with a late thermal pulse. However, despite J003643 having similar stellar parameters and [s/Fe], this model fails to reproduce its observed abundances, particularly for C, O, several hs and ls elements, and most notably

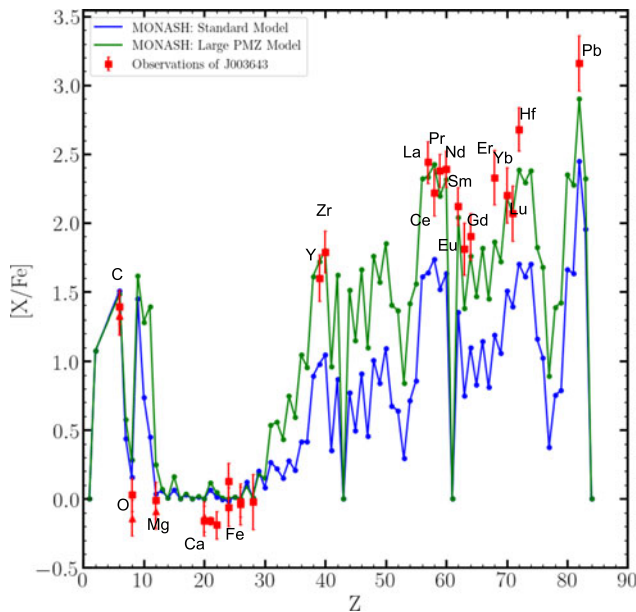


Figure 11. Comparison of the spectroscopically derived abundances of J003643 with predictions from the MONASH stellar evolution code. The y-axis represents the elemental abundance ratio $[X/Fe]$, and the x-axis denotes the atomic number Z . The red squares and triangles with error bars show the LTE and NLTE-corrected abundances of J003643 derived in this study (see Section 3.2). The blue line with dots corresponds to the predicted abundance pattern from the standard MONASH model with no convective overshoot, with an initial mass of $1.7 M_{\odot}$ and metallicity $Z = 0.0014$. The green line with dots corresponds to the predicted abundance pattern from the MONASH model with an initial mass of $1.7 M_{\odot}$ and metallicity $Z = 0.0014$, incorporating a large PMZ of $0.006 M_{\odot}$. Some elements are labelled for reference. See text for details.

Pb. Other models considered in the same study similarly fail to simultaneously match the full abundance pattern of J003643.

To perform a more targeted analysis of the heavy-element abundance of J003643, we strategically employed two sets of stellar evolution and stellar evolutionary models: the MONASH (Section 5.2) and FRUITY (Section 5.3) grids.

MONASH: The standard MONASH model (see Section 5.2 and Figure 11; blue line) significantly underpredicts the derived heavy-element abundances of J003643. However, the MONASH model, assuming a large PMZ of $0.006 M_{\odot}$ (see Section 5.2 and Figure 11; green line), predicts an s -process distribution that is very similar to the derived abundance of J003643, particularly for Fe-peak, the light s -process (ls) peak (Y, Zr) and the second peak (Ce, Nd). Despite this improvement, the predicted Pb abundance remains lower than derived. Additionally, elements such as Er and Hf are also underpredicted. The model attains a final $C/O = 12.5$, slightly overestimating the oxygen abundance.

FRUITY: The new magnetic mixing FRUITY model (see Section 5.3 and Figure 12; black line) slightly overestimates the abundances of CNO while the Fe-peak, ls and second s -process peak elements are well reproduced. The FRUITY model also underpredicts the derived Pb abundance. Additionally, it underpredicts the derived abundances of Eu, Er, Lu, Yb, and Hf. To explore this, we considered a modified version of the model that includes an initially r -process enhanced composition, adopting a solar r -process distribution as prescribed by Prantzos et al. (2020), scaled by $+2$ dex ($[r/Fe] = +2$ dex) from Ga to Bi (see Figure 12, magenta line). While the pre-enrichment scenario improves the fit for several r -process sensitive elements, particularly Eu, Er,

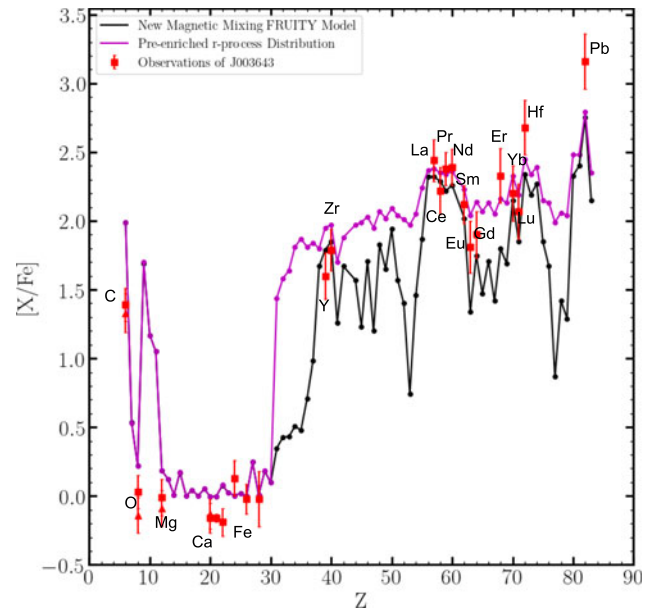


Figure 12. Comparison of the spectroscopically derived abundances of J003643 with theoretical nucleosynthesis predictions from the new magnetic mixing FRUITY model. The y-axis represents the elemental abundance ratio $[X/Fe]$, and the x-axis denotes the atomic number Z . The red squares and triangles with error bars show the LTE and NLTE-corrected abundances of J003643 derived in this study (see Section 3.2). The black line corresponds to the predicted abundance pattern from the new magnetic mixing FRUITY model with an initial mass of $2 M_{\odot}$ and metallicity $Z = 0.001$. The magenta line represents a version assuming a pre-enriched r -process component with $[r/Fe] = 2$ dex, applied from Ga to Bi. Some elements are labelled for reference. See text for details.

and Hf, it does not broadly affect the overall abundance pattern. This raises the possibility that J003643 may have formed from a locally r -process enriched ISM. This is supported by studies of the SMC, where field stars at low metallicities show systematically elevated $[Eu/Fe]$ ratios compared to their Galactic counterparts, indicating a more efficient early r -process enrichment in the SMC (Reggiani et al. 2021; Mucciarelli et al. 2023a). Although the average $[Eu/Fe]$ in the SMC remains below $+0.5$ dex, the possibility of localised enrichment episodes, e.g. from neutron star mergers, remains plausible.

i -process Models: Additionally, studies by Hampel et al. (2019) suggest that the abundance patterns of some Pb-poor post-AGB stars ($[Pb/Fe] < 2.5$ dex) may be better explained by i -process nucleosynthesis (Cowan & Rose 1977; Malaney 1986; Hampel et al. 2016). At intermediate neutron densities, the i -process boosts the ls and hs elements without producing large amounts of Pb. Although J003643 is not Pb-poor, we tested whether i -process nucleosynthesis could nonetheless reproduce its observed abundance pattern. The i -process model of Choplin et al. (2024), computed for a $1.5 M_{\odot}$, $Z = 0.001$ AGB star (Figure 13; cyan line), substantially overestimates the abundances of the ls elements while severely underpredicting the hs elements, including Pb. Similarly, the best-fitting i -process model from Hampel et al. (2019), assuming a neutron density of $n = 10^{11} \text{ cm}^{-3}$ (Figure 13; orange line), overestimates many of the heavy elements but still fails to reproduce the observed Pb abundance. These discrepancies suggest that i -process nucleosynthesis is unlikely to account for the observed abundance pattern of J003643.

