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# A window on the efficiency of the s-process in AGB stars: chemical abundances of n-capture elements in the planetary nebula NGC 3918

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**Abstract.** The chemical content of the planetary nebula NGC 3918 is investigated through deep, high-resolution (R∼40,000) UVES at VLT spectrophotometric data. We identify and measure more than 750 emission lines, making ours one of the deepest spectra ever taken for a planetary nebula. Among these lines we detect very faint lines of several neutron-capture elements (Se, Kr, Rb, and Xe), which enable us to compute their chemical abundances with unprecedented accuracy, thus constraining the efficiency of the *s*-process and convective dredge-up in the progenitor star of NGC 3918.

**Key words.** Stars: AGB and post-AGB – ISM: abundances – ISM: planetary nebulae – individual: NGC 3918

## 1. Introduction

About half of the heavy elements (Z > 30) in the Universe are formed during the AGB phase through slow neutron-capture (*n*-capture) nucleosynthesis (the "*s*-process"). In the intershell between the H- and He-burning shells, Fe-peak nuclei experience neutron captures interlaced with $\beta$-decays, which transform them into heavier elements. In the same layer, carbon is formed and brought to the surface by the third dredge-up along with n-capture elements, to be successively expelled to the interstellar medium by stellar winds and planetary nebula (PN) ejection. The efficiency of nucleosynthesis and the third dredge-up in AGB stars can be effectively constrained by measuring the s-element abundances; but *n*-capture elements are extremely underabundant and detecting their lines requires very deep spectra.

Although first identified in 1994 (Péquignot & Baluteau 1994), *n*-capture element emission lines were not well-studied in ionized nebulae until recently. Sharpee et al. (2007) carried out high-resolution observations of 4 PNe on 4- and 6-m class telescopes, identifying lines of Br, Kr, Xe, Rb, Ba, Te, and I ions. But even at their resolution of ∼22,000, many heavy element features were not unambiguously detected. Sterling

& Dinerstein (2008) performed the first large scale study of n-capture elements in PNe, with a K band survey of [Kr III] and [Se IV] emission lines in 120 PNe. However, their abundance determinations were uncertain by factors of 2–3, since only one ion of each element was detected (leading to large and uncertain corrections for unobserved ions). Deep, high-resolution optical spectroscopy of PNe enables dramatic improvements to the accuracy of *n*-capture element abundance determinations. The optical region is home to a multitude of *n*-capture element transitions including lines from multiple ions of Br, Kr, Rb, and Xe. Detecting multiple ions of these species allows their abundances to be determined to unprecedented accuracy, thereby providing strong constraints to models of AGB nucleosynthesis and chemical evolution.

Therefore, to improve the accuracy of *n*-capture element abundance determinations in PNe, we embarked on an ambitious observational program aimed at detecting multiple ions of several *n*-capture species in a small sample of about 8 PNe. The data gathered will enable us to compute accurate total abundances for the object of the sample, as well as verify the consistency of current ionization correction factors (ICFs) based on photoionization modelling for future, less in-depth studies. In addition, the comparison of different lines of the same ionization species will enable us to assess the quality of the (as yet poorly-tested) atomic data for heavy elements. Both aspects are crucial to hone nebular spectroscopy into an effective tool for studying *s*-process nucleosynthesis.

In this work, we present the results obtained for the PN NGC 3918 with UVES at VLT (Fig. 1). The main aim is measuring the abundances of several *n*-capture elements and compare them with theoretical predictions. Nucleosynthesis models predict a correlation between *s*-process enrichment and carbon abundance. As it has been pointed out before, this work is part of an ambitious project oriented, among other things, to test this correlation. In García-Rojas et al. (2015) we present the extended analysis of the work presented in this proceeding.

