# PROBING THE *slow* NEUTRON CAPTURE PROCESS IN AGB STARS USING BARIUM STAR ABUNDANCES

B. Cseh[1]*, B. Világos[1,2], M. P. Roriz[3], B. Soós[1,2], V. D'Orazi[4], C. B. Pereira[3], A. I. Karakas[5], N. A. Drake[6,7], S. Junqueira[3], C. Sneden[8], M. Lugaro[1,2,5]

[1] Konkoly Observatory, Research Centre for Astronomy and Earth Sciences, Eötvös Loránd Research Network (ELKH) H-1121 Budapest
[2] Eötvös Loránd University, Pázmány Péter stny. 1/A, H-1118 Budapest, Hungary
[3] Observatorio Nacional, Rua General José Cristino, 77 Sao Cristovao, Rio de Janeiro, Brazil
[4] INAF Osservatorio Astronomico di Padova, vicolo dell'Osservatorio 5, 35122 Padova, Italy
[5] Monash Centre for Astrophysics, School of Physics and Astronomy, Monash University, VIC 3800, Australia
[6] Saint Petersburg State University, Universitetski pr. 28, 198504, Saint Petersburg, Russia
[7] Laboratório Nacional de Astrofísica, Rua dos Estados Unidos 154, Bairro das Nações, 37504-364, Itajubá, Brazil
[8] Department of Astronomy and McDonald Observatory, The University of Texas, Austin, TX 78712, USA

*mail to: cseh.borbala@csfk.org

## MOTIVATION

**What are Barium (Ba) stars?** giants or dwarfs with G-K spectral type in a binary system enhanced in *slow* neutron-capture (*s*-process) elements

**Why are they important?** companion: former AGB (now white dwarf (WD)) → mass transfer → secondary enhanced in *s*-process elements (now observed as Ba star) → constraints on AGB *s*-process nucleosynthesis

**Where are the data from?** largest, self-consistent sample of 169 giants, abundances from high resolution spectra (de Castro et al., 2016): Ba star if $[s/\mathrm{Fe}] \geq 0.25$ ($s$=Y+Zr+La+Ce+Nd)

**How can we compare the abundances to AGB models?** The ratio of the 2. peak ("heavy") and 1. peak ("light") *s*-process elements ([hs/ls]) is a measure of the *s*-process efficiency → [Ce/Y] or other hs (Ba, La, Ce, Nd, Sm) and ls (Sr, Y, Zr) elemental ratios (Cseh et al., 2018) (see Fig. 1 below)

## SAMPLE STARS

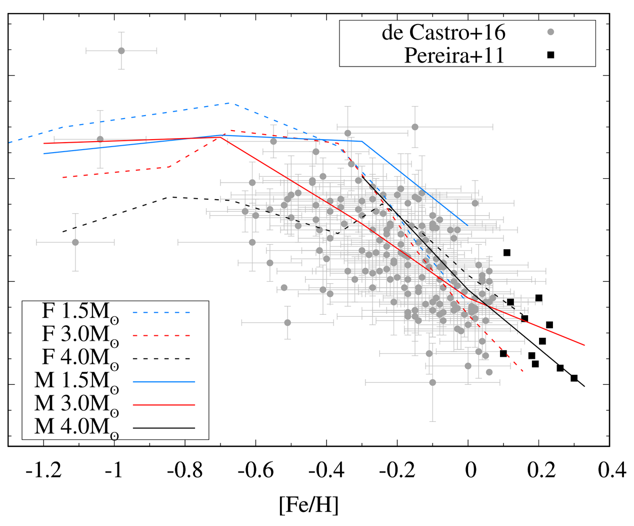


**Figure 1:** Ba stars observations from de Castro et al. (2016) and [Ce/Y] final surface abundances of different AGB models as a function of metallicity. M label stands for models from Karakas and Lugaro (2016) and Fishlock et al. (2014), while F is for models from Cristallo et al. (2015).

## ACKNOWLEDGEMENTS

The authors would like to thank A. Jorissen for providing data. B.Cs. and M.L. acknowledge the support of the Hungarian National Research, Development and Innovation Office (NKFI), grant KH_18 130405. B.Cs., V.d'O. and M.L. acknowledge support from the "ChETEC" COST Action (CA16117), supported by COST (European Cooperation in Science and Technology). B. V. is supported by the ÚNKP-20-1 New National Excellence Program of the Ministry for Innovation and Technology from the source of the National Research, Development and Innovation Fund. M. P. R. acknowledges financial support by Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (CAPES). N.A.D. acknowledges financial support by Russian Foundation for Basic Research (RFBR) according to the research projects 18_02-00554 and 18-52-06004. C. S. thanks the U.S. National Science Foundation for support under grant AST 1616040. C. S. also thanks the Brazilian Astronomical Society and Observatório Nacional for travel support.

