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A Statistical Exploration of CEMP Star Classification with *s*-process Models

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Introduction

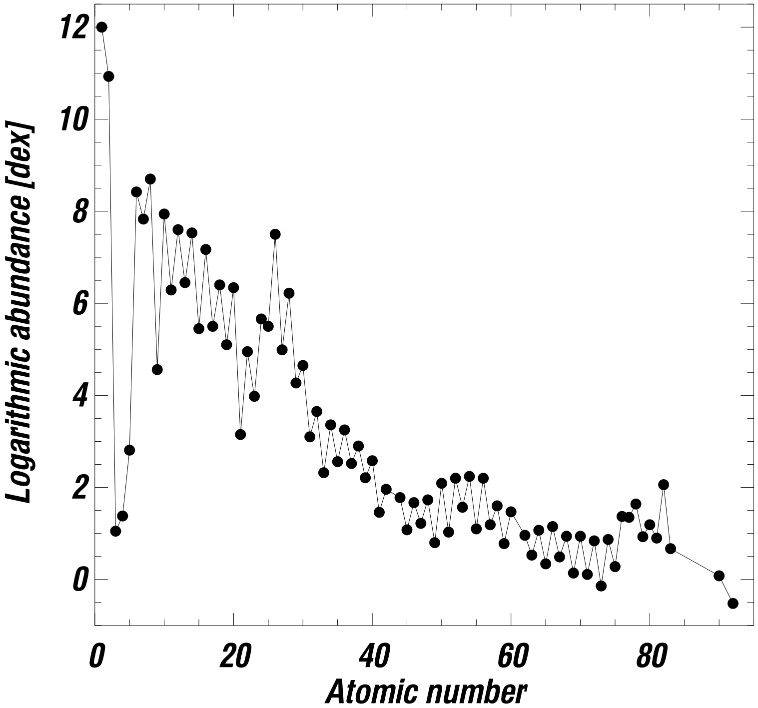
Definitions

- Stellar Nucleosynthesis
- Slow neutron capture process (s-process)
- Asymptotic giant branch (AGB) star, Planetary Nebula (PN), White Dwarf (WD)
- Barium (Ba) star, Carbon-enhanced metal poor star (CEMP)

Introduction

Stellar nucleosynthesis

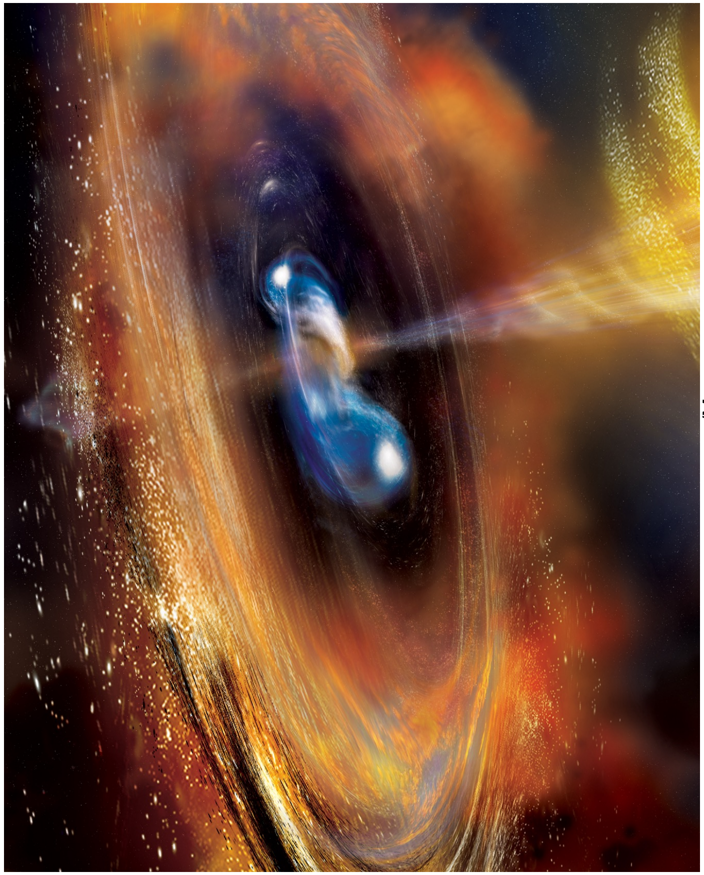
Nucleosynthesis, i.e., element formation, that happens inside of stars or due to processes involving stars.



