What process(es) produced neutron capture elements in the Early Universe?

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Neutron capture elements
from Truran 1981 to ~5 years ago

- s-process
- Massive stars (& NS mergers)
  - O-Ne-Mg core explosions?
  - NS stars mergers?
  - Magneto rot. driven SN?
  - many scenarios...

- r-process
- < 30Myr (excluding NS mergers)
- >=300Myr

Site
- Low-(intermediate) mass stars
- Early Galaxy

Time scale
- >300Myr

Yields
- Busso et al. 2001
- Cristallo+11
- Karakas+12

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Site(s) of the r-process?

Electron Capture SNe (Wanajo+11)

Magnetorotat. driven SNe (Winteler+12)

Neutron star mergers (Rosswog+13)

Neutrino winds SNe (Arcones+07, Wanajo 13)

other possible sites?

(Cescutti+15, Matteucci+14, ...)

(Cescutti+13, Cescutti+14)
Magneto Rotationally Driven SN scenario (MRD)  
(Winteler+12, Nishimura+15)

The progenitors of MRD SNe are believed to be rare: only a small percentage of the massive stars (~1–5%).

We have results for 5% and for an higher value (10%).

This percentage is not well constrained, in particular for the early Universe.
Stochastic chemical evolution models

Problem:
Neutron capture elements present
a spread alpha elements do not

Bonifacio+09
Stochastic chemical evolution models

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Solution:
The volumes in which the ISM is well mixed
are discrete. Assuming a SNe bubble as
typical volume with a low regime of star
formation the IMF is not fully sampled.
This promotes spread among different
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Bonifacio+09
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Density plot of long living stars for stochastic model

Cescutti 2008
Cescutti et al. 2013
data collected in Frebel 2010

Bonifacio+09
We run the stochastic model (based on Cescutti '08) with these yields for the Ba production:

10% of all the massive stars produce $8 \times 10^{-6}$ Msun
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Density plot of long living stars for inhomogeneous model

Data from:
- Placco+14
- Hansen+12
- Hansen+16
- Cescutti+16
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10% of all the massive stars produce $8 \times 10^{-6} \text{ Msun}$

We can reproduce the [Ba/Fe] spread… see also the poster by Komiya
Puzzling result for the “heavy to light” n.c. element ratio

For Sr yields: scaled Ba yields according to the r-process signature of the solar system (Sneden et al ‘08)

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It is impossible to reproduce the data, assuming only the r-process component, enriching at low metallicity. (see Sneden+03, François+07, Montes+07)
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Another ingredient (process) is needed to explain the neutron capture elements in the Early Universe!
Rotating massive stars in the early Universe

In the Early Universe
Low metals: stars rotate faster (more compact)

Rotation ➔ Mixing inside star

Ejected matter will be rich in $^{14}\text{N}, ^{13}\text{C}, ^{12}\text{C}$, & s-process

Massive stars rotate in the Local Universe

Signatures:
1. Large amounts of N in the early Universe (Chiappini et al. 2006 A&A Letters)
2. Increase in the C/O ratio in the early Universe
3. Large amounts of $^{13}\text{C}$ in the early Universe (Chiappini et al. 2008 A&A Letters)
4. Early production of Be and B by cosmic ray spallation (Prantzos 2012)
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Test the production of neutron capture elements from this s-process (Sr, Ba, . . .)!
Low metallicity and rotating massive stars

Frischknecht et al. 2012, 2016 (self-consistent models with reaction network including 613 isotopes up to Bi)
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Rotating massive stars can contribute to s-process elements!

\[ V_{\text{ini}} / V_{\text{crit}} = 0 \]

\[ V_{\text{ini}} / V_{\text{crit}} = 0.4 \]

\[ V_{\text{ini}} / V_{\text{crit}} = 0.5 \]

\[ V_{\text{ini}} / V_{\text{crit}} = 0.5, \text{CF88/10} \]

\[ V_{\text{ini}} / V_{\text{crit}} = 0.5, \text{CF88/10} \] 17O+alpha
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Rotating massive stars can contribute to s–process elements!

Can they explain the puzzles for Sr and Ba in halo?
Neutron capture elements
from Chiappini+11

s-process

Early Galaxy

r-process

site
Low-(intermediate) mass stars

Massive stars
(& NS mergers)

rotating
Massive stars

O-Ne-Mg core explosions? NS stars mergers? Magneto rot. driven SN? many scenarios...

