r-process enrichment traced by Pu and Ba near the sun and in the Draco

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capturing electromagnetic waves

stellar spectra

earth archives

meteorites

deep-sea crusts

r-process site/nucleosynthesis

Observational Signatures of r-process nucleosynthesis in neutron star mergers on August 1st, 2017
Talk outline

I. Pu near the sun

✓ short-radioactive nuclei $^{244}\text{Pu}$ evolution in the solar vicinity

✓ event frequency & propagation of neutron star merger (ejecta)

II. Ba in the Draco

✓ The Milky Way satellite galaxies are the excellent testbed for the $r$-process study

✓ two distinct $r$-process events in the early Draco
last $r$-process event at the early solar system
from short-lived radioactive nuclei

Galactic chemical evolution

chemical enrichment inside giant molecular cloud

isolation by CCSNe

last $r$-process event

meteoritic abundances unstable/stable

production ratio

time interval between last $r$-process event and the solar system formation

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Production Ratio</th>
<th>Time Interval</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{247}$Cm/$^{235}$U = $(1.1-2.4) \times 10^{-4}$</td>
<td>0.4</td>
<td>123 Myr (Lugaro et al. 2014)</td>
</tr>
<tr>
<td>$^{129}$I/$^{127}$I = $1.19 \pm 0.20 \times 10^{-4}$</td>
<td>1.35</td>
<td>109 Myr (Lugaro et al. 2014)</td>
</tr>
<tr>
<td>$^{244}$Pu/$^{238}$U ~ 0.008</td>
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<td>100 Myr (Dauphas 2005)</td>
</tr>
</tbody>
</table>

Lugaro et al. 2014

$n$-process

{-100 Myr

- 30 to -10 Myr

star-forming nebula

star birth, self-pollution by massive star winds and supernovae

Solar System formation

+4570 Myr
today meteoritic analysis

0.4

1.35

0.53

123 Myr

109 Myr

100 Myr

unstable/stable

(1.56 \times 10^7 \text{ yr})

(1.57 \times 10^7 \text{ yr})

(8.1 \times 10^7 \text{ yr})
On the other hand, meteoritic abundances of radionuclides originated from CCSNe such as

\[
\begin{align*}
^{26}\text{Al} & \text{ (half-life: } 1.03 \text{ Myr)} \\
^{60}\text{Fe} & \text{ (half-life: } 2.2 \text{ Myr)}
\end{align*}
\]

imply the injection from a nearby CCSN since their abundances are higher than the steady-state abundance inferred from γ-ray observations.

last event of CCSNe $<< 100$ Myr

\( r \)-process production events may occur much less frequently than CCSNe

the whole evolution of \(^{244}\text{Pu} \) abundance in the solar vicinity

a nice paper by Hotokezaka et al. (2015): neutron star merger = the \( r \)-process site
244Pu evolution in the solar system

1. the early solar system (ESS) from meteorites
   ✓ 244Pu/238U ~ 0.008 at 4570Myr ago from meteorites

2. the present from deep sea
   ✓ current abundance of 244Pu from deep sea measurement

very low, compared with at the ESS

~0.15 × ESS value from a sediment
~0.01 × ESS value from a crust

Wallner et al. 2015

FeMn crust with a total thickness of 25cm was sampled in 1976 from the Pacific Ocean at 4,830m water depth.
How to calculate $^{244}$Pu evolution

step 1. the ejected mass of $^{244}$Pu per volume per event

meteoritic abundances of short-lived radioactive nuclei hold the information on one last r-process event

$^{244}$Pu/$^{238}$U $\sim 0.008$ & meteoritic abundance of $^{238}$U

$^{244}$Pu$=2\times10^{-12}$: mass fraction by one event in the ISM

step 2. the total event number till the solar system formation

solar abundances (meteorites) of stable nuclei hold the information on an accumulation of all r-process events till the ESS

an ejected mass of Eu per one event per cm$^3$ $=2.5\times10^{-11}$

$3.7\times10^{-10}/2.5\times10^{-11} \sim 15$

step 3. dating of individual events using a star formation history

$^{244}$Pu/$^{238}$U $=0.33$

(Goriely & Janka 2016, Eichler et al. 2015)
(i) We integrate the SFR from the beginning of the Galaxy to the time of ESS and bin by the inferred number (~15) of contributing r-process events during that time.

(ii) We integrate the SFR forward from the ESS time to the present, and at any time that the integrated number of newly formed stars reaches the threshold number, $^{244}$Pu is ejected into the ISM.
star formation history: never constant but has a bursting feature

Relatively current low star formation rate compared with at ESS results in a longer time interval of events and leads to a low Pu detection in deep sea.

(TT et al. 2017)
the frequency of $r$-process production event

by counting the number of supernovae
for the current interval of $\sim$400Myr

/step 1. the present-day local supernova rate
✓ from the local present-day star formation rate: $0.48-1.1M_\odot$/Gyr/pc$^2$
the relation between SFR and CCSN rate
SFR=1.65/yr & CCSN rate=2.3/century in the Galaxy
→ one per 2.1-4.8 Myr per 100 pc-radius disk region
✓ from $^{60}$Fe detection in deep sea crusts (Wallner et al. 2016)
Two supernovae occurs at 1.5-3.2 Myr ago and 6.5-8.7 Myr ago
at distances up to 100 pc
→ one CCSN per 4Myr per 100pc-radius disk region

/step 2. the volume where a NSM propagates
The volume contains gas of $\sim$$3.5\times10^6$ $M_\odot$
local surface density of gas = $8 M_\odot$ pc$^{-2}$
$\sim$370 pc-radius disk region