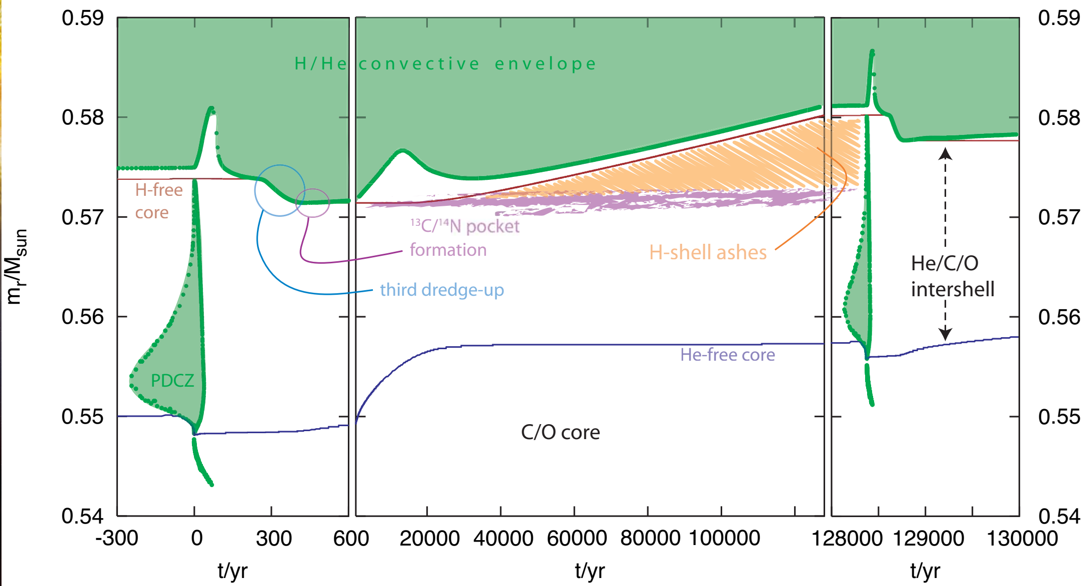
Solar composition, Asplund+ 2009

Introduction

Stellar nucleosynthesis



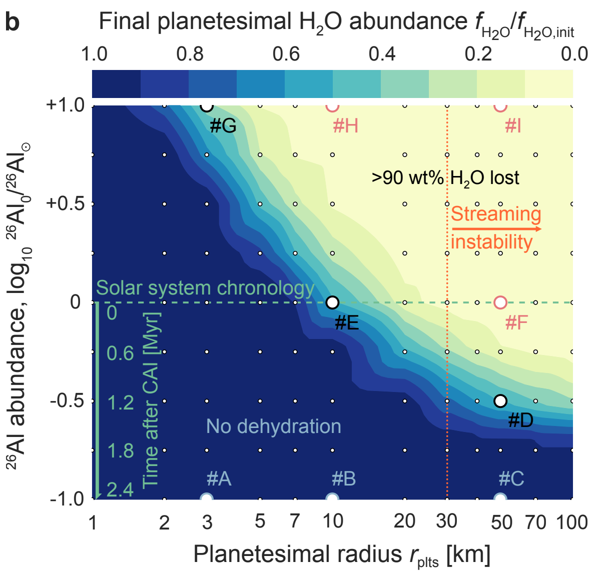
GRB (NASA images)



http://www.astro.uvic.ca/~fherwig

Introduction

Why nucleosynthesis?

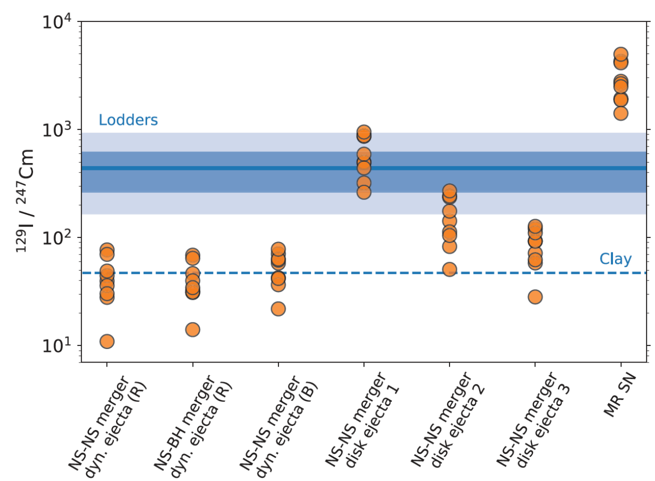


Lichtenberg+ 2019

NUCLEAR ASTROPHYSICS

^{129}I and ^{247}Cm in meteorites constrain the last astrophysical source of solar r-process elements

Benoit Côté[1,2,3]*, Marius Eichler[4], Andrés Yagüe López[1], Nicole Vassh[5], Matthew R. Mumpower[6,7], Blanka Világos[1,2], Benjámin Soós[1,2], Almudena Arcones[4,8], Trevor M. Sprouse[5,6], Rebecca Surman[5], Marco Pignatari[9,1], Mária K. Pető[1], Benjamin Wehmeyer[1,10], Thomas Rauscher[10,11], Maria Lugaro[1,2,12]



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Introduction

Slow neutron capture process

Happens mostly in AGB stars

This is the last phase in the lives of lighter stars

Its products can be seen in two places: the surface of AGB stars and in PNe

Also in case of binary stars, on the surface of the companion

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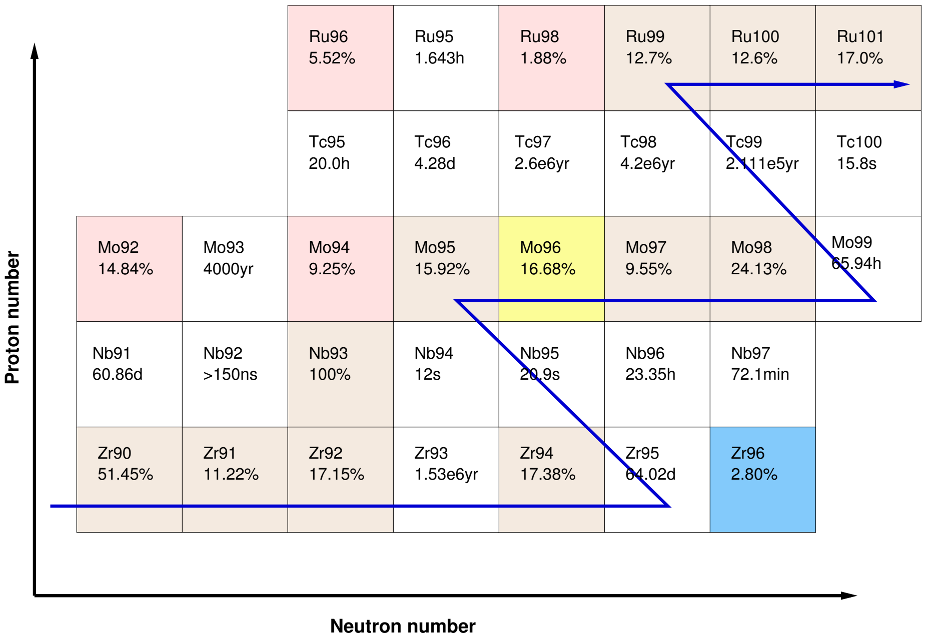

Karakas & Lattanzio 2014

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Introduction

Binary stars

Most stars are not single stars

Massive stars evolve faster than lighter stars, so one star can reach the AGB phase before the other leaves the main sequence

Evolved stars lose mass at a high rate, so the synthesized elements may transfer to the lighter star, where they get diluted