< 30Myr
(excluding NS mergers)

> 300Myr

< 30Myr

Early Galaxy

yields
Busso+ 2001

(Frischknecht+ 2012)
(Frischknecht+ 2016)

< 30Myr
( excluding NS mergers)

Cristallo+ 2011
Karakas+ 2012

Pignatari+ 2008
Limongi yields still unpublished

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s-process from rotating massive stars
+ an r-process site (the 2 productions are not coupled!)

Cescutti et al. (2013)
Cescutti & Chiappini (2014)
s-process from rotating massive stars
+ an r-process site (the 2 productions are not coupled!)

Cescutti et al. (2013)
Cescutti & Chiappini (2014)
A s-process (from rotating massive stars) and an r-process (from rare events) can reproduce the neutron capture elements in the Early Universe.
The only possible answer?

Another possible solution is the production of
+ a weak r-process
(not able to produce all the elements up to thorium)
+ a main r-process

Wanajo 2013, r-process production in proto neutron star wind
The only possible answer?

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(not able to produce all the elements up to thorium)
+ a main r-process

Boyd et al. 2012, truncated r-process due to fallback
The rotating massive stars scenario naturally predicts different Ba isotopic ratios in halo stars.

This prediction can be used to test our scenario.

Challenging to check these predictions

See results on HD 140283 from Magain (1995) to Gallagher+ (2015)
Magneto Rotational Driven scenario: 10% of SNe produce r-process

Star Formation is very low due to low density in these systems, rate of massive stars is low.

Tiny probability to produce a r-process event.

Enriched manly by rotating massive stars, with a low enrichment of Ba.

Situation 2 years ago...
New data (Ji et al. 2016, Roederer et al. 2016) support this model: some UF galaxies are indeed enriched by r-process elements…

Not only, we can put new constraints to the r-process events thanks to these new data…

(ask if you want to know!)
Conclusions

The neutron capture elements in the Galactic halo have been produced by (at least) 2 different processes:

A (main) r-process, rare and able to produce all the elements up to Th with a pattern as the one observed in r-process rich stars.

Another process more frequent and that can produce both Sr and Ba (and [Sr/Ba] > 0) with a production that is compatible with the s-process by rotating massive stars.

In the near future we will be able to confirm this scenario thanks to the isotopic measurements of the barium line at 455.4 nm.

Theoretical results and more robust statistic from the observational data will enable (soon?) us to put more constraints to the r-process events. At the moment we can just constrain that they should be:

- relatively rare (~10% of the SNII)
- have a short timescale (~ SN II - <10-30Myr)
Distribution functions in Ultra faint Galaxies

Canberra, 23/11/2016
Conclusions I
Fast rotating massive stars
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Solution for 4 signatures in the early Universe

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First stars were fast rotators! (?)
Possible way to constrain through

Nucleosynthesis the Nature of the First Stellar Generations:

The oldest stars in our Galaxy formed from the gas ejected by the First Stars
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Massive Stars – short lifetimes

Core collapse Supernova

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Massive Stars – short lifetimes

Low mass stars – long lifetimes

Core collapse Supernova

First polluters in the Universe

The Sun

Imprints of the First stars
Where are the oldest fossil stars in the MW

Face on

Edge on

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Where are the oldest fossil stars in the MW

In the Halo

\([\text{Fe/H}] < -3\)

data by Li et al. 2010

In the Bulge

\([\text{Fe/H}] \sim -1\)

data by Ness et al. 2013
Halo model

Comparison between the metallicity distribution function of our halo model and the observed MDF by Li+ (2010) main-sequence turnoff stars in the HESS (Hamburg ESO survey)
In the best model shown here the amount of r-process in each event is roughly the same as the max (8Msun) in the previous model (scaled to Eu!)

The percentage of event in the massive stars is higher than expected (at least at the solar metallicity), but it is expected to increase toward the metal poor regime (Woosley and Heger 2006)

No need for Eu of an extended production, just upper limit—really Eu low or just observational limits?
The amount of a single event is increased to match again the distribution.

The model is in reasonable agreement but already at this stage present a too high spread in the intermediate metallicity.

