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Tungsten in barium stars

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Abstract. Classical barium (Ba) stars are red giants enriched in elements produced primarily by the *slow* neutron capture mechanism (*s*-process). Their chemical peculiarities, attributable to mass-transfer events that took place in an interacting binary system, are powerful tools to trace back their polluter sources, former thermally-pulsing asymptotic giant branch stars. In this contribution, we report abundance results from a chemical analysis focused on the exotic element tungsten (W, $Z = 74$) for a sample of 180 Ba giants. As far the authors are aware, abundances of that element poorly explored in the literature were published for 17 objects only. The present study intends to change that picture, using two absorption features of W I at 4843.8 Å and 5224.7 Å observed in the high-resolution spectra of Ba stars. The [W/Fe] ratios, which range from ~ 0.0 to 2.0 dex, increase for lower metallicity regimes and strongly correlate with the *s*-process averaged abundances. By comparing the observational data set with predictions from the FRUITY and Monash nucleosynthesis models, we noticed that stars with high [W/hs] ratios may represent evidence for the operation of the *intermediate* neutron-capture process at metallicities close to solar.

Keywords. nuclear reactions, nucleosynthesis, abundances – stars: abundances – stars: AGB and post-AGB – stars: chemically peculiar.

1. Introduction

In the Universe, roughly half of the cosmic abundances of the elements beyond the iron group are produced in the deep interiors of Thermally-Pulsing Asymptotic Giant Branch (TP-AGB) stars, through the *slow* neutron capture mechanism, or the *s*-process (see review by Lugaro et al. 2023). In addition to heavy elements, AGB stars are also important contributors to the Galactic Chemical Evolution (GCE) of carbon and nitrogen. In that sense, the chemical imprints of their atmospheres are valuable probes of the nucleosynthetic conditions at work within them, providing strong observational constraints to the theoretical models. Nevertheless, from an observational perspective, their cool and complex atmospheres yield very difficult spectra. This compromises detailed chemical analysis for several elements, thus hiding possible nuances of the nucleosynthesis processes within these fascinating objects. To overcome such difficulties, barium (Ba) stars become ideal targets.

Classical Ba stars (Bidelman and Keenan 1951) are red giants whose envelopes were contaminated by the outflows of their binary companions, former AGB stars which are now unseen white dwarfs. In addition to providing insights of the mass-transfer mechanisms and evolution of binary systems, Ba stars figure as powerful tracers of the *s*-process nucleosynthesis. As a continuation of the homogeneous chemical analysis of de Castro et al. (2016) and Roriz et al. (2021a,b), we have subjected to study a large sample of 180 Ba stars. In this contribution,

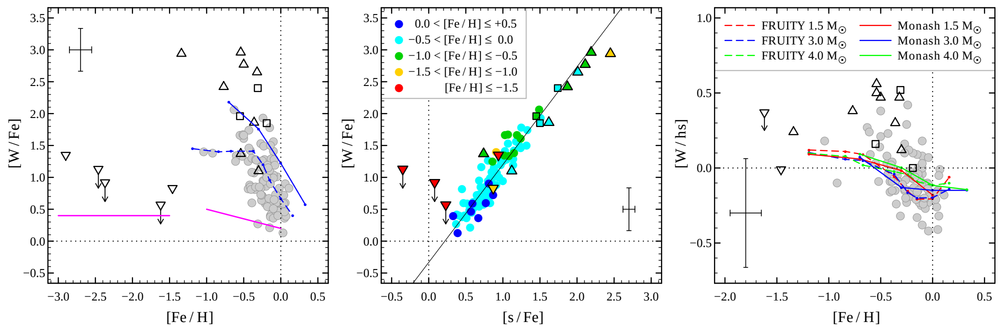

Figure 1: *Left panel:* [W/Fe] ratios observed in Ba stars (grey dots) versus [Fe/H], along with data (black symbols) gathered from different references of literature for metal-poor stars (inverted triangles), post-AGB stars (up triangles), and other chemical peculiar stars (squares). Magenta lines mimic GCE predictions (Kobayashi et al. 2020), while blue curves are some examples of theoretical expectations of the *s*-process for TP-AGB stars of 3.0 $M_\odot$ FRUITY (dashed) and Monash (solid) nucleosynthesis models. *Middle panel:* [W/Fe] ratios as a function of the averaged *s*-process abundance; the colors identify different metallicity ranges. A linear fit is also shown. *Right panel:* comparison between the [W/hs] ratios and different sets of the nucleosynthesis models.