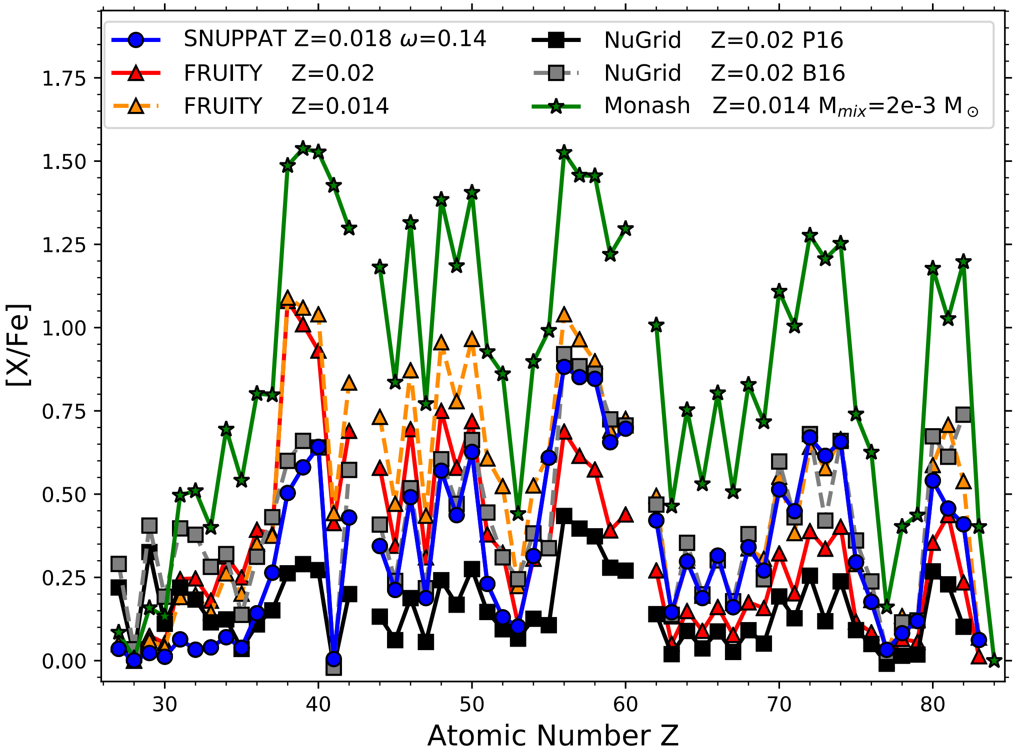
$$\left[\frac{X}{Fe}\right] = \log_{10}\left((1 - \delta)10^{[X/Fe]_i} + \delta 10^{[X/Fe]_{AGB}}\right)$$

Introduction

Models for s-process nucleosynthesis

There are a few known groups with publicly available models

The models present a great variation for what should be the same star



Where to see the abundances

Ba stars

Main sequence stars that

- Are enhanced in heavy elements – particularly Ba
- Are in a binary system
- The main (i.e., heavier) star is now a WD, so it was an AGB star before

The story we can tell is that the main star evolved to the AGB, synthesized heavy elements, including Ba, and these elements were deposited and diluted on the companion

We can compare these abundances with the s-process models. That way we can both provide evidence for the models and help derive physical parameters for those cases where they are difficult to derive otherwise

Ba stars

Motivation

A&A 660, A128 (2022)
https://doi.org/10.1051/0004-6361/202142468

Astronomy & Astrophysics

Barium stars as tracers of *s*-process nucleosynthesis in AGB stars

I. 28 stars with independently derived AGB mass

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

- Homogeneous sample of 169 Ba stars
- 28 of which have independently derived mass from the WD companion
- Comparing with well-known *s*-process models (FRUITY and Monash)
- Using [Ce/Fe] as anchor abundance for dilution factor
- Found best matching models within mass and metallicity constrains "by eye"
- **Can we improve on this?**

Ba stars

Motivation

We settle on 2 approaches:

- A custom metric similar to chi-2 where we can use abundance correlations and calculate a tail distribution (with MC) for a goodness of fit
  - $\chi_m = \sum \frac{(X_i - O_i)^2}{E_i}$
- An artificial neural network ensemble where we can train the network to recognize the same model at different dilution levels
  - Ensemble of 20 networks per model (FRUITY or Monash)
  - 1 or 2 hidden layers
  - First layer with one neuron per abundance
  - Hidden layer(s) with 10 to 100 neurons per label

We experimented with different element sets until achieving the best classifications

Ba stars

Results

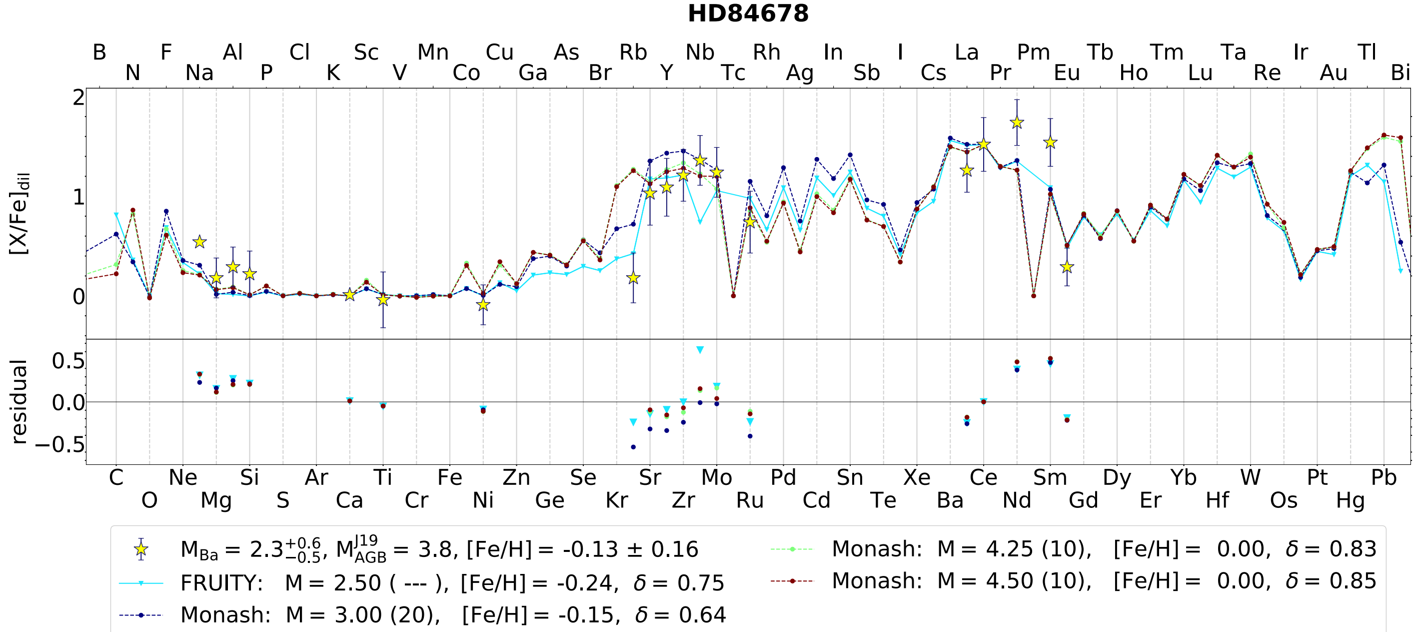
Out of the 28 stars classified by Cseh et al. we find that:

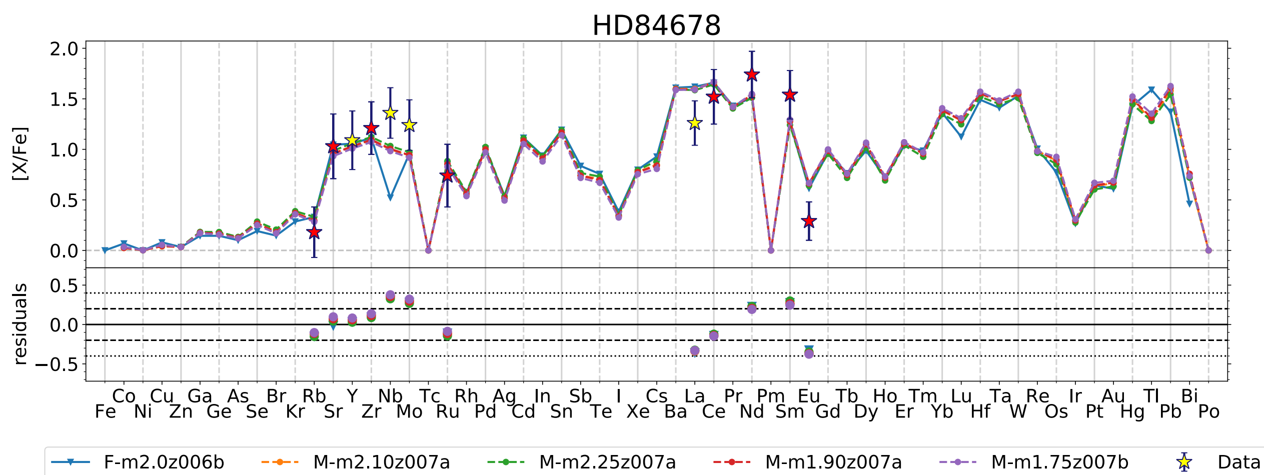
- We agree with 24 (4 hard to classify by Cseh+)
- We do not need to use the mass information
- It takes a few minutes with any method

Success! We can classify almost all the other 141 stars even without independent mass determination

We settle on the following element set for classification: [Fe/H], Rb, Sr, Zr, Ru, Ce, Nd, Sm and Eu. We leave out Nb*, Y, Mo and La improving the classification for 43 (~25%) stars. The Sr-Y-Zr peak, and La-Ba may be different in these stars due to *i* process.

Ba stars


HD84678
[X/Fe]dil
residual
M_Ba = 2.3 +0.6 −0.5, M^J19_AGB = 3.8, [Fe/H] = -0.13 ± 0.16
FRUITY: M = 2.50 (---), [Fe/H] = -0.24, δ = 0.75
Monash: M = 3.00 (20), [Fe/H] = -0.15, δ = 0.64
Monash: M = 4.25 (10), [Fe/H] = 0.00, δ = 0.83
Monash: M = 4.50 (10), [Fe/H] = 0.00, δ = 0.85


HD84678
[X/Fe]
residuals
F-m2.0z006b
M-m2.10z007a
M-m2.25z007a
M-m1.90z007a
M-m1.75z007b
Data

CEMP stars

Introduction

Similar to Ba stars but at low metallicity

- [C/Fe] > 0.7 dex (> 5 times solar)
- Main sequence stars
- With binary companion

Differences

- Not always enhanced in heavier-than-Fe elements
- When enhanced, not always showing an *s*-process pattern
- There is a “zoo”: CEMP-no, CEMP-s, CEMP-r, CEMP-r/s (or CEMP-i), traditionally separated by the Ba and Eu abundances
- Already many traditional classifications with pairs of elements

CEMP stars

Motivation

Not only there are many CEMP star types, but nobody agrees what is the “best way” to separate them

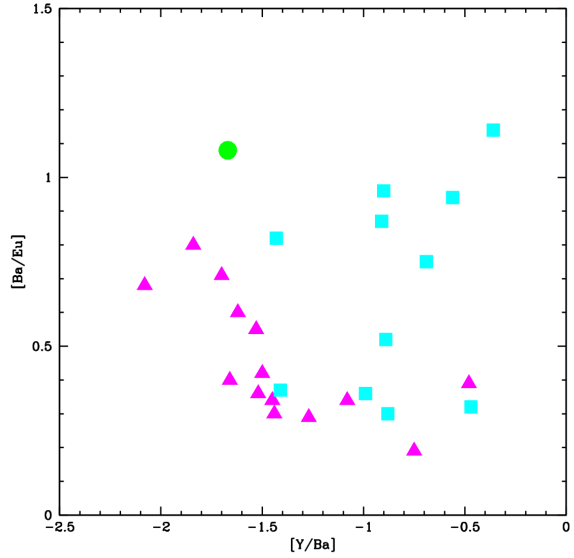


Figure 8. [Ba/Eu] abundance ratio for the entire sample plotted against [Y/Ba]. It depicts the traditional ([Ba/Eu]) against our proposed ([Y/Ba]) classification of CEMP-s and CEMP-r/s stars. The distinction between CEMP-s and CEMP-r/s stars has so far been made at [Ba/Eu] = 0.5. As can be seen, it does not well separate the stars according to the corresponding CEMP-s and CEMP-r/s classes. [Y/Ba] provides a better way to group and classify the stars. Cyan squares correspond to stars traditionally defined as CEMP-s, magenta triangles to stars defined as CEMP-r/s. The green filled circle corresponds to HE 0414−0343.

Hollek+ 2015

CEMP stars

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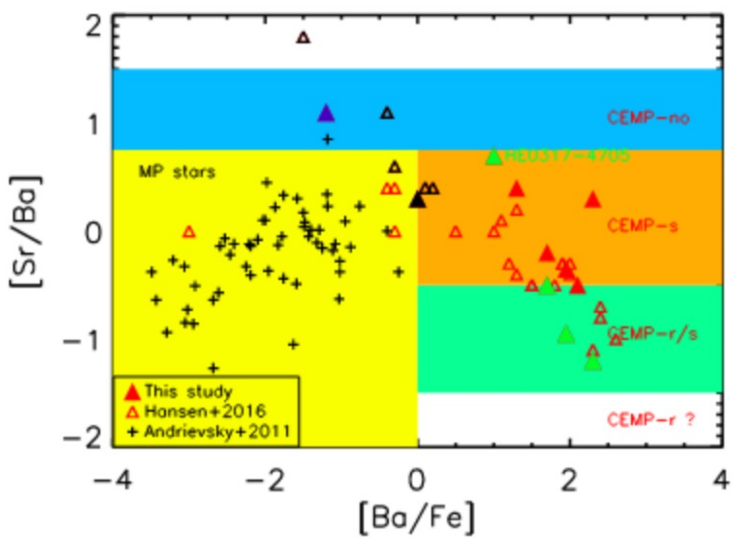

Fig. 7. [Sr/Ba] vs. [Ba/Fe] from this study compared to Hansen et al. (2016b, Paper I) and NLTE values (+) from Andrievsky et al. (2011). The blue symbol colour indicates CEMP-no stars, red CEMP-*s*, and green CEMP-*r*/*s*, while black (yellow region) shows C-normal metal-poor stars. Our suggested sub-classifications are highlighted in similar colours to the symbols.