Figure 13 summarises the best-fitting models, including ATON, MONASH, and FRUITY, as well as the i -process models

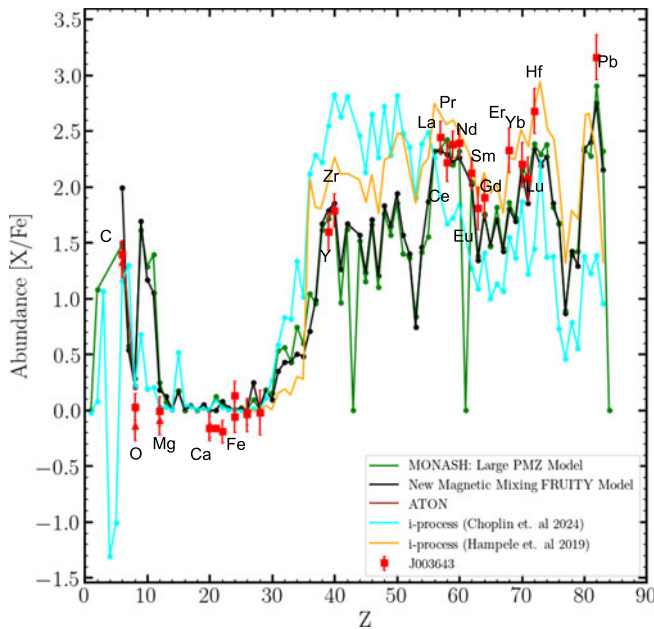


Figure 13. Comparison of the spectroscopically derived abundances of J003643 with theoretical nucleosynthesis predictions from various stellar evolutionary models. The y-axis represents the elemental abundance ratio $[X/Fe]$, and the x-axis denotes the atomic number Z . The red squares and triangles with error bars show the LTE and NLTE-corrected abundances of J003643 derived in this study (see Section 3.2). The green and black lines correspond to predictions from the best-fitting MONASH and FRUITY models, respectively, while the magenta line represents a version assuming a pre-enriched r -process component with $[r/Fe] = 2$ dex, applied from Ga to Bi. Additional comparisons include the ATON model (brown line; Ventura et al. 1998), an s -process model (yellow line; Lugaro et al. 2015), and i -process models (cyan Choplin et al. 2024 and orange lines; Hampel et al. 2019). Some elements are labelled for reference. See text for details.

from Hampel et al. (2019) and Choplin et al. (2024) for comparison. Overall, the comparison between the observed abundances of J003643 and predictions from various stellar evolutionary models indicates that its heavy element enrichment results from an intrinsic s -process nucleosynthesis involving efficient TDU. However, the observed Pb abundance remains higher than predicted by all current models, despite varying nucleosynthetic assumptions. This persistent discrepancy highlights a gap in our understanding of Pb production in AGB stars. As the first post-AGB star with a direct and precise Pb abundance measurement, J003643 offers a valuable benchmark for refining theoretical models of heavy-element nucleosynthesis.

6.3 Investigating the Pb abundances and the longstanding Pb discrepancy in post-AGB stars

Pb is expected to be a major product of the s -process in low-mass AGB stars ($<3M_{\odot}$), particularly at low metallicities where the neutron exposure is higher (e.g. Gallino et al. 1998; Goriely & Mowlavi 2000). As the endpoint of the s -process chain, theoretical models predict that Pb should be strongly overabundant relative to the ls and hs peaks, resulting in high $[Pb/hs]$ and $[Pb/ls]$ ratios (e.g. Busso et al. 2001; Lugaro et al. 2012). Accurate Pb measurements are thus essential to constrain the efficiency and termination of the s -process in these stars.

Despite these predictions, observational studies of s -process enriched post-AGB stars have consistently failed to detect Pb at

the expected levels. In most cases, only upper limits have been obtained using SSF, due to the weakness of Pb lines in the optical, blending issues, and uncertainties in atomic data (e.g. De Smedt et al. 2016; Kamath & Van Winckel 2021). Depending on stellar temperature, Pb is probed using either the Pb I 4 057.807 Å line or the Pb II 5 608.853 Å line. Upper limits of derived Pb abundance for both single and binary s -process enriched post-AGB stars, compiled from the literature, are summarised in Table 6. For J003643, however, we derive the first direct Pb abundance measurement.

Previous studies have shown that for post-AGB stars with low metallicities ($[Fe/H] < -0.5$ dex), the derived $[Pb/hs]$ and $[Pb/ls]$ upper limits were significantly lower than theoretical predictions, with the discrepancy growing at lower metallicities (see Van Winckel & Reyniers 2000; De Smedt et al. 2012, 2015, 2016). This persistent disagreement between predicted and deduced Pb abundances remains one of the key unresolved challenges in s -process nucleosynthesis (Kamath & Van Winckel 2021).

Proposed explanations for this discrepancy include incomplete or inaccurate atomic data for Pb lines, limitations in spectral modelling, poor S/N in the blue region near the Pb I line, and incomplete treatment of physical processes governing the s -process in low-mass stars (e.g. Lugaro et al. 2012; Karakas & Lugaro 2016; De Smedt et al. 2016). Additional effects – such as rotation, internal mixing (e.g. gravity-wave induced), and enhanced mass loss during or prior to the thermally-pulsing AGB phase – may add further uncertainty to the results (e.g. Herwig 2005; Siess, Goriely, & Langer 2004; Karakas & Lattanzio 2014; Piersanti et al. 2013).

NLTE effects may also contribute to the discrepancy, particularly in warm, low-gravity post-AGB stars. As discussed in Kamath & Van Winckel (2021), NLTE calculations by Mashonkina et al. (2012) for the Pb I line at 4 057.807 Å in the Sun and a sample of metal-poor stars ($-2.95 < [Fe/H] < -0.7$) showed that NLTE effects lead to systematically lower line absorption, resulting in positive abundance corrections of $\Delta_{NLTE} \sim 0.2$ – 0.45 dex. These effects become more pronounced at lower metallicities. However, the calculations were performed for stars with lower T_{eff} and higher surface gravity than typical post-AGB stars.

In this study, we perform an exploratory NLTE calculation using a simplified toy model for neutral Pb I to estimate NLTE effects on Pb abundance determinations. We focus on the neutral Pb I line, as Pb II – the dominant ionisation stage – is expected to remain close to LTE due to its stronger coupling with the local radiation field, making NLTE effects less significant (Mashonkina et al. 2012).

As in Section 3.2.1, the NLTE calculations were performed using Balder (Amarsi et al. 2018b), based on Multi3D (Leenaarts & Carlsson 2009). The calculations were performed on a grid of MARCS model atmospheres (see Amarsi et al. 2020 for details), for a range of microturbulence values (1, 2, and 5 km s⁻¹) and $[Pb/Fe]$ (from -1.5 to $+3.5$ in steps of 0.5 dex). The abundance corrections were interpolated or extrapolated (taking the edge values) onto the stellar parameters of interest.

For this test, a simple ‘toy’ model atom was constructed for neutral lead (Pb I). Energy levels and bound-bound transition rates were taken from the National Institute of Standards and Technology Atomic Spectra Database (NIST ASD; Ralchenko & Kramida 2020). Photoionisation cross-sections were assumed to be hydrogenic. Inelastic electron collisions were estimated using the recipe of van Regemorter (1962) for excitation and Allen (1973) for ionisation. Inelastic hydrogen collisions were estimated

Table 6. LTE and NLTE abundance ratios of lead ([Pb/ls] and [Pb/hs]) for s-process enriched single and binary post-AGB stars in the Galaxy and MCs, where lead abundance measurements are available. The table also includes their effective temperature and metallicity. See text for details.

