Probing the Galactic s-process nucleosynthesis using metal-deficient Barium stars

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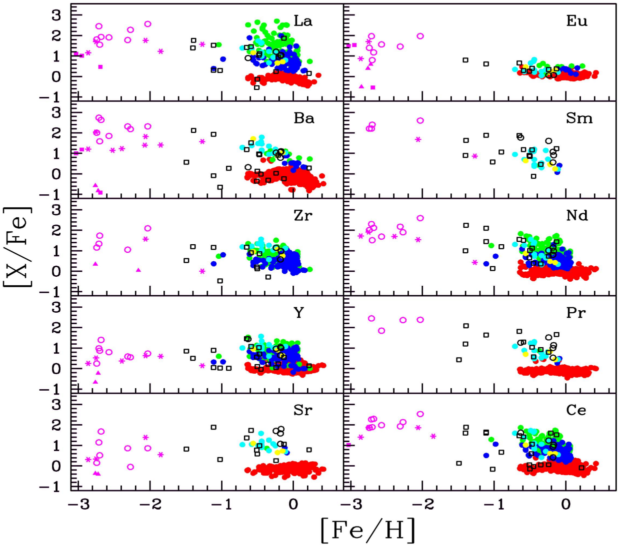
What are Barium stars?

- First identified as a distinct group of peculiar objects by Bidelman & Keenan (1951)
- They belong to G & K spectral types
- Mostly in Main-Sequence and giant phase of stellar evolution.
- Enhanced in s-process elements.
- Characterized by $C/O < 1$ (Barbuy et al. 1992, Allen and Barbuy 2006, Drake and Pereira 2008, Pereira and Drake 2009).
- Low radial velocity, members of Galactic disk
- A small fraction of them show mild metal deficiency.

Why do we care about Ba stars?

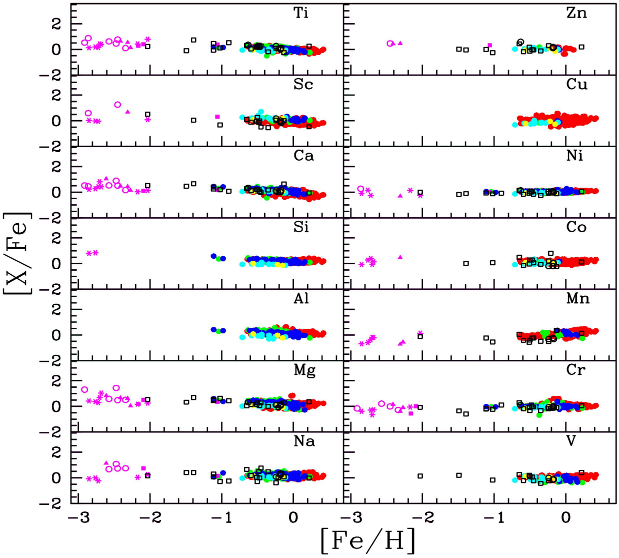
- Extrinsically s-process enhanced
- They can be used as a probe to study the origin of neutron-capture elements, especially s-process nucleosynthesis.

Why the neutron-capture elements?



normal giants
strong Ba giants
weak Ba giants
Ba dwarfs
Ba subgiants
* - CEMP-s
■ - CEMP-r
◯ - CEMP-r/s
▲ - CEMP-no
□ - CH giants
◯ - SG-CH

Inhomogeneous ISM/different origin for different stars???