Hansen+ 2019

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CEMP stars

Motivation

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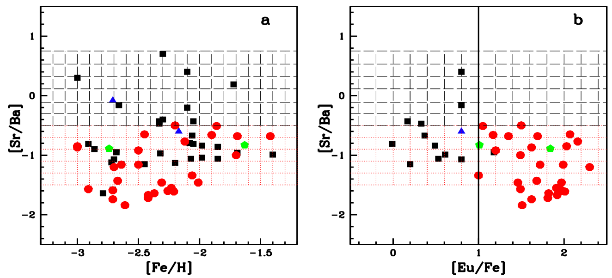


Fig. 14. [Sr/Ba] as a classifier of CEMP-s and CEMP-r/s stars. The filled red circles represent CEMP-r/s stars, filled black squares represent CEMP-s stars, and filled blue triangles and filled green pentagons respectively represent CEMP-s and CEMP-r/s stars in this work. The grid formed by the dashed black lines represents the region of CEMP-s stars, and the grid formed by the dotted red lines represents the region of CEMP-r/s stars put forward by Hansen et al. (2019). In panel (b) the solid black line at [Eu/Fe] = 1.0 separates the CEMP-s and CEMP-r/s stars according to the classification criteria adopted by Abate et al. (2016).

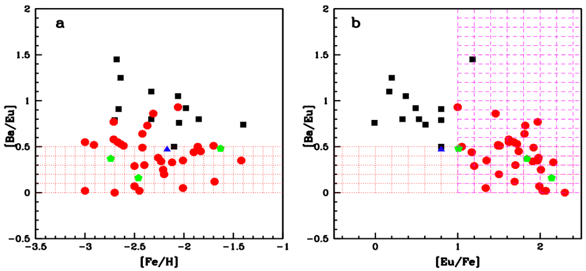


Fig. 15. Same as Fig. 14, but for [Ba/Eu]. The filled red circles represent CEMP-r/s stars, filled black squares represent CEMP-s stars, and filled blue triangles and filled green pentagons respectively represent CEMP-s and CEMP-r/s stars in this work. The grid formed by the dotted red lines represents the region of CEMP-r/s stars put forward by Beers & Christlieb (2005). The grid formed by the dashed magenta lines represents the region of CEMP-r/s stars put forward by Abate et al. (2016).

Goswami+ 2021

CEMP stars

Motivation

Not only there are many CEMP star types, but nobody agrees what is the "best way" to separate them

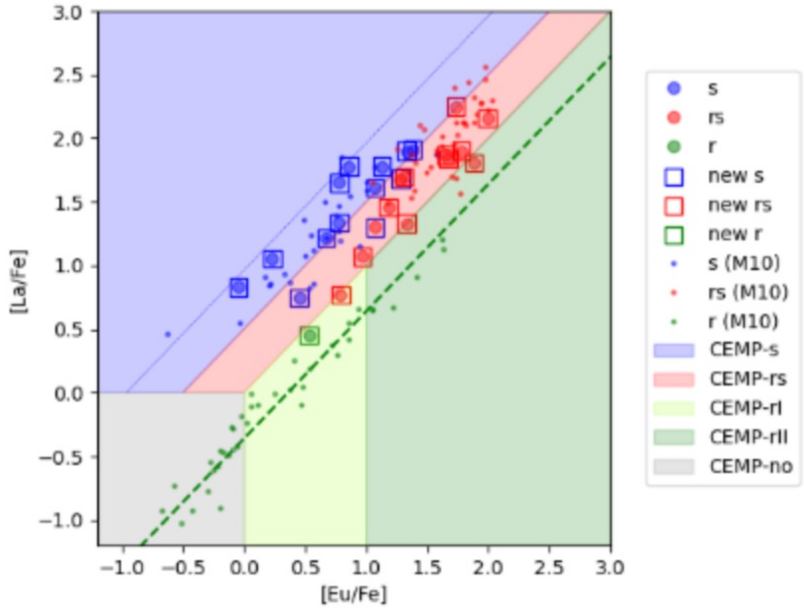
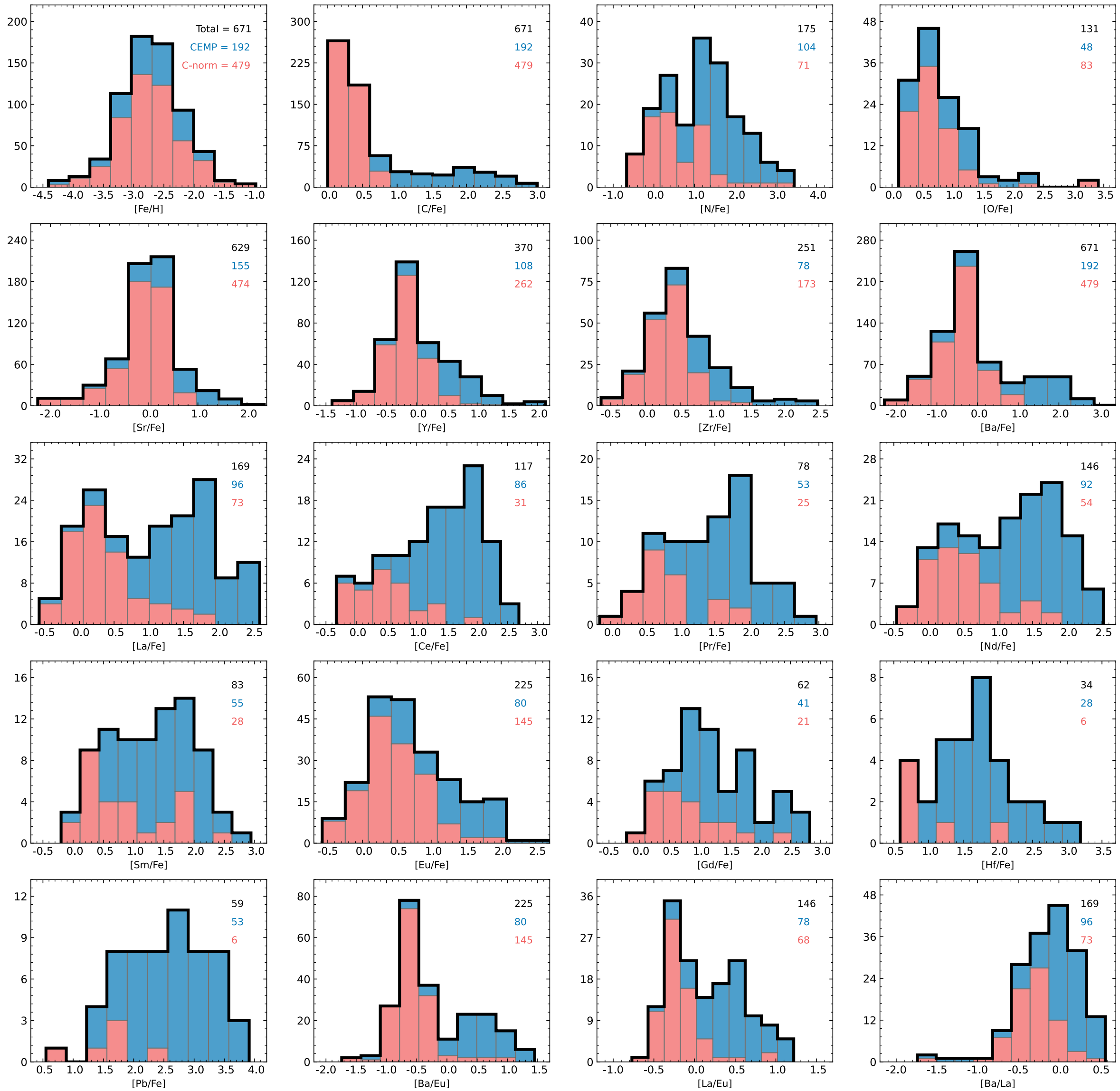