Other reason to discard this model are connected with the [Sr/Ba] distribution in halo stars.
Also this progenitor are rare: only few percent of the massive stars are formed in binary system which can produce a NS merger.

Again this percentage is not constrained at all the metallicities, the rate is constrained just at the present time.

The key difference between NS merger and MRD SN is the delay between the formation of the binary system of neutron stars and the merging event. We investigate delay of 1, 10 and 100Myr.

This scenario has been also investigated by Matteucci et al. (2014). The novelty here is the use of the stochastic model.
Neutron stars mergers

delay for the merging 1Myr

For these results, 4% of the massive stars are progenitors NS merger which produce r-process material.

The amount of a single event is similar to the one for the MRD scenario with 5%.

The model is really similar and indeed produces a similar spread.

Probably more interesting is the impact of increasing the delay for the merging.
Neutron star mergers
delay for the merging 10 Myr

If we increase the delay up to 10 Myr no strong impact is visible.

The progenitors enrich in a timescale which is still compatible to the a normal SNII timescale.
For a delay of 100 Myr the model results are not anymore compatible to the observational data.

Therefore from the point of view of the chemical evolution of the Galactic halo, we can conclude that only if most of the NS mergers enriches in timescale <10Myr, the scenario can be supported.

If a distribution of delays is available we can simulate the results.

This is not a new result, it has been shown by Argast+ 2004, Matteucci+2014, Komiya+2014... just an exception the recent astro-ph Shen+2014?
Different scenarios for r-process do not alter the results concerning spinstars. They are still needed to explain the spread between heavy to light neutron capture elements.

A unbiased distribution of observed stars would be a key to disentangle between the different scenarios.

We present here also predictions for the distribution of Rb (few data available only for GCs).
**Distribution functions**

A more detailed comparison between model and observational data.

Still some problems (possible biases) but future data can help to improve the comparison (at the moment large bins to have a significant number of stars in each bin).

Both models are acceptable.

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Cescutti et al. (2014)
We cannot at the present exclude none of the scenarios. Stronger theoretical constraints from the stellar evolution will help as well as the future large survey with well known observational biases.

Other option at the present is explore different Galactic structures as the Bulge or other galaxies as the satellites of the Milky Way.

Some results already present in Barbuy et al. (2014) for the bulge

Some previews on the faintest dSphs . . .
What’s going on in the other fossil early Universe – the Bulge?

NGC 6522 stars can be explained if polluted by an early generation of fast rotating massive stars

Chiappini et al. (2011, Nature)
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NGC 6522 stars can be explained if polluted by an early generation of fast rotating massive stars. Chiappini et al. (2011, Nature)

Inhomogeneous model for the Bulge – FIRST RESULTS in Barbuy et al. 2014
Stochastic C.E. model for the bulge

Gaussian infall law with an high final density which promotes a fast chemical evolution.
We aim to reproduce only the tail of the most metal poor and old stars of the bulge.
The SN bubble is dependent to the density ($\sim \rho^{-0.4}$), so the dimension of the volumes are decreased.
The bulge model
alpha elements
and the comparison with the halo model

Bulge stars:
- Bensby old (Age > 11 Gyr)
- Bensby not old
- NGC 6522
- NGC 6522 [Ba/Eu] > 0
Only r-process with the EC-scenario

bulge stars:
Bensby old (Age>11Gyr)
Bensby not old
NGC 6522
NGC 6522 [Ba/Eu]>0
spinstars + r-process
with the EC-scenario (lifetime ~30Myr)

bulge stars:
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with the MRD-scenario (lifetime ~4 Myr)

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C.Johnson, McWilliam and Rich 2013
spinstars + r-process
with the MRD-scenario (lifetime ~4Myr)

Conclusions III

We model for the first time a chemical stochastic model for the Galactic bulge.

If in the halo the spinstars are a very promising way to explain the scatter in the \([Y/\text{Ba}] \([ls/hs])\).

At the moment in the bulge there are not enough data.

(... but the plateau seems to indicate the necessity of an extra production).

There are hints of a spread in \([\text{Ba/Fe}]\) at low metallicity in bulge stars. We can reproduce this spread if the site of production of the \(r\)-process elements has a very short time scale, in better agreement to the magneto-rotational driven SNe scenario (compared to electron-capture SNe scenario).