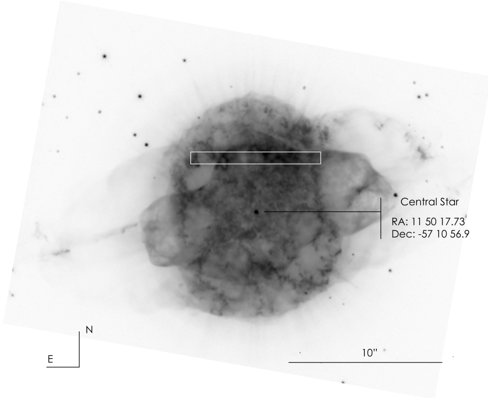


**Fig. 1.** HST H$\alpha$ image of NGC 3918 showing the UVES slit position.

## 2. Data and analysis

We detect, identify and measure more than 750 lines, several of them belonging to different ionic species of *n*-capture elements (Fig. 2). In the cases of very tight blends we used PySSN, a python version of the emission line spectral synthesis code X-SSN (Péquignot et al. 2012), to perform the line fitting (Fig. 3). The large number of line intensities allowed us to derive physical conditions using multiple diagnostics. These computations were carried out with PyNeb (v. 1.0.9; Luridiana et al. 2015), a python-based package dedicated to the analysis of emission line spectra. For the calculation of ionic abundances we assumed a three-zone ionization scheme (low-, medium- and high-ionization zone) and each abundance was calculated with the representative physical conditions. Fig. 4 shows several diagnostic ratios for the case of the medium-ionization zone. The total abundances of common elements were computed either by adding the ionic abundances or by using ICFs for C, N, O, Ar, Cl, and Ne developed by Delgado-Inglada et al. (2014).

## 3. s-Process enrichments of n-capture elements

We computed the total abundances of four *n*-capture elements – Se, Kr, Rb and Xe, in order to establish if the central star has undergone a

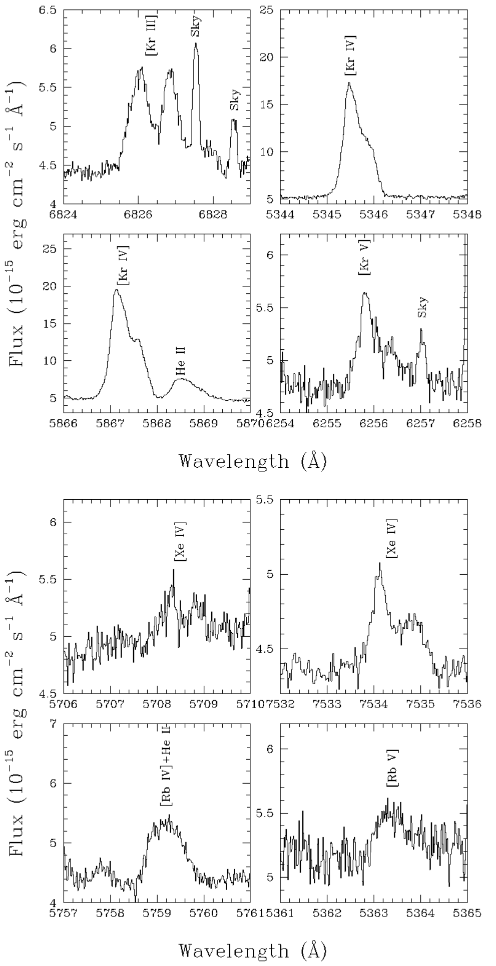


**Fig. 2.** Lines of different ionic species of Kr, Xe and Rb.

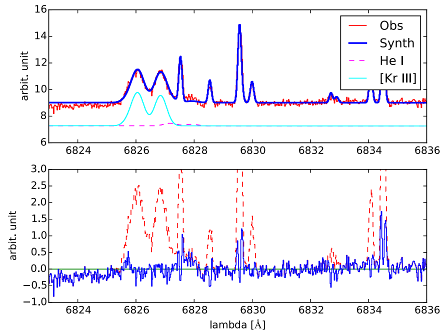


**Fig. 3.** PySSN fitting of the [Kr III] $\lambda$6826.70 + He I $\lambda$6827.88 feature. Top: observed spectrum (red line) and PySSN fits (cyan: [Kr III]; magenta: He I; blue: total spectrum; the flux is in arbitrary units). A model of the telluric emission is included in the fit. Bottom: residuals of the fit.