Fig. 6. Same as in Fig. 5, but for [La/Fe] as a function of [Eu/Fe].

Karinkuzhi+ 2021

CEMP stars



Total = 671
CEMP = 192
C-norm = 479
[Fe/H]
[C/Fe]
[N/Fe]
[O/Fe]
[Sr/Fe]
[Y/Fe]
[Zr/Fe]
[Ba/Fe]
[La/Fe]
[Ce/Fe]
[Pr/Fe]
[Nd/Fe]
[Sm/Fe]
[Eu/Fe]
[Gd/Fe]
[Hf/Fe]
[Pb/Fe]
[Ba/Eu]
[La/Eu]
[Ba/La]

CEMP stars

Challenges

The two challenges for these classifications are

- 1) It is an heterogeneous sample
- 2) Not always showing an *s*-process signature

Set	Classifiable	Classified	[Fe/H]	[Sr/Fe]	[Y/Fe]	[Zr/Fe]	[Ba/Fe]	[La/Fe]	[Ce/Fe]	[Eu/Fe]
3	62 (48)	12 (11)	15 (14)	14 (13)	19 (17)	15 (14)	14 (13)	14 (13)	13 (12)	22 (19)
4	66 (49)	17 (14)	23 (18)	19 (16)	-	22 (19)	20 (17)	19 (16)	22 (19)	29 (22)
5	81 (50)	21 (16)	27 (20)	24 (19)	-	27 (22)	24 (18)	23 (17)	-	41 (27)
6	78 (50)	17 (15)	-	18 (16)	25 (20)	24 (20)	24 (20)	21 (18)	-	47 (24)
7	86 (51)	23 (16)	-	23 (16)	32 (21)	30 (20)	-	25 (17)	-	57 (29)
9	63 (49)	18 (16)	-	18 (16)	20 (18)	22 (19)	20 (18)	18 (16)	19 (17)	30 (20)
10	66 (49)	12 (10)	19 (16)	16 (14)	22 (19)	16 (14)	-	13 (11)	14 (12)	24 (19)
11	76 (49)	14 (12)	18 (15)	17 (15)	25 (20)	16 (14)	16 (14)	15 (13)	-	24 (18)
12	67 (50)	21 (18)	-	22 (18)	26 (20)	27 (21)	-	22 (18)	22 (19)	39 (25)
13	89 (69)	44 (36)	64 (48)	64 (55)	-	-	59 (46)	56 (46)	55 (45)	-
14	81 (65)	30 (27)	44 (33)	37 (32)	47 (39)	-	41 (34)	38 (32)	34 (29)	-

Table 1. Classification summary for different sets of elements. Classifiable is the number of stars that have data for at least all the elements in the set. Classified is the number of stars with GoF higher than 0.5. Each one of the columns labelled with an elemental ratio is the number of stars for wich GoF + impact for that ratio is higher than 0.5. A dash in an elemental ratio column indicates that the element is not part of the set. The number in parenthesis is number of stars with [C/Fe] > 0.7

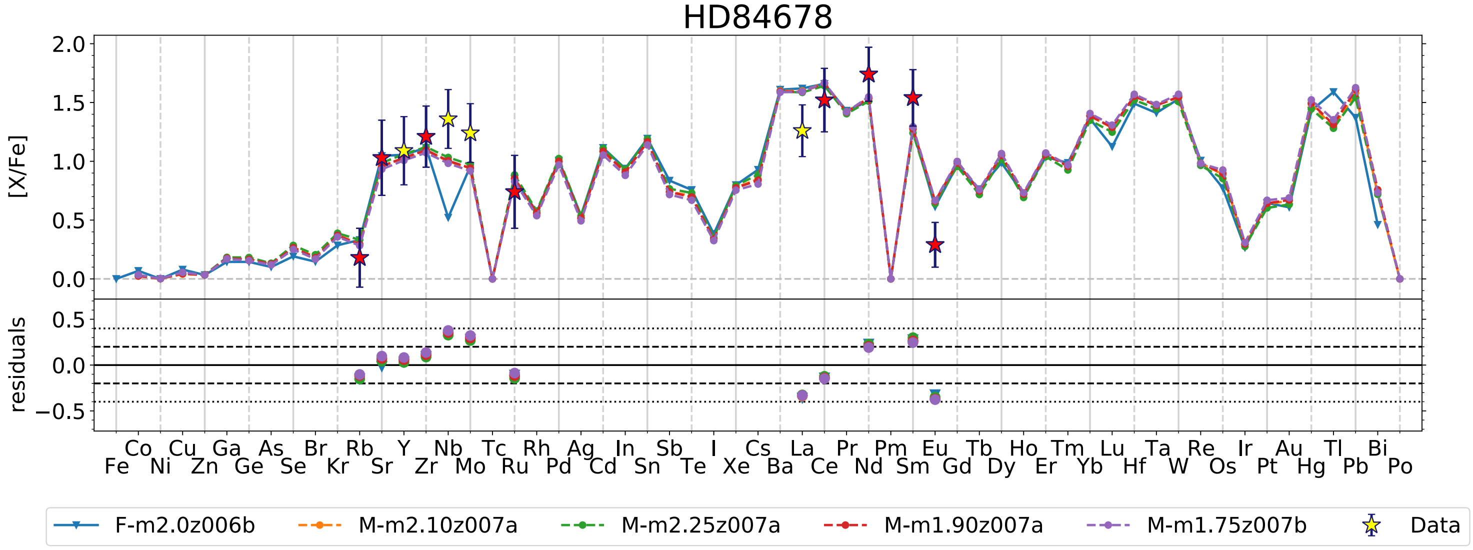
Can we apply the same methods? How do we have to modify them? Can we learn something new?

