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

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12 October, 2018
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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.
- 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???
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

Well-mixed ISM
Origin of s-process nucleosynthesis

slow neutron-capture (s-) process
- $\tau_n \gg \tau_\beta$
- $\tau_n \approx 100 - 10^5$ 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
- $T \geq 90$ MK

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

(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

\[ t_{1/2}(^{99}_{43}Tc) \sim 2.1 \times 10^5 \text{ years} \]
Introduction

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~60,000)
- High resolution spectra of some stars are taken from UVES/FEROS archive. (R~48,000)
- S/N ≥ 30
Methodology

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

\[
\begin{aligned}
\text{line list} \\
\text{Kurucz database}
\end{aligned}
\]

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

- $[Fe/H] \implies -0.55$ to $-0.02$
- $T_{\text{eff}} \implies 4550$ to $5800$
- $\log g \implies 2.20$ to $3.86 \Rightarrow$ Typical of giants/dwarf
Abundance of neutron-capture elements

Results & Conclusions

- Normal giants
- Strong Ba giants
- Weak Ba giants
- Ba dwarfs
- Ba subgiants
  * - CEMP-s
  ■ - CEMP-r
  ▲ - CEMP-no
  ○ - CEMP-r/s
  □ - CH giants
  ○ - SG-CH stars

Metal-deficient Ba stars

\[ \frac{[X/Fe]}{10} \Rightarrow X_\odot \]

\[ \frac{[X/Fe]}{-10} \Rightarrow \frac{1}{10} X_\odot \]
Abundance of light 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 stars
Black symbols - program stars

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- Ba stars ⇒ de Castro et al. 2016, Yang et al., 2016, Allen & Barbuy 2006
- CEMP stars ⇒ Masseron et al., 2010
- Normal giants ⇒ Luck & Heiter, 2007
Results & Conclusions

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.

\[ \frac{[hs]}{[ls]} = \frac{[hs]}{[Fe]} - \frac{[ls]}{[Fe]} \]
- \( hs \Rightarrow \) Ba, La, Ce, Nd, Sm
- \( ls \Rightarrow \) Sr, Y, Zr

At higher neutron exposures: \( hs \) is predominantly produced over \( ls \)

Neutron exposure: \( 22\text{Ne}(\alpha,n)25\text{Mg} < 13\text{C}(\alpha,n)16\text{O} \)

\[ \Downarrow \]

low \( [hs/ls] \)
\[ ^{13}C(\alpha, n)^{16}O \text{ is anti-correlated with metallicity (Clayton 1988, wallerstein 1997).} \]

- 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.

\[ N_n \geq 5 \times 10^8 \text{ n/cm}^3 \text{ (massive AGB)} \]
\[ N_n < 10^8 \text{ n/cm}^3 \text{ (low-mass AGB)} \]

\[ ^{85}\text{Kr} \xrightarrow{N_n \geq 5 \times 10^8 \text{ n/cm}^3} ^{87}\text{Rb} \]
\[ ^{85}\text{Kr} \xrightarrow{N_n < 10^8 \text{ n/cm}^3} ^{86}\text{Rb} \rightarrow ^{88}\text{Sr} \]

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

Program stars
Intrinsic AGB stars
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

- Organizers of the 2\textsuperscript{nd} \textit{BINA workshop} for giving me an opportunity to present my work and also for the local hospitality and the financial support.
- My host institute for the financial support.
Thank you