Modelling the galactic chemical evolution of r-process elements

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http://www.nasa.gov/images/content/138785main_image_feature_460_ys_full.jpg
In the beginning…

BANG!
What the Big Bang made...

(The primordial abundance pattern)
What We Find Today

(The solar abundance pattern)

Asplund+ (2009)

Extracted from Fields et al. (2002),
slide from A. Heger
What happens in between???
Where do the (heavy) elements come from?

Stars are “fusion reactors”
Freeing binding energy via fusion is possible up to Fe/Ni

From "physics forums"
Entropy and magnetic field in an exploding star
Puppis A

SN ~3500 years ago
Ejected neutron star is visible!
**SN Ia:**
Thermonuclear explosion of a WD (from an IMS) in a binary system

Ejects ~0.6 solar masses of Ni

=> decays to Fe.

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SN 1994D
in NGC 4526

http://www.spacetelescope.org/images/html/upo9919i.html
Where do the (heavy) elements come from?

=> How do we produce the heavier elements?
One solution: “rapid neutron capture process”

=> “Walk around” the binding energy peak, then decay towards valley of stability
Responsible for ~50% of the heaviest elements
You need a lot of neutrons!!
„Classical“ r-process site: NSM
Problem solved???

...unfortunately not!
Brief introduction: Galactic Chemical Evolution

**Look at the night sky:** Unsorted stars.
Brief introduction: Galactic Chemical Evolution

Now: **Identify Fe contents**: Solar metallicity, metal poor, extremely metal poor
Brief introduction: Galactic Chemical Evolution

Sort the stars according to their Fe contents:

$$\frac{X}{Y} = \log \left( \frac{X}{Y} \right)_{\text{star}} - \log \left( \frac{X}{Y} \right)_{\text{Sun}}$$
Brief introduction: Galactic Chemical Evolution

Now: introduce alpha element y-axis.

\[ [X/Y] = \log \frac{(X/Y)_{\text{star}}}{(X/Y)_{\text{Sun}}} \]
Now: Real data.

From SAGA database, e.g., T. Suda et al., PASJ, 60, 1159-1171, 2008.
How can this evolution be explained?

The amount of scatter in the [Mg/Fe] evolution originates in the different Mg-Fe ratio from different CCSN progenitor masses.

Roughly constant abundances due to simultaneous ejection at constant [Mg/Fe] ratio in CCSNe.

Decrease due to large iron contribution of type Ia SNe.
r-process elements vs. metallicity

Europium is taken as diagnostic for r-process elements
- ~96% produced by the r-process
- Has two good lines at 4192.70 Å and 4205.05 Å

From SAGA database, e.g., T. Suda et al., PASJ, 60, 1159-1171, 2008.
Let’s model that!
Classical site (NSMs) works in 1D models

Ejecta of a site propagate *everywhere immediately*
1D models always predict a **line**
Overlap of lines matches observations
But the classical site (NSM) has a hard time in 3D

3D models **can account for the scatter of elements**

No matter which parameter is altered, it is **difficult to match the observed abundances**:  
- Red dots are model stars with the canonical parameters  
- Green dots are model stars in a model with extremely low coalescence time scales for NSM, but shift is marginal  
- Blue dots are model stars with increased NSM probability
A neutron star merger requires 2 neutron stars
Thus 2 supernovae necessary!
A solution: A **second** r-process site
Acting at low metallicities, e.g., MHD-SNe

MHD-SNe are a very rare sub-class of CCSNe
Their progenitors are extremely fast rotating and highly magnetized
During explosion, the magnetic field lines force the emergence of polar jets
In the jets, requirements for an r-process are met (Winteler+12, Nishimura+15)
Advantage: r-process contribution already at low metallicities!!
Low-met region accessible!

MHD-SNe eject Fe and Eu simultaneously!
MHD-SNe and NSMs together are a good combination
Confirmed by Haynes & Kobayashi (2019)
Using cosmological zoom-in model
Another possibility? BHNSMs
What do we need?