## INDIVIDUAL STARS

Masses for 28 Ba stars out of our sample were estimated by Jorissen et al. (2019) and we have started a project to compare to the stellar models individually. Additionally, other elemental abundances were determined for the same stars (Roriz et al. (2021), Cseh et al., in prep.). Here we show a comparison of AGB nucleosynthesis models and the available *s*-process element abundances for 4 individual stars. Dilution factors were calculated for each model to match the [Ce/Fe] ratio of the observations, the difference between the normalised and the original models is given as $\delta$ for each of the models. We will further investigate the dilution due to mass transfer and its implication in relation to each individual binary system.

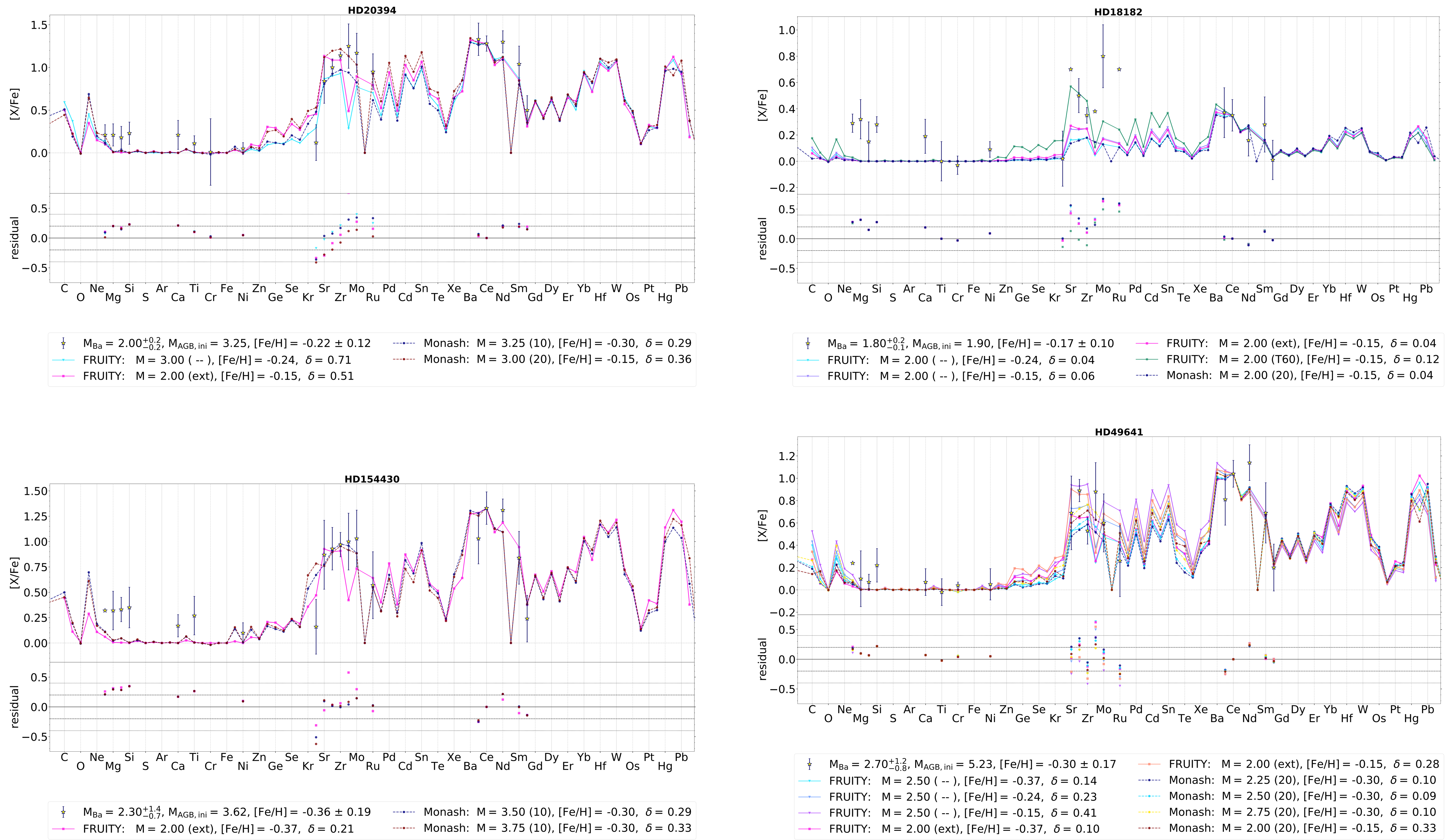


**Figure 2:** The determined abundances for 4 Ba stars and final surface abundances of different AGB models within the given error bar of the metallicity. $M_{\mathrm{Ba}}$ is the mass of the current Ba star and $M_{\mathrm{AGB,ini}}$ is the estimated initial AGB mass. Monash label indicates the models from Karakas and Lugaro (2016), where $M_{mix}$ indicates the mass (in solar masses) of the partial mixing zone leading to the formation of the $^{13}$C neutron source multiplied by $10^4$, while FRUITY stands for models from Cristallo et al. (2015) and Cristallo et al. (2016), where ext means models with larger $^{13}$C pocket without rotation, while the T60 model has a larger pocket size and also an initial rotational velocity of 60 km/s. $\delta$ means the dilution factor applied to the original models to match the model [Ce/Fe] values to the derived abundances.

We show different models for each of the Ba star, with masses close to the estimated initial AGB mass, and within the margin of the errors of the metallicities. Two of the stars (HD 20394 and HD 154430, left panel) can be matched by models close to their estimated initial AGB mass, although in both cases the FRUITY 2.0 $M_\odot$ model with extended $^{13}$C pocket is closer to the [Rb/Fe] value of the stars. In the case of HD 18182, the first *s*-process peak abundances are higher than the models. Only the FRUITY extended pocket model with initial rotation velocity of 60 km/s