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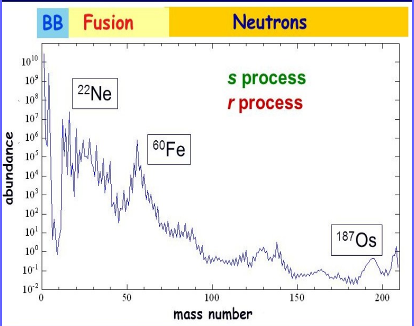
Well-mixed ISM

Origin of s-process nucleosynthesis



slow neutron-capture (s-) process

- $\tau_n >> \tau_\beta$
- $\tau_n \approx 100 - 10^5$ years
- $N_n \approx 10^7$ - 10^{10} neutrons/cm^3
- $23 \leq A \leq 46$, $63 \leq A \leq 209$
- site $\rightarrow$ low & intermediate mass AGB stars

All the low & Intermediate mass stars pass through AGB phase of stellar evolution

AGB stars with M $\leq 3M_{\odot}$

- neutron source: ${}^{13}C(\alpha, n){}^{16}O$
- N$_n$ $\sim 10^8$ neutrons/cm^3
- $\tau \geq 10^3$ years
- $T \geq 90MK$

Massive AGB stars

- neutron source: ${}^{22}Ne(\alpha, n){}^{25}Mg$
- N$_n$ $\sim 10^{13}$ neutrons/cm^3
- $\tau \sim 10$ years
- $T \geq 300MK$

(Busso et al. 2001, Goriely & Mowlavi 2000)

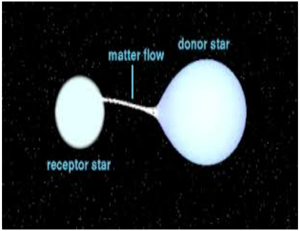
Tc lines

Presence of Tc lines ⇒ Indication that the star is a real AGB star that has undergone recent s-process nucleosynthesis

$$t_{1/2}(^{99}_{43}Tc) \sim 2.1 * 10^5 \text{ years}$$

Ba stars: Binary star system

Binary mass transfer???



- Most of the Ba stars are found to be in binaries (McClure et al. 1980, McClure 1983, 1984, McClure & Woodsworth 1990, Udry et al. 1998a,b) with radial velocity variability.
- Binarity is a necessary condition to produce Ba stars, but it is not a sufficient condition (Jorissen et al. 1998).
- The binary companion which has evolved through the AGB phase might have transferred the s-process rich material to the Ba star.

Possible mass-transfer mechanism

Either RLOF or wind mass transfer depending on the orbital parameters.

Samples & Observations

Candidate selection

From various sources in literature (Lu 1991, Bartkevicius 1996)

Data acquisition/Data resource

- Observations are done with 2m HCT/HESP. (R$\sim$60,000)
- High resolution spectra of some stars are taken from UVES/FEROS archive. (R$\sim$48,000)
- S/N $\geq$ 30

Data processing & analysis

Data reduction

Standard procedures in Image Reduction and Analysis Facility (IRAF) software

Data analysis

Using the radiative Transfer code MOOG by Sneden, employing the Local Thermodynamic Equilibrium (LTE)

- Measured equivalent width
- The log *gf*
- Excitation potential
- Model atmosphere

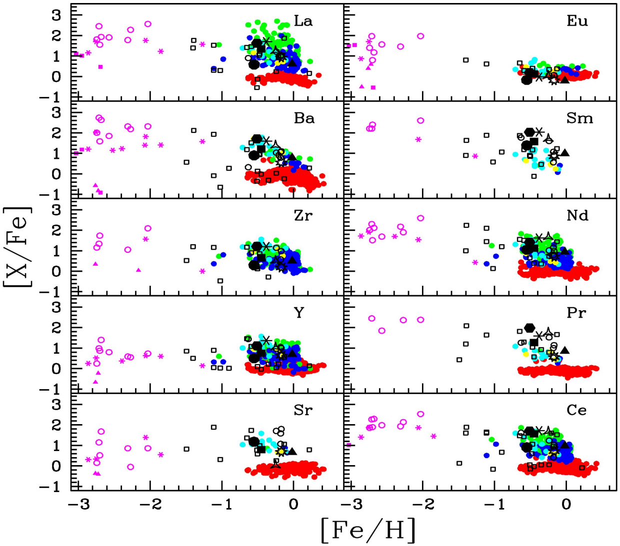
(The log *gf*, Excitation potential, Model atmosphere: Kurucz database; Measured equivalent width, The log *gf*, Excitation potential: line list)