Index	Object name	LMC/SMC/Galaxy	T_{eff}	[Fe/H]	$\log \varepsilon \text{ Pb I}$	[Pb I/Fe]	$\log \varepsilon \text{ Pb II}$	[Pb II/Fe]	[Pb/hs]	[Pb/ls]	NLTE [Pb/hs]	NLTE [Pb/ls]
1	J003643	SMC	$7\,552 \pm 91$	-0.92 ± 0.11	...	...	4.29	3.58	1.39 ± 0.15	1.865 ± 0.16	...	...
2	J004441.04-732136.4	SMC	$6\,250 \pm 125$	-1.34 ± 0.32	<3.00	<2.58	...	...	<0.00	<0.52	<0.34	<0.86
3	J050632.10-714229.8	LMC	$6\,750 \pm 125$	-1.22 ± 0.17	<2.05	<1.52	...	...	<0.45	<0.10	<0.80	<0.45
4	J052043.86-692341.0	LMC	$5\,750 \pm 125$	-1.15 ± 0.17	<2.00	<1.40	...	...	<-0.45	<-0.27	<-0.15	<0.03
5	J053250.69-713925.8	LMC	$5\,500 \pm 125$	-1.22 ± 0.11	<2.23	<1.70	...	...	<-0.24	<0.19	<0.03	<0.46
7	J051213.81-693537.1	LMC	$5\,875 \pm 125$	-0.56 ± 0.15	<3.30	<2.11	...	...	<0.37	<0.78	<0.47	<0.88
8	J051848.86-700246.9	LMC	$6\,000 \pm 125$	-1.03 ± 0.14	<2.62	<1.93	...	...	<-0.19	<0.47	<0.09	<0.75
11	IRAS 05113+1347	Galaxy	$5\,500 \pm 125$	-0.49 ± 0.20	<2.65	<1.44	...	...	<-0.21	<0.11	<-0.06	<0.26
12	IRAS 05341+0852	Galaxy	$6\,750 \pm 125$	-0.54 ± 0.20	<3.15	<2.10	...	...	<-0.14	<0.23	<0.12	<0.49
13	IRAS 06530-0213	Galaxy	$7\,375 \pm 125$	-0.32 ± 0.20	<4.10	<2.73	<4.19	<2.76	<0.69	<0.98	<1.03	<1.32
14	IRAS 07134+1005	Galaxy	$7\,250 \pm 125$	-0.91 ± 0.20	<2.79	<2.01	...	...	<0.38	<0.37	<0.75	<0.74
15	IRAS 07430+1115	Galaxy	$6\,000 \pm 125$	-0.31 ± 0.20	<2.50	<1.07	...	...	<-0.48	<-0.23	<-0.32	<-0.07
16	IRAS 08143-4406	Galaxy	$7\,000 \pm 125$	-0.43 ± 0.20	<3.20	<1.90	...	...	<0.32	<0.13	<0.61	<0.42
17	IRAS 08281-4850	Galaxy	$7\,875 \pm 125$	-0.26 ± 0.20	<4.20	<2.74	<4.20	<2.71	<1.13	<1.14	<1.48	<1.49
19	IRAS 13245-5036	Galaxy	$9\,500 \pm 125$	-0.26 ± 0.20	...	...	<4.40	<2.94	<0.91	<1.38	...	...
20	IRAS 14325-6428	Galaxy	$8\,000 \pm 125$	-0.56 ± 0.20	...	...	<3.79	<2.6	<1.27	<1.35	...	...
21	IRAS 14429-4539	Galaxy	$9\,375 \pm 125$	-0.64 ± 0.20	...	...	<4.40	<2.83	<1.36	<1.54	...	...
22	IRAS 19500-1709	Galaxy	$8\,000 \pm 125$	-0.59 ± 0.20	<3.89	<2.72	...	...	<1.38	<1.35	<1.77	<1.74
24	IRAS 22223+4327	Galaxy	$6\,500 \pm 125$	-0.3 ± 0.20	<3.25	<1.82	...	...	<0.94	<0.48	<1.14	<0.68
25	IRAS 22272+5435	Galaxy	$5\,750 \pm 125$	-0.77 ± 0.20	<2.70	<1.72	...	...	<-0.18	<0.11	<0.02	<0.31
43	HD 168616	Galaxy	$7\,250 \pm 125$	-0.64 ± 0.20	<2.75	<1.51	...	...	<0.59	<0.77	<0.92	<1.10

Notes: All lead abundances and ratios, except for J003643, are upper limits derived using the SSF technique and have been adopted from De Smedt et al. (2016) and Kamath & Van Winckel (2021). NLTE-corrected Pb abundance ratios are presented in the last two columns. See text for details.

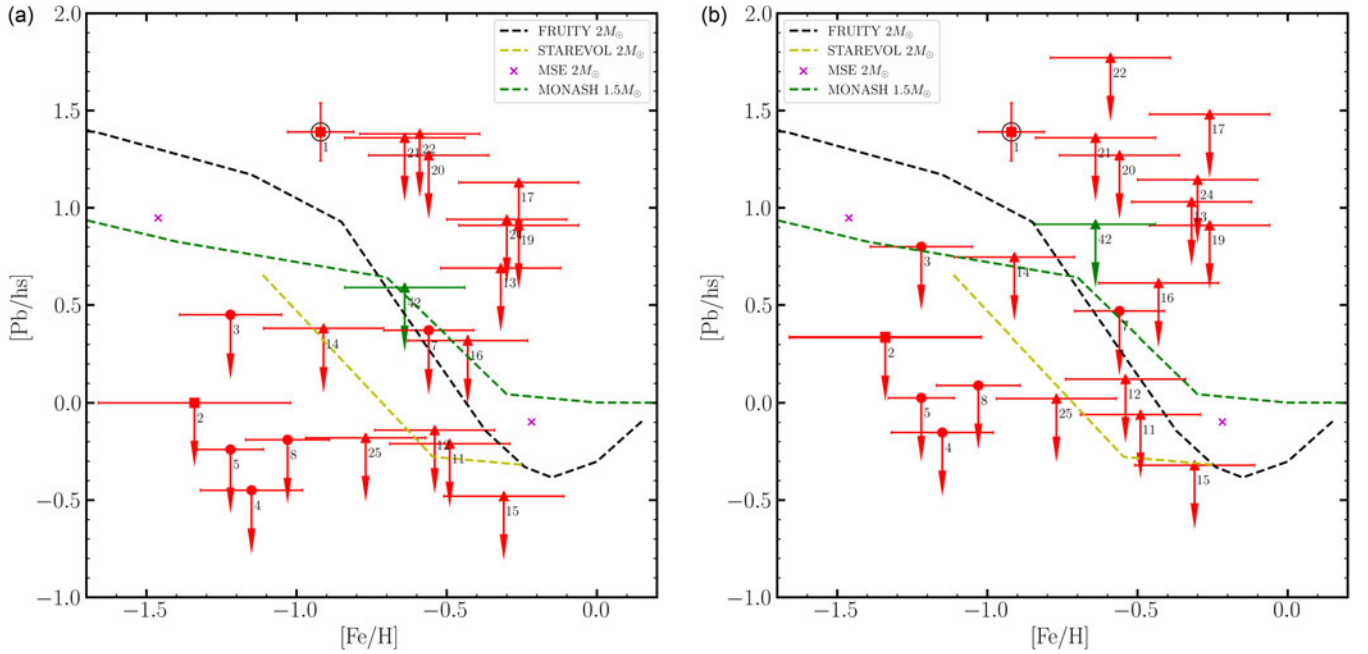


Figure 14. Comparison of $[Pb/hs]$ versus $[Fe/H]$ for post-AGB stars with and without NLTE corrections. The left panel shows LTE-based upper limits of Pb abundances, while the right panel includes NLTE-corrected upper limits of Pb abundances derived in this study. Red symbols represent single s-process enriched post-AGB stars, while green symbols indicate binary s-process enriched post-AGB stars. LMC stars are shown as circles, SMC stars as squares, and Galactic stars as triangles. Downward arrows denote upper limits for all stars except J003643. The error bars along the x-axis indicate uncertainties in $[Fe/H]$. Theoretical predictions from FRUITY, STAREVOL, MSE, and MONASH stellar evolutionary models are overlaid for reference. See text for more details.

using the Drawin recipe Lambert (1993); hydrogen collisional ionisation was assumed to be negligible (Barklem *et al.* 2011). For the collisional excitation recipes, $\log gf$ was assumed to be -1.5 for permitted lines (if missing from NIST ASD), and -3 for forbidden lines.

This toy model is somewhat simpler than that used in Mashonkina *et al.* (2012). Possibly the main limitation here relative to that work is the absence of bound-bound transitions of high excitation potential (where Mashonkina *et al.* 2012 include these via their own calculations using the Cowan code). Nevertheless, the resulting abundance corrections for the non-detected and hence upper limit of the Pb I 4 057.807 Å line are of the same order of magnitude as those presented in their Table 1, taking into account different assumptions about the inelastic hydrogen collisions. This could be because the NLTE effects are controlled by the photoionisation transitions as well as the radiative pumping of UV lines, which are included in our toy model. The $[Pb/Fe]$ after applying the NLTE corrections for the post-AGB stars are presented in the last column of Table 6.