+ synthesized Pu mass
$^{244}$Pu density
$\sim$100 x SNR

the number of CCSNe within 370pc-radius for 400 Myr: $\sim$1400 CCSNe

NSM rate = one per $\sim$1400 CCSNe at the current solar system
NS merger rate deduced from stellar abundances

\[ \text{slope} = \frac{\text{NSM Eu yield} \times \text{NSM rate}}{\text{supernova Mg yield} \times \text{supernova rate}} \]

\[ M_{\text{Fe}} \sim 0.07 \, M_\odot \]
(from light curve, Hamuy 2003)

\[ \text{Mg} = 0.1 \, M_\odot \]
\[ [\text{Mg/Fe}]_{\text{halo}} = 0.4 \]
(from the observed halo ratio)

\[ M_{\text{NSM, ejecta}} = 0.01 \, M_\odot \]
+ the solar \( r \)-process pattern

NSM rate = one per \( \sim 1400 \) CCSNe
The Milky Way satellite galaxies

Dark energy survey
(credit: A. Frebel)
Why dwarf galaxies?

supernovae vs. NS mergers

one NSM event per ~1000-2000 CCSNe

For instance, a dwarf galaxy with $10^5 M_\odot$

~500 CCSNe in total

no NS Merger event in such a galaxy is predicted.

Note! the Milky way experiences more than $2 \times 10^5$ NS mergers.
I. faint (small-mass) dwarf galaxies

No increase in $r$-process abundance strongly suggests a NS merger is the $r$-process origin.

II. massive ($M > 10^7 M_\odot$) dwarf galaxies

An increasing Eu/H trend is reasonable since NS mergers happened $\sim$100 times in total in the Fornax galaxy ($2\times10^7 M_\odot$).
Very early $r$-process enrichment in faint dwarf galaxies

Where Eu comes from?

Most of $[\text{Eu}/\text{H}]$ values for $[\text{Fe}/\text{H}]<-2$ are derived from $[\text{Ba}/\text{H}]$ assuming the pure $r$-process $\text{Ba}/\text{Eu}$ ratio.

$r$-process abundance remarkably increases for $[\text{Fe}/\text{H}]<-2$

\[ a \text{ gradual increase?} \]

\[ \text{or a sporadic increase?} \]
We measured $r$-process abundance in the Draco dSph galaxy from here!
Twelve Draco stars for $-2.5 < [\text{Fe/H}] < -2$

Whereas the Ca and Fe lines are quite similar, the strengths of the Ba and Y lines are different between the eight objects form the top and the other four objects.

The two stars have similar stellar parameters but show the different Ba, Y, and Eu abundances.
Two distinct $r$-process populations

The occurrence of an episode boosting $[\text{Ba}/\text{H}]$ by one order of magnitude around $[\text{Fe}/\text{H}] \approx -2.3$. 
Two distinct r-process populations are also implied from their Eu abundances

The abundance of a light neutron-capture element, Y, shows a feature similar to Ba and Eu

spectral lines of Eu are not detected

nearly pure r-process Ba/Eu ratio

a jump-like increase in [Y/H] as large as that seen in [Ba/H]

~ 1 dex jump
Similarities to $r$-process event in Reticulum II

I. A single $r$-process event in both galaxies increases $[\text{Ba/H}]$ up to approximately the same level, i.e., $[\text{Ba/H}] \sim -2$.

II. This increase in $[\text{Ba/H}]$ is accompanied with an increase in the abundance of light neutron-capture element, Sr and Y, by the same magnitude as the increase of Ba.
the mass of Ba ejected from the r-process event in the Draco

$$\Delta [\text{Ba/H}] = \frac{\text{the ejected Ba mass}}{M_{\text{ISM}}}$$

[Barium to Hydrogen] from -2.9 to -1.9

Ba mass $\sim 3 \times 10^{-4} M_\odot$

Who is the r-process producer?

- a NS merger
- a magneto-rotational supernova

The latest results suggest Ba production as much as $2.8 \times 10^{-4} M_\odot$.

The ejecta composed of elements with $A \geq 89$ including Y with a mass of $0.01 M_\odot$ contain the Ba mass of $3.2 \times 10^{-4} M_\odot$, assuming the solar r-process pattern.

Nishimura et al. 2017
Two types of $r$-process events

two types of $r$-process events differing at least one order of magnitude in the degree of enrichment of ISM

eject a large amount of $r$-process elements

lifting $[\text{Ba/H}]$ up to $\sim -2$ at $[\text{Fe/H}] \approx -2.3$

eject a much smaller amount of $r$-process elements as low as <10% of the event around $[\text{Fe/H}] = -2.3$

lifting $[\text{Ba/H}]$ up to $\sim -3.5$ at $[\text{Fe/H}] \approx -3$

not found in the Ret II

identical to the one in the Ret II

two types of $r$-process events differing at least one order of magnitude in the degree of enrichment of ISM
Keep in mind:

$r$-process events are not necessarily associated with the high production.

Open question:

The presence of two $r$-process events may suggest the same site generates a different amount of nucleosynthesis products owing to, e.g., a large variety of ejecta mass of NS mergers or $r$-process yields in magneto-rotational SNe ?? or it implies the presence of two distinct $r$-process sites ??

“We witness a neutron star merger and a supernova! ??”
Conclusions

✓ $^{244}$Pu evolution in the solar system
  method: short-radioactive & stable $r$-process elements
  meteorites & deep-sea archives

$r$-process site: neutron star mergers
event frequency: one per $\sim 1400$ core-collapse supernovae
ejecta spread: $\sim 100 \times$ SN ejecta

✓ Ba abundance feature in the Draco dwarf galaxy
  method: high-dispersion spectroscopy

Two distinct $r$-process events
which are associated with high and low $r$-process yields