All the abundances are found relative to the respective solar value (Asplund et al., 2009)

Results & Conclusions

- $[Fe/H] \Longrightarrow$ -0.55 to -0.02
- $T_{eff} \Longrightarrow$ 4550 to 5800
- $\log g \Longrightarrow$ 2.20 to 3.86 $\Rightarrow$ Typical of giants/dwarf

Abundance of neutron-capture elements



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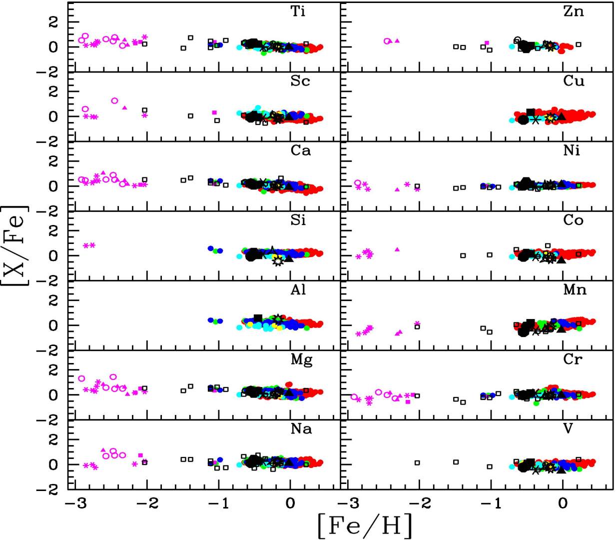
Black symols-program stars

$[X/Fe]=1 \Rightarrow 10*X_{\odot}$

$[X/Fe]=-1 \Rightarrow \frac{1}{10}*X_{\odot}$

Abundance of light elements



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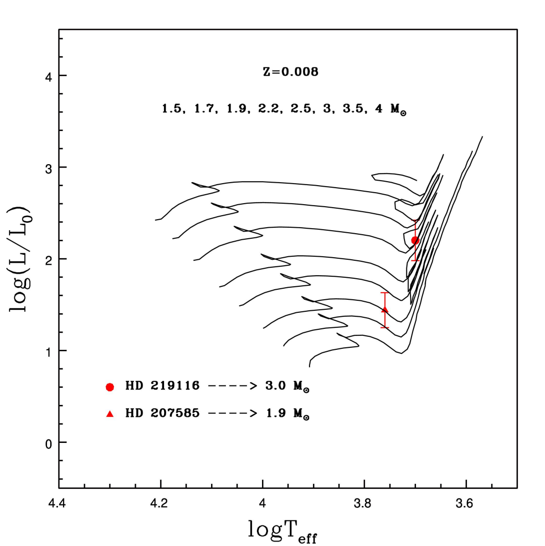
Black symols- program stars

- Ba stars ⇒ de Castro et al. 2016, Yang et al., 2016, Allen & Barbuy 2006
- CEMP stars ⇒ Masseron et al., 2010
- CH stars ⇒ Karinkuzhi & Goswami 2014, 2015, Goswami et al. 2006, 2016, Sneden & Bond 1976, Vanture 1992, Goswami & Aioki 2010, Jonsell et al. 2006, Masseron et al. 2010
- Normal giants ⇒ Luck & Heiter, 2007

HR diagram



- The stars are either on SGB/FGB.
- The heavy elements observed in them have an extrinsic origin

What do we care in Ba stars?

[hs/ls] ratio

- Indicator of s-process efficiency.
- Neutron source & mass of AGB star.