we present chemical abundance results of tungsten (W, $Z = 74$) for these stars. Tungsten is an exotic element for which the literature lacks data, currently reporting abundances for a sample of only 17 targets, including 2 Ba stars. The present work, concentrating efforts on the study of tungsten in Ba stars, represents therefore a significant change in that picture.

2. Methods

To derive W abundances, we followed the same methodology applied by Roriz et al. (2023), by performing spectral synthesis of two absorption features of W I at 4843.8 Å and 5224.7 Å. We run the current version of the MOOG radiative transfer program (Sneden 1973) to generate the synthetic spectra. MOOG assumes the local thermodynamic equilibrium and a plane-parallel atmosphere. In our approach, we were able to extract W abundances for 94 stars from a total sample of 180 Ba stars. The meteorite value $\log \varepsilon(\mathrm{W}) = 0.65$, also used in the nucleosynthesis models, was taken as the tungsten content in the solar photosphere.

The W abundances derived in this work were examined in the light of two sets of the *s*-process nucleosythesis models for TP-AGB stars: the FRUITY database tabulated by the INAF group and models calculated by the Monash group. For details on these sets of models, the reader is invited to see the papers of Cristallo et al. (2015) and Karakas et al. (2018), respectively, as well as references therein. A thorough comparison between the FRUITY and Monash models is performed by Karakas and Lugaro (2016).

3. Results and Concluding Remarks

As shown in the left panel of Figure 1, the [W/Fe] ratios observed in the program stars range from ~ 0.0 to 2.0 dex. Additionally, these values increase with decreasing metallicity, a notable feature of the *s*-process nucleosynthesis. Note that GCE models (magenta lines) are not able to reproduce the observations. For comparison purposes only, *s*-process predictions are also shown in Figure 1 (blue lines), which evidences the high amounts of W produced by these models. The predicted [W/Fe] ratios increase from ~ 0.5 to ~ 2.2 dex with decreasing metallicities. When we compare the [W/Fe] ratios to the averaged *s*-process abundances, [*s*/Fe], a strong correlation between these quantities can be observed (middle panel of Figure 1). This is an observational evidence that W was produced and dredged-up along with other *s*-process elements from the interior of the former polluter, a TP-AGB star. A linear fit to the data yields $[\mathrm{W/Fe}] = (1.49 \pm 0.06) \times [\mathrm{s/Fe}] - (0.41 \pm 0.06)$; it is noticed that post-AGB stars fall in the same trend. We also observed that for Ba stars with [*s*/Fe]$< +0.40$ dex the two W I lines become undetectable in their spectra even at the high spectral resolution used in our study.

The Monash and FRUITY nucleosynthesis models provide *s*-process theoretical predictions for a wide range of masses and metallicities, covering the interval observed in our stars. Thus, we have analyzed the observational data set in light of these two sets of models, concentrating our focus in low-mass models ($\lesssim 4.0$ $M_{\odot}$). To eliminate dilution effects, we compare the observed [W/hs] ratios with the predicted ones, where $[\mathrm{W/hs}] = [\mathrm{W/Fe}] - [\mathrm{hs/Fe}]$, and [hs/Fe] is the mean abundance of the elements belonging to the second *s*-process peak (La, Ce, and Nd). The [W/hs] ratios range from -0.40 to $+0.60$ dex. We observe that predicted spread is not able to cover the full observational spread (right panel of Figure 1). Some of this spread may be attributed to the observational error bars, however, there are a few data points that show significant excesses of W. These may be interpreted as a signature of the *intermediate* neutron capture mechanism close to solar metallicity (the *i*-process; see also Lugaro et al. 2015).

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