To further investigate the impact of NLTE effects on Pb abundance determinations, we compare the derived $[Pb/hs]$ and $[Pb/l_s]$ upper limits by incorporating the derived NLTE corrections from the toy model for the Pb I lines. Figures 14 and 15 present the $[Pb/hs]$ and $[Pb/l_s]$ upper limits (except for J003643) as a function of metallicity ($[Fe/H]$), respectively, adapted from De Smedt *et al.* (2016), for the comparative sample. These figures also include predictions from various stellar evolutionary models: $2M_{\odot}$ FRUITY model (Cristallo *et al.* 2015), $2M_{\odot}$ STAREVOL code (Goriely & Siess 2004; Siess 2007, and references therein), $2M_{\odot}$ Mount-Stromlo Evolutionary (MSE) predictions (Fishlock *et al.* 2014; Karakas 2010, and references therein), and $1.5 M_{\odot}$ MONASH

model (Karakas 2014; Karakas & Lugaro 2016; Karakas *et al.* 2018, see). In both cases, the left figure shows LTE-based upper limits of Pb abundances, while the right figure includes NLTE-corrected upper limits of Pb abundances derived in this study. We note that NLTE corrections have been derived and applied exclusively to the upper limits of Pb abundances derived using Pb I lines, with no corrections applied to Pb II lines. For all stars except J003643, the $[Pb/hs]$ and $[Pb/l_s]$ ratios represent upper limits. The error bars along the x-axis indicate uncertainties in the metallicity ($[Fe/H]$) of the stars.

The comparison reveals that even after applying NLTE corrections, the majority of post-AGB stars at low metallicities ($[Fe/H] < -0.5$ dex) exhibit significantly lower upper limits of $[Pb/hs]$ and $[Pb/l_s]$ values than theoretical predictions. Figure 14 shows that roughly half of the existing sample with $[Fe/H] < -0.5$ dex are compatible with the theoretical predictions within the error bars. This, however, may reflect observational bias because the current sample is far from complete. Although NLTE corrections tighten the upper limits of the Pb abundances, they do not fully resolve the disagreement at low metallicities. Additionally, at higher metallicities, the NLTE corrections lead to an overall increase in the derived upper limits of $[Pb/hs]$ and $[Pb/l_s]$ compared to their LTE-based values. This result suggests that NLTE effects must be accounted for in Pb abundance determinations, but they are insufficient to explain the observed discrepancies at low metallicities. Furthermore, J003643 is the first post-AGB star with a clear detection and precise derivation of Pb abundance, rather than an upper limit, which is significantly higher than that of the comparative sample (see Table 6). Yet, even this robust detection remains markedly underpredicted by current nucleosynthesis models. This underscores persistent shortcomings in

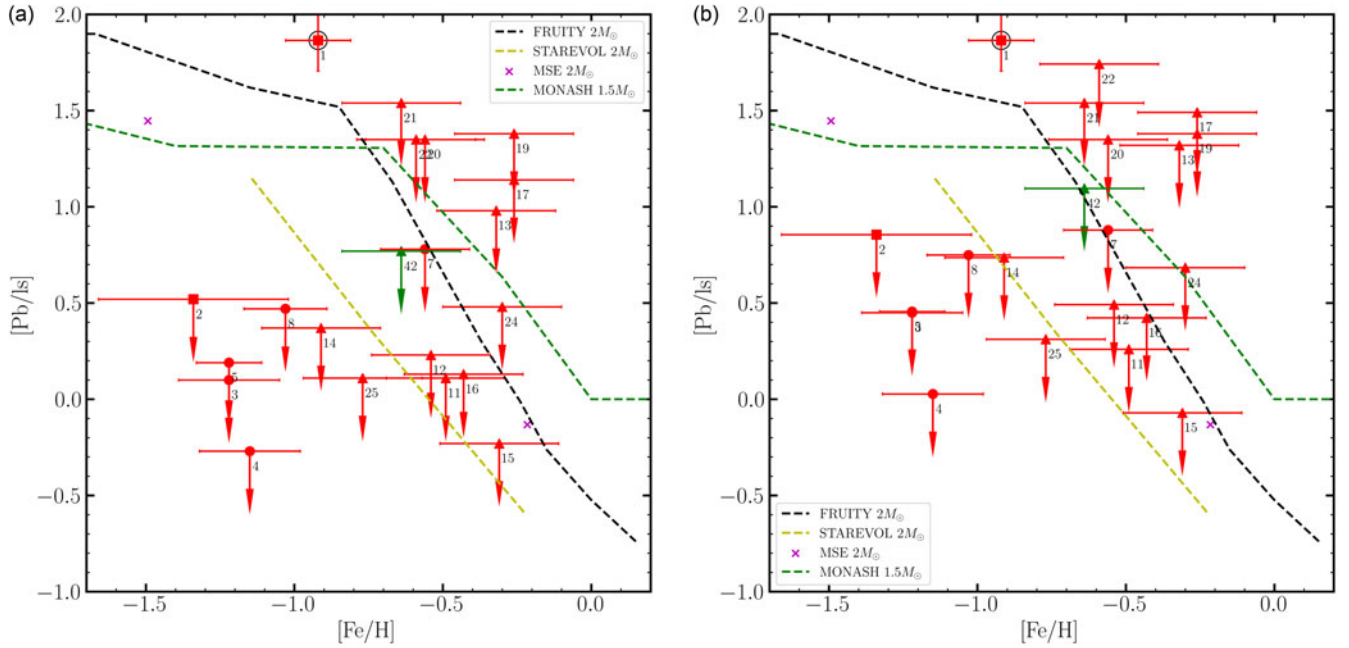


Figure 15. Same as Figures 14, but for [Pb]/[s] versus [Fe/H].

our theoretical understanding of s -process nucleosynthesis, particularly in the context of explaining Pb production at low metallicities.

7. Summary and conclusions

In this paper, we expand the known chemical diversity among s -process enriched post-AGB stars, presenting a detailed abundance analysis of J003643, a single post-AGB star in the SMC. Using high-resolution VLT/UVES spectra and detailed analysis with E-iSpec, we derived the atmospheric parameters and elemental abundances of J003643. J003643 exhibits a C/O ratio of 16.21 ± 0.22 . With a $[s/\text{Fe}] = 2.09$ dex, J003643 also provides the first direct Pb abundance measurement in a post-AGB star ($[\text{Pb}/\text{Fe}] = 3.16 \pm 0.18$ dex) using the Pb II 5608 Å line, consistent across both EW and SSF methods.

To investigate the origin of J003643's relatively high C/O ratio, we compared its key abundance ratios with those of ~ 28 comparative sample of post-AGB stars from the Galaxy, LMC, and SMC. While J003643 follows the expected $[\text{C}/\text{Fe}]$ – $[s/\text{Fe}]$ trend, consistent with a typical TDU history, it stands out as a clear outlier when compared in both the $[\text{O}/\text{Fe}]$ – $[\text{C}/\text{Fe}]$ and $[\text{O}/\text{Fe}]$ – $[\text{Fe}/\text{H}]$ planes. J003643 exhibits a relatively low $[\text{O}/\text{Fe}] = -0.08 \pm 0.20$ dex and $[\alpha/\text{Fe}] \approx 0$ dex compared to its Galactic and LMC counterparts with similar $[\text{C}/\text{Fe}]$ and $[\text{Fe}/\text{H}]$, which typically show $[\text{O}/\text{Fe}] \approx 0.5$ – 1.0 dex. This relatively low $[\text{O}/\text{Fe}]$ and α -abundance of J003643 is consistent with the chemical evolution of SMC at $[\text{Fe}/\text{H}] \approx -1$ dex, and contrasts with the α -enhanced trend observed in the Galaxy and LMC at the same metallicity. These comparisons suggest that the high C/O ratio in J003643 arises primarily from an oxygen-poor natal environment, rather than from an unusually high carbon enrichment.

Additionally, to investigate the nucleosynthetic origin of J003643's heavy-element abundances, we first considered whether

they could reflect its birth environment in the SMC. However, its abundance pattern differs markedly from that of typical SMC field giant stars, which are commonly used to trace the chemical evolution of the SMC. We then compared its abundances with predictions from various stellar evolutionary models: ATON, MONASH, and FRUITY, the latter two incorporating post-processing nucleosynthesis. While the models reproduce the observed abundance of CNO, α , Fe-peak and s -process elements, they systematically underpredicts Pb abundance, despite the varying nucleosynthetic assumptions. This highlights persistent gaps in our understanding of lead production in AGB stars.