can potentially match the first peak elements, although not reaching the overabundance of Mo and Ru in this star. The high first *s*-process element abundances require somewhat lower neutron exposures (potentially due to diffusive mixing, see Battino et al. (2019)). This point needs to be further investigated in connection to these stars. HD 49641 has an estimated initial AGB mass of 5.23 $M_\odot$. None of the models with high mass can reproduce the overabundance seen in this star. As pointed out by Jorissen et al. (2019), the constant Q model used to estimate the initial AGB mass might overestimate the AGB masses if the WD mass is around 1 $M_\odot$. We found that AGB models around 2.5 $M_\odot$ have the best match with the abundance pattern, although unfortunately no [Rb/Fe] abundance is available for this star to confirm the mass estimate. Further elemental abundances of Pb (the third peak of the *s*-process) could help to investigate the nature of the *s*-process nucleosynthesis in the AGB stars that lead to the formation of the observed Ba stars.

## REFERENCES

Battino, U., Tattersall, A., Lederer-Woods, C., Herwig, F., Denissenkov, P., Hirschi, R., Trappitsch, R., den Hartogh, J. W., Pignatari, M., and NuGrid Collaboration: 2019, *MNRAS* **489(1)**, 1082
Cristallo, S., Karinkuzhi, D., Goswami, A., Piersanti, L., and Gobrecht, D.: 2016, ApJ **833**, 181
Cristallo, S., Straniero, O., Piersanti, L., and Gobrecht, D.: 2015, ApJS **219**, 40
Cseh, B., Lugaro, M., D'Orazi, V., de Castro, D. B., Pereira, C. B., Karakas, A. I., Molnár, L., Plachy, E., Szabó, R., Pignatari, M., and Cristallo, S.: 2018, *A&A* **620**, A146
de Castro, D. B., Pereira, C. B., Roig, F., Jilinski, E., Drake, N. A., Chavero, C., and Sales Silva, J. V.: 2016, MNRAS **459**, 4299
Fishlock, C. K., Karakas, A. I., Lugaro, M., and Yong, D.: 2014, ApJ **797**, 44
Jorissen, A., Boffin, H. M. J., Karinkuzhi, D., Van Eck, S., Escorza, A., Shetye, S., and Van Winckel, H.: 2019, *A&A* **626**, A127
Karakas, A. I. and Lugaro, M.: 2016, ApJ **825**, 26
Pereira, C. B., Sales Silva, J. V., Chavero, C., Roig, F., and Jilinski, E.: 2011, A&A **533**, A51
Roriz, M. P., Lugaro, M., Pereira, C. B., Drake, N. A., Junqueira, S., and Sneden, C.: 2021, MNRAS **501(4)**, 5834