- Binary system
- One star goes supernova (leaves behind a NS)
- The other one “fails” > collapses to BH

How to find the stars that “fail”?
Use PUSH to determine where CCSNe "fail"

- PUSH is a parametrized CCSN code
- Treats $v_e$ self-consistently
- Heating via parametrized heavy $v$ energy deposition
- Normalized to SN87A Ni-56 output
- Fast execution allows to scan entire progenitor range for "failed" SNe

Credit to:
Ebinger+18/19 Darmstadt,
Curtis+18/19 Raleigh NC,
Perego+15 Darmstadt/Basel
Use PUSH to determine where CCSNe “fail”

>Put these results into the GCE suite!

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Model results show good agreement with observations!

BW, Fröhlich, Côté, Pignatari, Thielemann (2019)
- Skip one CCSN per r-process event
- Age-metallicity relation is slowed down
- Effect is very localised
Dominant process

We know location and time of all nucleosynthesis sites
> Allows us to determine which process is dominant at which Galactic
Exotic SNe have same advantage as MHDs: Ejecting Fe and Eu simultaneously!
Problem: Sr probably overproduced….

Similar: “exotic SNe”
Short lived (~My) radioisotopes have an additional advantage: They provide **timing** information!

Production value, observed value, elapsed time: If you know two, you may derive the third!
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Production value, observed value, elapsed time: If you know two, you may derive the third!

**HINT! HINT!** If you find a good set of SLRs, And built their ratio:
You’ll end up with a **LINE!**
...and if you do everything correctly, will point directly at the last event where it was produced....

...allowing you to directly probe the yield ratios of the last r-process event!!!!

![Graph](image)

**Fig. 2.** $^{129}$I/$^{247}$Cm abundance ratios predicted by our theoretical r-process models (see Methods section). The red horizontal line and horizontal bands show the meteoritic ratio along with its 1σ and 2σ uncertainty (see Methods section).
If you look at the whole Galaxy, however, And have variable delay times (NSMs)...
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...this tends to extend the steady-state value...

Figure 2. Visualization of the key parameters involved in our Monte Carlo calculations. Here $\gamma$ is the constant time interval between the formation of two progenitors. The delay times (blue arrows) represent the time intervals between the formation of the progenitors and their associated enrichment event. Those delay times are randomly sampled from an input DTD function. The different $\delta$ values are the time intervals between two consecutive enrichment events, regardless of the formation time of the progenitors. This means that $\delta$ cannot have negative values.
...leading rather to a \textbf{spectrum} of abundances:

\begin{figure}
\centering
\includegraphics[width=\textwidth]{figure3}
\caption{Top panels: evolution of the median and 68\% and 95\% confidence levels of the mass of radionuclei ($M_{\text{radio}}$) as a function of time using Monte Carlo calculations with 100, 1000, and 10,000 runs (from left to right), with $\gamma = 10$ Myr and the 3–50 Myr box DTD function. The gray shaded area represents the maximum and minimum values reached during the calculations. Bottom panels: distribution of predicted $M_{\text{radio}}$ at 12 Gyr (black histograms) for the calculations with 100, 1000, and 10,000 runs (from left to right). The gray histograms show the distribution of $M_{\text{radio}}$ when all time steps between 12 and 14 Gyr are stacked together to improve the statistics.}
\end{figure}

...this is still \textbf{1D}!!!
Moving to 3D this gets even more complicated!

**Remarks:**
- Radioactive decay is visible in single cells (between nucl events)
- This is hidden behind the SN blast wave effect
- Pu-244 & Fe-60 always seem to appear **simultaneously**
What happens if NSM ejecta get “bulldozed” by SNe?
Solar System

Area of high density

NSM and CCSN ejecta
Moving to 3D this gets even more complicated!

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Ultimate goal is implementing SLRs in Kobayashi chemodynamical cosmological zoom-in model

Imagine the possibilities:
• Know exactly where (spiral arms?) in the Galaxy which SLRs can be found
• Deep sea sediments measurements
• Planet formation / heating => liquid water!
  • **Thus ultimately**, which areas of the Galaxy could host life!!
Conclusions

- **Low metallicity**
  - NSMs as exclusive r-process sites have difficulties
  - Can be cured by BHNSMs / second, early acting site

- **SLRs**
  - Provide additional timing/production/observation information
  - Seem to arrive on Earth simultaneously
  - May be used as proxy for cosmic life searches

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