To explore this, we analysed Pb abundances across the comparative sample of s -process enriched post-AGB stars using NLTE-corrected values from a simplified toy model. While NLTE corrections bring the upper limits a bit nearer to the model predictions, improving consistency in some cases, major discrepancies remain for stars with $[\text{Fe}/\text{H}] \lesssim -0.5$ dex, further reinforcing our limited understanding of lead production.

In summary, J003643 with its high C/O ratio and the first precise measurement of Pb abundance presents a valuable benchmark for advancing our understanding of CNO and s -process nucleosynthesis, providing critical constraints on AGB nucleosynthesis, dredge-up efficiency, and the development of improved model prescriptions for key heavy elements.

Acknowledgement. This study is based on observations collected with the Very Large Telescope at the ESO Paranal Observatory (Chile) of program number 092.D-0485. MM1 acknowledges the financial support provided by the International Macquarie Research Excellence Scholarship (iMQRES) program for the duration of this research. MM1, DK, and MM2 also acknowledge the ARC Centre of Excellence for All Sky Astrophysics in 3 Dimensions (ASTRO 3D). DK and HVW acknowledge the support of the Australian Research Council Discovery Project DP240101150. AMA acknowledges the support from the Swedish Research Council (VR 2020-03940) and from the Crafoord Foundation via the Royal Swedish Academy of Sciences

(CR 2024-0015). SC acknowledges the funding by the European Union – NextGenerationEU RFF M4C2 1.1 PRIN 2022 project ‘2022RJLWHN URKA’ and the INAF Theory Grant ‘Understanding Rprocess & Kilonovae Aspects (URKA)’. DV acknowledges the financial support from the German-Israeli Foundation (GIF No. I-1500-303.7/2019). AK acknowledges the support of the Australian Research Council Centre of Excellence for All Sky Astrophysics in 3 Dimensions (ASTRO 3D), through project number CE170100013. P.V. acknowledges the support received from the PRIN INAF 2019 grant ObFu 1.05.01.85.14 (‘Building up the halo: chemodynamical tagging in the age of large surveys’, PI. S. Lucatello). HVW acknowledges support from the Research Council, KU Leuven, under grant numbers IRI-I000225N and I000325N.

Supplementary material. The supplementary material for this article can be found at <https://doi.org/10.1017/pasa.2025.10085>.

Data availability statement. The data underlying this article is made available online.

References

- Abia, C., de Laverny, P., & Wahlin, R. 2008, *A&A*, 481, 161
- Allen, C. W. 1973, *AQ*
- Amarsi, A. M., Barklem, P. S., Asplund, M., Collet, R., & Zatsarinny, O. 2018a, 616, A89
- Amarsi, A. M., Barklem, P. S., Collet, R., Grevesse, N., & Asplund, M. 2019, 624, A111
- Amarsi, A. M., et al. 2018b, 615, A139
- Amarsi, A. M., et al. 2020, 642, A62
- Arellano Ferro, A., Giridhar, S., & Mathias, P. 2001, *A&A*, 368, 250
- Asplund, M., Amarsi, A. M., & Grevesse, N. 2021, 653, A141
- Asplund, M., Grevesse, N., Sauval, A. J., & Scott, P. 2009, 47, 481
- Barklem, P. S., et al. 2011, 530, A94
- Bensby, T., Feltzing, S., Lundström, I., & Ilyin, I. 2005, 433, 185
- Bessell, M. S. 1990, 102, 1181
- Blanco-Cuaresma, S. 2019, 486, 2075
- Blanco-Cuaresma, Soubiran, Heiter, Jofrà Blanco-Cuaresma, S., Soubiran, C., Heiter, U., & Jofré, P. 2014, 569, A111
- Buntain, J. F., et al. 2017, 471, 824
- Busso, M., Gallino, R., Lambert, D. L., Travaglio, C., & Smith, V. V. 2001, *ApJ*, 557, 802
- Busso, M., Gallino, R., & Wasserburg, G. J. 1999, 37, 239
- Cardelli, J. A., Clayton, G. C., & Mathis, J. S. 1989, *ApJ*, 345, 245
- Castelli, F., & Kurucz, R. L. 2003, in *IAU Symposium*, Vol. 210, *Modelling of Stellar Atmospheres*, ed. N. Piskunov, W. W. Weiss, & D. F. Gray, 20P
- Chopin, A., Siess, L., & Goriely, S. 2021, 648, A119
- Chopin, A., Siess, L., Goriely, S., & Martinet, S. 2024, 684, A206
- Cowan, J. J., & Rose, W. K. 1977, 212, 149
- Cristallo, S., Straniero, O., Piersanti, L., & Gobrecht, D. 2015, 219, 40
- Cristallo, S., et al. 2011, *ApJS*, 197, 17
- Cseh, B., et al. 2018, 620, A146
- Cutri, R. M., et al. 2003, *VizieR Online Data Catalog*, II/246
- Cutri, R. M., et al. 2012, *Explanatory Supplement to the WISE All-Sky Data Release Products*, *Explanatory Supplement to the WISE All-Sky Data Release Products*
- De Smedt, K., et al. 2012, *A&A*, 541, A67
- De Smedt, K., et al. 2016, *A&A*, 587, A6
- De Smedt, K., Van Winckel, H., Kamath, D., & Wood, P. R. 2015, *A&A*, 583, A56
- Dekker, H., D’Odorico, S., Kaufer, A., Delabre, B., & Kotzlowski, H. 2000, in *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*, Vol. 4008, *Optical and IR Telescope Instrumentation and Detectors*, ed. M. Iye, & A. F. Moorwood, 534
- Dell’Aglì, F., et al. 2015, 447, 2992
- Deroo, P., Reyniers, M., van Winckel, H., Goriely, S., & Siess, L. 2005, 438, 987
- Fishlock, C. K., Karakas, A. I., Lugaro, M., & Yong, D. 2014, *ApJ*, 797, 44
- Gallino, R., et al. 1998, *ApJ*, 497, 388
- Gezer, I., et al. 2015, 453, 133
- Goriely, S., & Mowlavi, N. 2000, 362, 599
- Goriely, S., & Siess, L. 2004, 421, L25
- Graczyk, D., et al. 2012, *PIAU*, 8, 222
- Hampel, M., Karakas, A. I., Stancliffe, R. J., Meyer, B. S., & Lugaro, M. 2019, 887, 11
- Hampel, M., Stancliffe, R. J., Lugaro, M., & Meyer, B. S. 2016, 831, 171
- Herwig, F. 2005, 43, 435
- Höfner, S., & Olofsson, H. 2018, 26, 1
- Iben, I., J. 1974, 12, 215
- Kamath, D., et al. 2023, 519, 2169
- Kamath, D., Karakas, A. I., & Wood, P. R. 2012, *ApJ*, 746, 20
- Kamath, D., & Van Winckel, H. 2021, *Universe*, 7, doi: [10.3390/universe7110446](https://doi.org/10.3390/universe7110446)
- Kamath, D., & Van Winckel, H. 2022, *Universe*, 8, 233
- Kamath, D., et al. 2022, *ApJL*, 927, L13
- Kamath, D., et al. 2017, *ApJ*, 836, 15
- Kamath, D., Wood, P. R., & Van Winckel, H. 2014, 439, 2211
- Karakas, A. I. 2010, *MNRAS*, 403, 1413
- Karakas, A. I. 2014, 445, 347
- Karakas, A. I., & Lattanzio, J. C. 2014, *PASA*, 31, e030
- Karakas, A. I., & Lugaro, M. 2016, *ApJ*, 825, 26
- Karakas, A. I., et al. 2018, *MNRAS*, 477, 421
- Klochova, V. G., & Kipper, T. 2006, *BaltA*, 15, 395
- Kluska, J., et al. 2022, 658, A36
- Lambert, D. L. 1993, *PhST*, 47, 186
- Lattanzio, J. C. 1986, 311, 708
- Leenaarts, J., & Carlsson, M. 2009, in *Astronomical Society of the Pacific Conference Series*, Vol. 415, *The Second Hinode Science Meeting: Beyond Discovery-Toward Understanding*, ed. B. Lites, M. Cheung, T. Magara, J. Mariska, & K. Reeves, 87
- Lind, K., Bergemann, M., & Asplund, M. 2012, *MNRAS*, 427, 50
- Lodders, K. 2021, *SSR*, 217, 44
- Luck, R. E., Moffett, T. J., Barnes III, T. G., & Gieren, W. P. 1998, *AJ*, 115, 605
- Lugaro, M., et al. 2015, 583, A77
- Lugaro, M., Herwig, F., Lattanzio, J. C., Gallino, R., & Straniero, O. 2003, 586, 1305
- Lugaro, M., Karakas, A. I., Stancliffe, R. J., & Rijs, C. 2012, 747, 2
- Lugaro, M., Pignatari, M., Reifarth, R., & Wiescher, M. 2023, *AnRNPS*, 73, 315
- Magg, E., et al. 2022, 661, A140
- Malaney, R. A. 1986, *MNRAS*, 223, 683
- Mallinson, J. W. E., Lind, K., Amarsi, A. M., & Youakim, K. 2024, 687, A5
- Mashonkina, L., Ryabtsev, A., & Frebel, A. 2012, 540, A98
- Menon, M., Kamath, D., Mohorian, M., Van Winckel, H., & Ventura, P. 2024, 41, e025
- Merrill, P. W. 1952, 116, 21
- Mohorian, M., et al. 2024, *MNRAS*, 530, 761
- Molina, R. E., Pereira, C. B., & Arellano Ferro, A. 2019, *ArXiv e-prints*, [arXiv:1901.05866](https://arxiv.org/abs/1901.05866)
- Mucciarelli, A., et al. 2023a, 671, A124
- Mucciarelli, A., et al. 2023b, 677, A61
- Nidever, D. L., et al. 2020, *ApJ*, 895, 88
- Ochsenbein, F., Bauer, P., & Marcout, J. 2000, 143, 23
- Oomen, G.-M., et al. 2018, *A&A*, 620, A85
- Pereira, C. B., Lorenz-Martins, S., & Machado, M. 2004, *A&A*, 422, 637
- Pereira, C. B., Sales Silva, J. V., Chavero, C., Roig, F., & Jilinski, E. 2011, *A&A*, 533, A51
- Pérez-Mesa, V., et al. 2019, *A&A*, 623, A151
- Piersanti, L., Cristallo, S., & Straniero, O. 2013, 774, 98
- Prantzos, N., Abia, C., Cristallo, S., Limongi, M., & Chieffi, A. 2020, 491, 1832
- Ralchenko, Y., & Kramida, A. 2020, *Atoms*, 8, 56
- Rao, S. S., Giridhar, S., & Lambert, D. L. 2012, *MNRAS*, 419, 1254
- Reddy, B. E., Bakker, E. J., & Hrivnak, B. J. 1999, *ApJ*, 524, 831
- Reddy, B. E., Lambert, D. L., & Prieto, C. A. 2006, *MNRAS*, 367, 1329
- Reggiani, H., Schlauffman, K. C., Casey, A. R., Simon, J. D., & Ji, A. P. 2021, 162, 229
- Reyneirs, M. 2000, PhD thesis, Institute of Astronomy, KU Leuven