CEMP stars

Methods

We drop the ANNs, but include a measure of “impact”. We want to detect outliers.

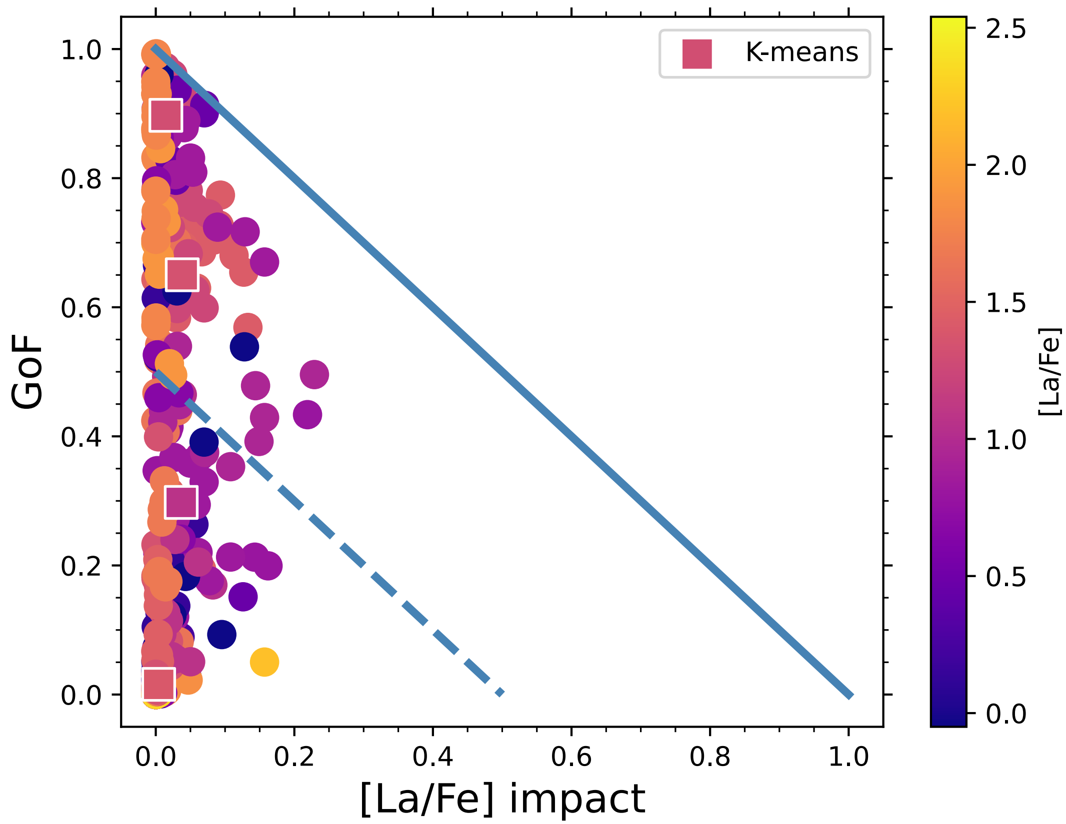
Impact example: This is a Ba star classification with a GoF of ~0.5. What is the impact in the GoF of one element?



CEMP stars

Results

Is there a correlation between the position in this plot and abundances?



CEMP stars

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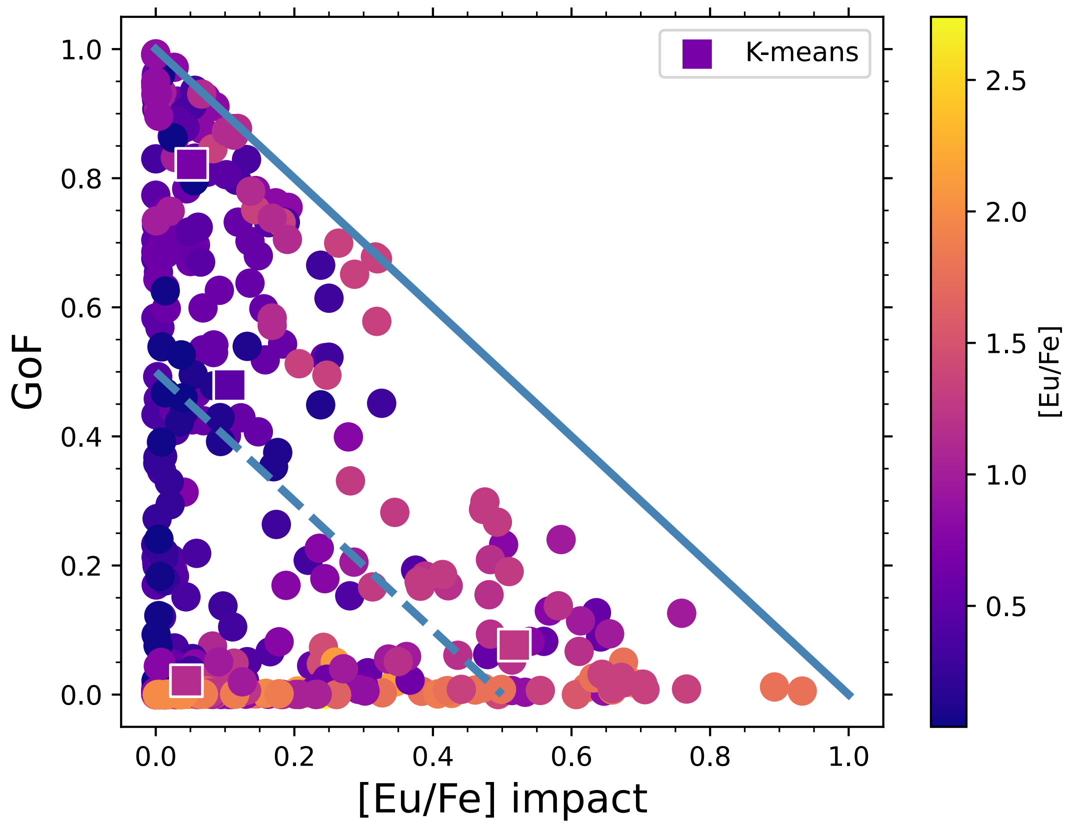


CEMP stars

Results

Are these good predictors of typical classifications?