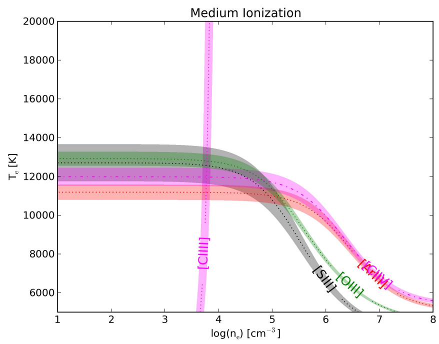


**Fig. 4.** Diagnostic diagram of the medium-ionization zone.

substantial *s*-process nucleosynthesis and convective dredge-up. The enrichment must be measured relative to a reference element which is neither enriched nor depleted in the PN. In the case of NGC 3918 (a non-type-I PN), oxygen is a suitable element. In Table 1 we show the *n*-capture element enrichments represented as [X/O]=log(X/O)−log(X/O)$_\odot$, where the solar abundances were taken from Asplund et al. (2005). For Kr we take advantage of the recent ICFs computed by Sterling et al. (2015) from detailed photoionization models, and we obtain [Kr/O]=0.60±0.13, a value well above the threshold assumed by Sterling & Dinerstein (2008); therefore, we conclude that Kr is strongly enriched in NGC 3918. For Rb and Xe we cannot draw a definite conclusion, as we do not have reliable ICFs and the adopted values are only lower limits to the real abundances; however, we cannot exclude that these elements are actually enriched. For Se, owing to the difficulties of its detection (see García-Rojas et al. 2015), the value we find is very uncertain.

**Table 1.** Total abundance ratios

| Ratio | [X/O] |
|---|---|
| [Se/O] | $0.18^{+0.17}_{-0.22}$ |
| [Kr/O] | 0.60±0.13 |
| [Rb/O] | $>0.17^{+0.17}_{-0.22}$ |
| [Xe/O] | >0.21±0.11 |

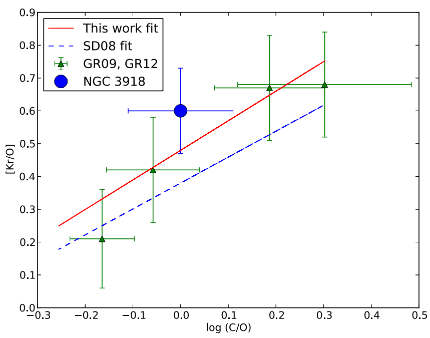


**Fig. 5.** [Kr/O] vs. log(C/O) correlation. NGC 3918 (blue dot) and objects from the sample of García-Rojas et al. (2009) and García-Rojas et al. (2012) with measured [Kr III] and [Kr IV] lines (green triangles). A least squares fit to the data is shown as a red line. For comparison we also show the fit to the Sterling & Dinerstein (2008) data (dashed blue line).

### 3.1. Correlation with Carbon

Nucleosynthesis models predict that *n*-capture element enrichments correlate with the C/O ratio, as carbon is brought to the surface of AGB stars along with *s*-processed material during third dredge-up episodes (see e. g. Karakas & Lattanzio 2014). In Fig. 5 we show the correlation we found for a sample of objects with measured krypton enrichments with the C/O ratio. Green triangles represent PNe observed and studied by García-Rojas et al. (2009) and García-Rojas et al. (2012), and the blue dot is NGC 3918. The red line is our fit and the blue line is the fit found by Sterling & Dinerstein (2008), with a larger sample of objects. Our C/O ratios where computed from optical recombination lines, whereas Sterling & Dinerstein ones where computed from UV and optical collisionally excited lines. In spite of the small size of our sample, both fits are very similar.

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