- Reyniers, M., & Cuypers, J. 2005, *A&A*, 432, 595
- Reyniers, M., Van Winckel, H., Gallino, R., & Straniero, O. 2004, 417, 269
- Richter, O. G., Tammann, G. A., & Huchtmeier, W. K. 1987, 171, 33
- Şahin, T., Lambert, D. L., Klochkova, V. G., & Tavganskaya, N. S. 2011, *MNRAS*, 410, 612, doi: [10.1111/j.1365-2966.2010.17467.x](https://doi.org/10.1111/j.1365-2966.2010.17467.x)
- Shetye, S., et al. 2020, 635, L6
- Siess, L. 2007, 476, 893
- Siess, L., Goriely, S., & Langer, N. 2004, 415, 1089
- Snedden, C. 1973, PhD thesis, Ph. D. thesis
- Trabucchi, M., & Mowlavi, N. 2022, 658, L1
- van Aarle, E., Van Winckel, H., De Smedt, K., Kamath, D., & Wood, P. R. 2013, 554, A106
- van Aarle, E., et al. 2011, *A&A*, 530, A90+
- Van der Swaelmen, M., Hill, V., Primas, F., & Cole, A. A. 2013, 560, A44
- van Regemorter, H. 1962, 136, 906
- Van Winckel, H. 1997, *A&A*, 319, 561
- Van Winckel, H. 2003, *ARA&A*, 41, 391
- Van Winckel, H., & Reyniers, M. 2000, 354, 135
- Ventura, P., D'Antona, F., & Mazzitelli, I. 2008, 316, 93
- Ventura, P., Karakas, A., Dell'Agli, F., Garca-Hernández, D. A., & Guzman-Ramirez, L. 2018, *MNRAS*, 475, 2282
- Ventura, P., Zeppieri, A., Mazzitelli, I., & D'Antona, F. 1998, 334, 953
- Vescovi, D., Cristallo, S., Busso, M., & Liu, N. 2020, 897, L25
- Vescovi, D., Cristallo, S., Palmerini, S., Abia, C., & Busso, M. 2021, 652, A100
- Werner, K., Rauch, T., Kučas, S., & Kruk, J. W. 2015, 574, A29

Appendix A. Linelist of J003643

Table A1. Linelist of J003643.

Ion	Wavelength (Å)	log gf	EP(eV)	EW (mÅ)
C 1	4 812.917	−3.377	7.480	15.50
C 1	4 932.049	−1.658	7.685	144.80
C 1	5 017.086	−2.457	7.946	43.90
C 1	5 024.919	−2.728	7.946	22.40
C 1	5 039.057	−1.790	7.946	100.40
C 1	5 057.681	−2.223	8.647	22.80
C 1	5 153.569	−2.187	8.647	31.00
C 1	5 380.325	−1.616	7.685	143.40
C 1	5 547.265	−2.253	8.640	20.80
C 1	6 002.980	−2.169	8.647	17.00
C 1	6 007.173	−2.062	8.640	20.40
...

Notes: Linelist used for the abundance determination of J003643. The last column shows the calculated equivalent width (EW). The full line list used for the spectroscopic analysis of J003643 is provided as online [supplementary material](#).

Appendix B. Comparative Sample of Post-AGB Stars

In this appendix, we present the comparative sample of post-AGB stars discussed in this study. Table 8 provides a comprehensive list of single *s*-process enriched post-AGB stars, single non-*s*-process enriched post-AGB stars, and binary *s*-process enriched post-AGB stars, spanning different galactic environments, including the LMC, SMC, and the Galaxy. This dataset serves as the basis for our comparative analysis of heavy-element enrichment, neutron irradiation efficiency, and the dependence of chemical signatures on stellar parameters, as discussed in [Section 6.1](#).

Table B1. Fundamental properties, chemical abundances, and s-process indices of the entire sample of s-process -rich single post-AGB stars, s-process non-enriched single post-AGB stars, and s-process -rich binary post-AGB stars in the Galaxy and MCs.