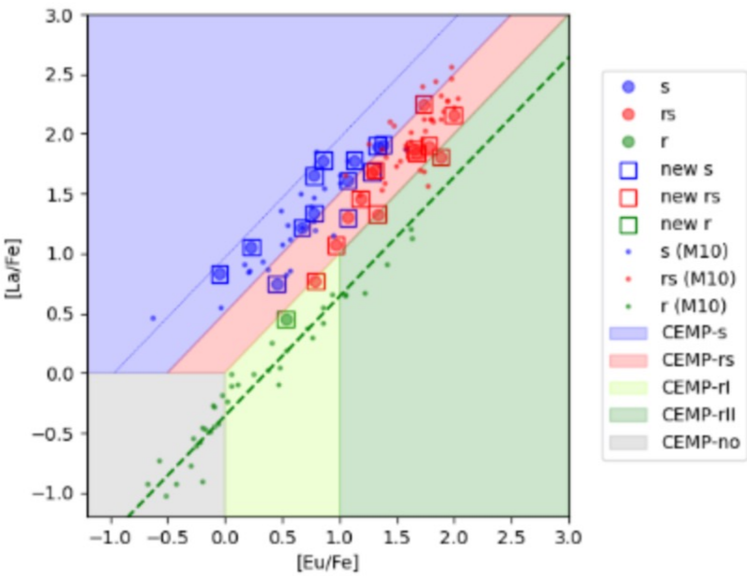
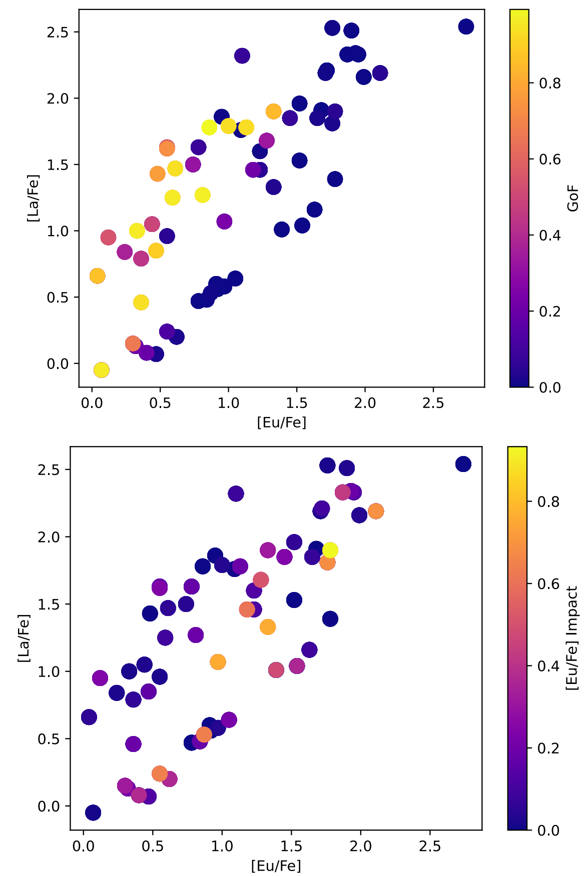


Fig. 6. Same as in Fig. 5, but for [La/Fe] as a function of [Eu/Fe].

Karinkuzhi+ 2021



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CEMP stars

Results

Now that we have the stars classified in 3 broad groups: Agree with s-process, almost agree with s-process and disagree with s-process, we can label them and use supervised learning to see what splits them

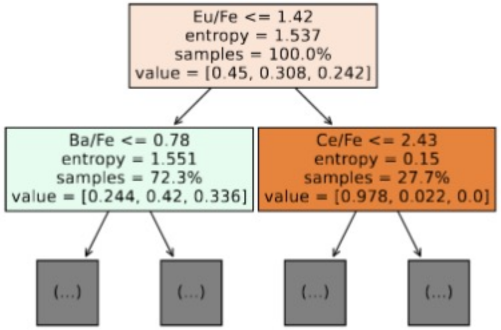

Fig. 12. Truncated example of one decision tree for set 9. The value array represents, from left to right, the proportion of: non-classified observations, observations that are classified with GoF + impact, and observations that are classified with GoF. In this tree, no samples are classified for [Eu/Fe] > 1.42 (right branch from root), so [Eu/Fe] ≤ 1.42 is a necessary condition for this sample to have a CEMP-s star. This is one instance where [Eu/Fe] is a high importance feature.

CEMP stars

Results

We can check what is the feature importance in the random forest. As expected, [Eu/Fe] has high importance, but among the other elements, it is not immediate to know which ones we can discard – maybe we should not

Set	[Fe/H]	[Sr/Fe]	[Y/Fe]	[Zr/Fe]	[Ba/Fe]	[La/Fe]	[Ce/Fe]	[Eu/Fe]
3	0.18	0.12	0.11	0.07	0.09	0.11	0.11	0.20
4	0.22	0.13	-	0.07	0.12	0.11	0.13	0.21
5	0.23	0.14	-	0.10	0.15	0.15	-	0.23
6	-	0.12	0.14	0.14	0.10	0.19	-	0.30
7	-	0.14	0.13	0.14	-	0.17	-	0.41
9	-	0.10	0.13	0.10	0.10	0.14	0.15	0.29
10	0.17	0.13	0.12	0.08	-	0.13	0.13	0.24
11	0.18	0.11	0.14	0.10	0.12	0.14	-	0.22
12	-	0.12	0.16	0.11	-	0.15	0.12	0.34
13	0.31	0.22	-	-	0.16	0.15	0.17	-
14	0.25	0.18	0.14	-	0.13	0.16	0.14	-

Table 3. Averaged feature importance from 1000 random forest classificators after training on our data. The data are separated in 3 classes. One class containing classifications with GoF ≥ 50% (e.g., CEMP-s), another class containing classifications with GoF + max(impact) ≥ 50% (e.g., CEMP-rs) and another class containing the rest of the classifications. The feature importance indicates the information gain provided by each feature. This is how effective each feature is for dividing the data in low-information categories. For a graphical example see Figure 12.

Conclusions

What we learned using statistical methods

We need to use different tools than with Ba stars

Classification much harder than Ba stars and statistical study may be more interesting

We do not find that 2 - 4 elements are enough to classify. Our smallest useful classification has 6

We have shown that ignoring most elements comes at a cost for analysis

That classification needs [Fe/H], [Sr/Fe], [Y/Fe], [Ba/Fe], [La/Fe], [Ce/Fe] and finds the *s*-process pattern but does not see all possible anomalies, so realistically we need to add more, such as [Eu/Fe]