$[hs/ls] = [hs/Fe] - [ls/Fe]$

- hs ⇒ Ba, La, Ce, Nd, Sm
- ls ⇒ Sr, Y, Zr

- At higher neutron exposures : hs is predominantly produced over ls
- neutron exposure: $^{22}Ne(\alpha, n)^{25}Mg < ^{13}C(\alpha, n)^{16}O$

$\Downarrow$

low [hs/ls]

- $^{13}C(\alpha, n)^{16}O$ is anti-correlated with metallicity (Clayton 1988, wallerstein 1997).
- low [hs/ls] value at near-solar metallicities for the $^{13}C(\alpha, n)^{16}O$ source.

[hs/ls]: 0.25 to 1.03 :: agrees with the model calculations of Busso et al. (2001) for similar metallicities, for low mass stars considering ^{13}C source

- Na and Mg are strongly produced as result of ^{22}Ne burning (Bisterzo et al. 2010).

$\Downarrow$

No enhancement found

[Rb/Sr] ratio

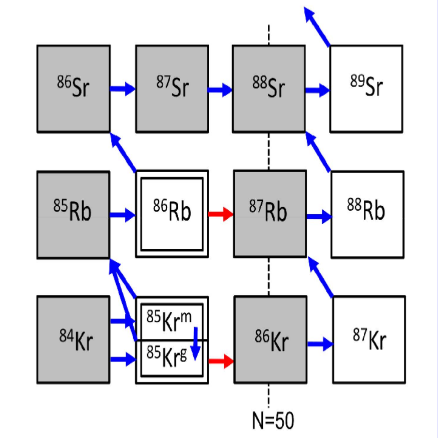
- Indicator of Neutron source & mass of AGB star.

$N_n \geq 5*10^8$ n/cm^3 (massive AGB)
$N_n < 10^8$ n/cm^3 (low-mass AGB)

$$^{85}\mathrm{Kr} \xrightarrow{N_n \geq 5*10^8 \ \mathrm{n/cm^3}} {}^{87}_{50}Rb$$

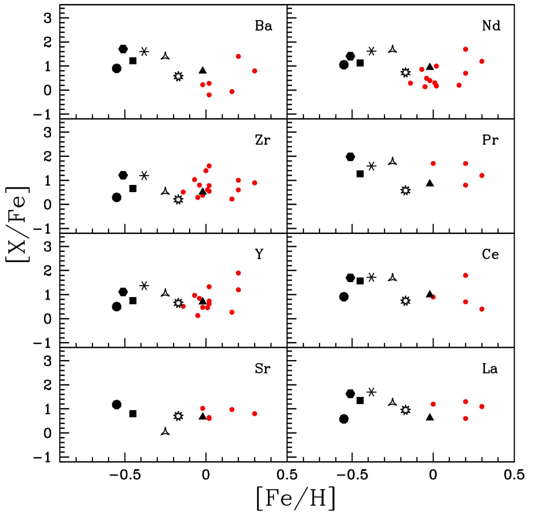
$$\uparrow$$

$$^{85}\mathrm{Kr} \xrightarrow{N_n < 10^8 \ \mathrm{n/cm^3}} {}^{86}\mathrm{Rb} \rightarrow {}^{88}_{50}Sr$$



$$[Rb/Sr] \begin{cases} < 0, \text{ low-mass AGB star, } {}^{13}C(\alpha, n)^{16}O \\ > 0, \text{ massive AGB star, } {}^{22}Ne(\alpha, n)^{25}Mg \text{ (Karakas et al. 2012)} \end{cases}$$

Comparison with AGB abundance



program stars

Intrinsic AGB stars

(Smith & Lambert 1985, 1986, 1990, Abia & Wallerstein 1998)

- The former AGB companion might be low-mass AGB stars with $^{13}C(\alpha, n)^{16}O$ source.

Future work

- We are planning to extent our study
    - To understand whether there is some mixing between the accreted material and the intrinsic material on the surface of the secondary star
    - To understand the timescales, physical conditions and mechanisms of mixing (dilution) in the secondary star

Acknowledgment

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Thank you