Index	Object name	SMC/LMC/Galaxy	T_{eff} (K)	$\log g$ (dex)	ξ_t (km/s)	[Fe/H]	C/O	[O/Fe]	[C/Fe]	[N/Fe]	[s/Fe]	[ls/Fe]	[hs/Fe]	[hs/ls]	L/L _⊙	L/L _⊙ upper limit	L/L _⊙ lower limit	Initial mass	Reference
Post-AGB single stars with s-process enrichment																			
1	J003643	SMC	7 552 ± 91	1.04 ± 0.16	4.02 ± 0.13	−0.97 ± 0.11	16.21 ± 0.22	0.03 ± 0.12	1.39 ± 0.12	...	2.09 ± 0.20	1.72 ± 0.17	2.19 ± 0.11	0.48 ± 0.12	7 623	8 606	5 761	2.0	
2	J004441.04-732136.4	SMC	6 250 ± 125	0.50 ± 0.50	3.50 ± 0.50	−1.34 ± 0.32	1.90 ± 0.70	1.14 ± 0.50	1.67 ± 0.36	...	2.40 ± 0.10	2.06 ± 0.10	2.58 ± 0.10	0.52 ± 0.10	7 600	7 800	7 400	1.3	1,2
3	J050632.10-714229.9	LMC	6750 ± 125	0.50 ± 0.25	3.00 ± 0.25	−1.22 ± 0.17	1.50 ± 0.30	0.91 ± 0.24	1.16 ± 0.11	...	1.19 ± 0.09	1.42 ± 0.07	1.07 ± 0.14	−0.35 ± 0.15	5 400	6 100	4 700	1.5	1,3
4	J052043.86-692341.0	LMC	5750 ± 125	0.50 ± 0.50	3.00 ± 0.25	−1.15 ± 0.17	1.60 ± 0.90	0.86 ± 0.35	1.53 ± 0.20	...	1.79 ± 0.08	1.67 ± 0.12	1.85 ± 0.10	0.19 ± 0.16	8 700	9 700	7 700	1.5	1,3
5	J053250.69-713925.8	LMC	5 500 ± 125	0.00 ± 0.25	3.00 ± 0.25	−1.22 ± 0.11	2.50 ± 0.70	0.88 ± 0.38	1.53 ± 0.21	...	1.80 ± 0.08	1.51 ± 0.16	1.94 ± 0.10	0.43 ± 0.19	6 500	7 500	5 500	1.5	1,3
6	J053253.51-695915.1	LMC	4 750 ± 125	2.50 ± 0.25	2.50 ± 0.25	−0.54 ± 0.12	...	...	...	...	0.85 ± 0.07	0.55 ± 0.10	0.95 ± 0.13	0.39 ± 0.14	1400	300	1100	1.5	1,3
7	J051213.81-693537.1	LMC	5875 ± 125	1.00 ± 0.25	3.00 ± 0.20	−0.56 ± 0.15	1.30 ± 0.40	0.52 ± 0.26	0.88 ± 0.26	...	1.61 ± 0.06	1.33 ± 0.08	1.74 ± 0.08	0.41 ± 0.12	6 700	6 900	6 500	1-1.5	1,4
8	J051848.86-700246.9	LMC	6 000 ± 125	0.50 ± 0.25	2.80 ± 0.20	−1.03 ± 0.14	1.30 ± 0.30	0.84 ± 0.19	1.21 ± 0.16	...	1.90 ± 0.07	1.46 ± 0.10	2.12 ± 0.08	0.66 ± 0.13	6 250	6 450	6 050	1-1.5	1,4
9	IRAS Z02229+6208	Galaxy	5 500 ± 250	0.50 ± 0.25	4.25 ± 0.25	−0.45 ± 0.14	...	...	0.78 ± 0.15	1.19 ± 0.30	1.40 ± 0.15	2.16 ± 0.12	1.29 ± 0.03	−0.87 ± 0.20	12 959	16 911	9 973	3-3.5	1,5
10	IRAS 04296+3429	Galaxy	7 000 ± 250	1.00 ± 0.25	4.00 ± 0.25	−0.62 ± 0.11	...	...	0.80 ± 0.20	0.39 ± 0.01	1.50 ± 0.23	1.70 ± 0.23	1.50 ± 0.17	−0.20 ± 0.23	10 009	20 082	5 971	1-1.5	1,6
11	IRAS 05113+1347	Galaxy	5 500 ± 125	0.50 ± 0.25	5.00 ± 0.25	−0.49 ± 0.17	2.42 ± 0.40	0.01 ± 0.27	0.65 ± 0.16	...	1.54 ± 0.07	1.33 ± 0.13	1.65 ± 0.07	0.32 ± 0.15	2 037	6 731	1 043	1-1.3	1,7
12	IRAS 05341+0852	Galaxy	6 750 ± 125	1.25 ± 0.25	3.50 ± 0.25	−0.54 ± 0.11	1.06 ± 0.30	0.75 ± 0.11	1.03 ± 0.10	...	2.12 ± 0.05	1.87 ± 0.08	2.24 ± 0.06	0.37 ± 0.10	324	592	197	0.5-0.6	1,7
13	IRAS 06530-0213	Galaxy	7 375 ± 125	1.25 ± 0.25	4.00 ± 0.25	−0.32 ± 0.11	1.66 ± 0.39	0.35 ± 0.11	0.83 ± 0.13	...	1.94 ± 0.06	1.75 ± 0.09	2.04 ± 0.08	0.29 ± 0.13	4 687	8 178	2 736	1.5-2	1,7
14	IRAS 07134+1005	Galaxy	7 250 ± 125	0.50 ± 0.25	3.25 ± 0.25	−0.91 ± 0.20	1.24 ± 0.29	0.81 ± 0.19	1.16 ± 0.22	0.57 ± 0.19	1.63 ± 0.14	1.64 ± 0.13	1.63 ± 0.20	−0.01 ± 0.24	5 505	6 098	4 955	0.9-1.2	1,7
15	IRAS 07430+1115	Galaxy	6 000 ± 125	1.00 ± 0.25	3.25 ± 0.25	−0.35 ± 0.15	1.71 ± 0.30	0.30 ± 0.22	0.79 ± 0.13	...	1.47 ± 0.06	1.30 ± 0.14	1.55 ± 0.06	0.25 ± 0.15	20	30	14	0.5-0.6	1,7
16	IRAS 08143-4406	Galaxy	7 000 ± 125	1.50 ± 0.25	5.50 ± 0.25	−0.43 ± 0.11	1.66 ± 0.39	0.19 ± 0.13	0.67 ± 0.12	0.01 ± 0.22	1.65 ± 0.05	1.77 ± 0.08	1.58 ± 0.06	−0.19 ± 0.11	4 509	5 452	3 927	1-1.5	1,7
17	IRAS 08281-4850	Galaxy	7 875 ± 125	1.25 ± 0.25	5.50 ± 0.25	−0.26 ± 0.11	2.34 ± 0.42	0.12 ± 0.11	0.75 ± 0.21	...	1.58 ± 0.09	1.57 ± 0.11	1.58 ± 0.12	0.01 ± 0.17	9 584	16 692	5 567	1.5-2	1,7
18	IRAS 12360-5740	Galaxy	7 273 ± 250	1.59 ± 0.25	3.00 ± 0.50	−0.40 ± 0.15	0.45 ± 0.20	0.31 ± 0.05	0.27 ± 0.18	0.22 ± 0.32	1.88 ± 0.20	1.73 ± 0.20	2.02 ± 0.20	0.29 ± 0.20	6 265	7 940	5 178	1-1.5	1,8
19	IRAS 13245-5036	Galaxy	9 500 ± 125	2.75 ± 0.25	4.50 ± 0.25	−0.30 ± 0.10	1.11 ± 0.30	0.26 ± 0.13	0.57 ± 0.21	...	1.88 ± 0.09	1.56 ± 0.14	2.03 ± 0.11	0.47 ± 0.18	11221	16800	7106	1.5-2	1,7
20	IRAS 14325-6428	Galaxy	8 000 ± 125	1.00 ± 0.25	5.75 ± 0.25	−0.56 ± 0.10	2.27 ± 0.40	0.57 ± 0.09	1.18 ± 0.23	0.18 ± 0.20	1.30 ± 0.14	1.25 ± 0.15	1.33 ± 0.19	0.08 ± 0.24	4 935	6 988	3 758	1.5-2	1,7
21	IRAS 14429-4539	Galaxy	9 375 ± 125	2.50 ± 0.25	4.75 ± 0.25	−0.18 ± 0.11	1.29 ± 0.26	0.31 ± 0.12	0.68 ± 0.23	...	1.41 ± 0.08	1.29 ± 0.15	1.47 ± 0.10	0.18 ± 0.08	5 049	14 624	1 591	1.5-2	1,7
22	IRAS 19500-1709	Galaxy	8 000 ± 125	1.00 ± 0.25	6.00 ± 0.25	−0.59 ± 0.10	1.02 ± 0.17	0.72 ± 0.09	0.99 ± 0.33	0.41 ± 0.17	1.35 ± 0.21	1.37 ± 0.29	1.34 ± 0.30	−0.03 ± 0.41	7 053	8 183	6 194	1.5-2	1,7
23	IRAS 20000+3239	Galaxy	5 000 ± 250	...	9.00 ± 0.25	−1.40 ± 0.20	...	...	1.70 ± 0.20	2.10 ± 0.20	1.40 ± 0.20	1.10 ± 0.20	1.47 ± 0.10	0.34 ± 0.20	14 342	25 218	9 332	3-3.5	1,9
24	IRAS 22223+4327	Galaxy	6 500 ± 125	1.00 ± 0.25	4.75 ± 0.25	−0.31 ± 0.20	1.04 ± 0.22	0.31 ± 0.13	0.59 ± 0.07	0.15 ± 0.21	1.03 ± 0.05	1.34 ± 0.07	0.88 ± 0.07	−0.46 ± 0.10	2 163	2 499	1 956	0.5-0.6	1,7
25	IRAS 22272+5435	Galaxy	5750 ± 125	0.50 ± 0.25	4.25 ± 0.25	−0.77 ± 0.20	1.46 ± 0.26	0.63 ± 0.09	1.05 ± 0.12	...	1.80 ± 0.05	1.61 ± 0.08	1.90 ± 0.07	0.28 ± 0.11	5 659	6 108	5 234	1-1.3	1,7
26	IRAS 23304+6147	Galaxy	6 750 ± 125	0.50 ± 0.25	3.00 ± 0.25	−1.00 ± 0.20	2.90 ± 0.30	0.20 ± 0.10	0.90 ± 0.12	0.50 ± 0.20	1.60 ± 0.07	1.55 ± 0.10	1.63 ± 0.09	0.09 ± 0.24	7 712	9 386	6 831	2-2.5	1,10
Post-AGB single stars without s-process enrichment																			
27	IRAS 01259+6823	Galaxy	5 000 ± 125	1.50 ± 0.25	3.30 ± 0.25	−0.60 ± 0.10	0.40 ± 0.30	0.31 ± 0.06	0.18 ± 0.30	...	0.30 ± 0.10	...	...	...	340	646	220	0.5-0.6	1,11
28	IRAS 08187-1905	Galaxy	6 250 ± 125	0.50 ± 0.25	3.80 ± 0.25	−0.60 ± 0.10	...	0.26 ± 0.10	0.62 ± 0.30	0.49 ± 0.30	...	...	...	...	2 619	3 286	2 099	0.5-0.6	1,11
29	SAO 239853	Galaxy	7 452 ± 250	1.49 ± 0.25	5.00 ± 0.25	−0.81 ± 0.10	...	0.80 ± 0.20	0.40 ± 0.20	0.60 ± 0.20	−0.40 ± 0.20	...	...	...	23 490	48 520	13 080	4-5	1,12
30	HD 107369	Galaxy	7 533 ± 250	2.45 ± 0.25	2.50 ± 0.25	−1.10 ± 0.10	...	0.00 ± 0.20	<−0.2	0.49 ± 0.30	−0.10 ± 0.20	...	...	...	910	1010	814	0.5-0.6	1,12
31	HD 112374	Galaxy	6 393 ± 250	0.80 ± 0.25	3.00 ± 0.50	−1.20 ± 0.10	...	0.80 ± 0.20	0.10 ± 0.20	0.50 ± 0.20	−0.30 ± 0.20	...	...	...	10 777	11 882	9961	2.5-3	1,12
32	HD 133656	Galaxy	8 283 ± 250	1.38 ± 0.25	3.00 ± 0.50	−0.70 ± 0.10	...	0.60 ± 0.20	0.30 ± 0.20	0.50 ± 0.20	−0.40 ± 0.20	...	...	...	5 227	5 690	4 861	0.8-1	1,12
33	HR 6144	Galaxy	6 728 ± 250	0.93 ± 0.25	3.00 ± 0.50	−0.40 ± 0.10	...	0.30 ± 0.20	0.30 ± 0.20	0.90 ± 0.20	0.20 ± 0.20	...	...	...	25 491	30 419	22 212	4-5	1,12
34	HD 161796	Galaxy	6 139 ± 250	0.99 ± 0.25	3.00 ± 0.50	−0.30 ± 0.10	...	0.40 ± 0.20	0.30 ± 0.20	1.10 ± 0.20	0.00 ± 0.20	...	...	...	5 742	6 322	5 209	1-1.2	1,12
35	IRAS 18025-3906	Galaxy	6 154 ± 250	1.18 ± 0.25	3.00 ± 0.50	−0.51 ± 0.15	0.43	0.56 ± 0.20	0.46 ± 0.20	0.74 ± 0.20	...	...	...	...	2 324	12 963	975	0.8-1	1,13
36	HD 335675	Galaxy	6 082 ± 250	1.58 ± 0.25	3.00 ± 0.50	−0.90 ± 0.20	0.25	0.77 ± 0.19	0.40 ± 0.20	<0.27	...	...	...	...	15 843	28 359	7 303	...	1,14
37	IRAS 19386+0155	Galaxy	6 303 ± 250	1.00 ± 0.25	3.00 ± 0.50	−1.10 ± 0.14	...	...	0.10 ± 0.20	...	−0.30 ± 0.20	...	...	...	9 611	22 765	4 345	0.7-0.8	1,15
38	IRAS 19475+3119	Galaxy	8 216 ± 250	1.01 ± 0.25	3.00 ± 0.50	−0.24 ± 0.15	0.19	0.30 ± 0.02	−0.09 ± 0.30	...	−0.30 ± 0.10	...	...	...	6 775	7 545	5 955	0.8-1	1,16
39	HR 7671	Galaxy	6 985 ± 250	0.83 ± 0.25	3.00 ± 0.50	−1.60 ± 0.10	0.05	0.46 ± 0.05	−0.57 ± 0.13	0.51 ± 0.16	...	...	...	...	3 579	3 734	3 449	0.5-0.6	1,17
40	J005252.87-722842.9	SMC	8 500 ± 125	1.50 ± 0.25	2 ± 0.25	−1.20 ± 0.15	...	0.70 ± 0.10	...	...	...	...	...	...	8 200	8 400	8 000	1.5-2.0	18

Table B1. Continued.

Index	Object name	SMC/LMC/Galaxy	T_{eff} (K)	$\log g$ (dex)	ξ_z (km/s)	[Fe/H]	C/O	[O/Fe]	[C/Fe]	[N/Fe]	[s/Fe]	[ls/Fe]	[hs/Fe]	[hs/ls]	L/L_{\odot}	L/L_{\odot} upper limit	L/L_{\odot} lower limit	Initial mass	Reference
Post-AGB binary stars with s-process enrichment																			
41	J005107.19-734133.3	SMC	5 768 ± 85	0.21 ± 0.25	4.08 ± 0.05	−1.57 ± 0.10	0.58 ± 0.37	1.06 ± 0.21	1.09 ± 0.21	...	1.52 ± 0.20	0.94 ± 0.12	1.59 ± 0.10	0.65 ± 0.13	2 868	6 469	1 405	0.8-1	19
42	MACHO 47.2496.8	LMC	4 900 ± 250	0.00 ± 0.50	3.00 ± 1.00	−1.50 ± 0.50	>2	...	...	<0.88 ± 0.20	1.96 ± 0.20	1.21 ± 0.17	2.06 ± 0.12	0.85 ± 0.12	2 208	4 087	1 877	1-1.2	19
43	HD 158616	Galaxy	7 250 ± 250	1.25 ± 0.25	3.00 ± 0.50	−0.64 ± 0.12	0.94 ± 0.22	0.24 ± 0.16	0.51 ± 0.20	−0.07 ± 0.35	0.96 ± 0.17	0.74 ± 0.12	0.92 ± 0.11	0.18 ± 0.10	8 256	10 301	6 288	2.5	19

Notes: References: 1 – Kamath et al. (2022), 2 – De Smedt et al. (2012), 3 – van Aarle et al. (2013), 4 – De Smedt et al. (2015), 5 – Reddy et al. (1999), 6 – Van Winckel & Reyniers (2000), 7 – De Smedt et al. (2016), 8 – Pereira et al. (2011), 9 – Klochkova & Kipper (2006), 10 – Reyneirs (2000), 11 – Rao et al. (2012), 12 – Van Winckel (1997), 13 – Molina et al. (2019), 14 – Şahin et al. (2011), 15 – Pereira et al. (2004), 16 – Arellano Ferro et al. (2001), 17 – Reyniers & Cuypers (2005), 18 – Kamath et al. (2017), 19 – Menon et al. (2024).