Chemical evolution of the Galactic halo with neutron star mergers based on the sub-halo clustering scenario

Yuhri ISHIMARU (ICU, Japan)

2. Ba in MPS must also come from r-process.
3. Similarly to Ba, we can expect Eu also decreases towards lower metallicity and reaches the lower limit at [Fe/H] ~ -3.5

Candidates of the r-process site(s)
Most of elements heavier than Fe are produced by r-process

1. Core-Collapse Supernovae
   (since Burbidge et al. 1957; Cameron 1957)

2. Neutron Star Mergers
   (since Lattimer et al. 1974; Symbalisty et al. 1982)
**But SNe are difficult to produce heavier r-elements...**

Wanajo, Janka, Müller (2011, 2014) suggests that electron capture SNe can be the source of lighter r-nuclei, using self consistent exploding model of ECSNe.

ECSNe possibly be the site of trans-Fe including weak r-process, but cannot produce main r-process elements.

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**Serious Problem in Chem. Evol. with NSMs**

Long merger timescale (~100 Myr) would cause the delayed appearance of Eu!

- Argast+ 2004
- Matteucci+ 2013
- Komiyama+ 2014
- Tsujimoto & Shibayama 2014

**NSMs with long merger time cannot explain observed scatters in MPS?**

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**Can NS merger be the r-process site?**

- Classical formation channel: $t_{NSM} = 100$ Myr – 10 Gyr
- New formation channel: $t_{NSM} = 10^2 – 10^3$ yr
- less than 8% of NSMs (Dominik+13)

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**BUT**

Hierarchical galaxy formation scenario may not exclude neutron star mergers!!
Mass-metallicity Relation

Observations of dwarf galaxies show good correlation between average metallicity and stellar mass, irrespective of their morphologies:

\[ \frac{\left< [Fe/H] \right>}{(M_*)} \propto (M_*)^{0.3} \]

Average metallicity indicates the metal productivity (so-called “galactic yield”) of each galaxy.

Massive sub-halos must have higher metal productivity!

Chemical Evolution of Sub-halos with NSMs

Ishimaru, Wanajo, Prantzos 2015

MMR suggests \( \frac{\left< [Fe/H] \right>}{SFR} \propto \frac{SFR}{OFR} \propto (M_*)^{0.3} \)

Therefore, more massive sub-halos have higher SFR or lower OFR.

Two extreme cases are considered:

**Case 1:**

\[ \frac{SFR}{M_{gas}} \propto (M_*)^{0.3}, \quad \frac{OFR}{M_{gas}} = \text{const.} \]

**Case 2:**

\[ \frac{SFR}{M_{gas}} = \text{const.}, \quad \frac{OFR}{M_{gas}} \propto (M_*)^{0.3} \]

Fixed values: \( \frac{SFR}{M_{gas}} = 0.20 \text{ Gyr}^{-1}, \frac{OFR}{M_{gas}} = 1.0 \text{ Gyr}^{-1} \) for \( M^* = 10^8 M_\odot \)

**NSM:**

- Merger time: 100 Myr : 1 Myr = 95% : 5%
- NSM event rate: 1 per 1000 SNe
- Constant Eu yield: \( 2 \times 10^{-6} M_\odot \)
**Chemical evolution of the Galactic halo with NSMs**

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**Metallicity Distribution Functions**

Taking into account of the structure formation simulations and MMR, we obtain the sub-halo mass function as: \( \frac{dN}{dM} \propto M^{-1.7} \)

The Galactic halo is regarded as the sum of sub-halos with the weight of the sub-halo mass function.

This scenario can confirm the observed MDF of the Galactic halo.

**Case 1:** \( \frac{SFR}{M_{\text{gas}}} \propto (M_\ast)^{0.3} \)

**Case 2:** \( \frac{SFR}{M_{\text{gas}}} = \text{const.} \), \( \frac{OFR}{M_{\text{gas}}} = \text{const.} \)

**Eu & Ba Enrichment with NSMs**

**Case 1:** \( \frac{SFR}{M_{\text{gas}}} \propto (M_\ast)^{0.3} \)

**Case 2:** \( \frac{SFR}{M_{\text{gas}}} = \text{const.} \), \( \frac{OFR}{M_{\text{gas}}} = \text{const.} \)

*Plateau of [Ba/Fe] at [Fe/H] \(-3\) possibly come from new formation channel of NSMs with shorter merger time scale*

**High [r/Fe] stars?**

Actually, the total number of NSM in low mass sub-halos must be extremely small!

In case of \( 10^4 M_\odot \) sub-halos, the average of total number of NSMs is as low as 0.1.

It means only one sub-halo out of ten suffers NSM!

But stars in such sub-halo must show strong enhancement of Eu!
**Stochastic Chemical Evolution of sub-halos with NSMs**

Ojima, Ishimaru, Wanajo, & Prantzos in prep.

Based on such scenario, we examine enrichment of each sub-halo by NSMs, using Monte-Carlo method.

According to the sub-halo mass function: $dn/dM \propto M^{-1.7}$, total number of model sub-halos which form the Galactic halo are given as follows:

<table>
<thead>
<tr>
<th>Stellar Mass [$M_\odot$]</th>
<th>$10^4$–$10^5$</th>
<th>$10^5$–$10^6$</th>
<th>$10^6$–$10^7$</th>
<th>$10^7$–$10^8$</th>
<th>$10^8$–$2\times10^8$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Num. of sub-halos</td>
<td>741</td>
<td>147</td>
<td>29</td>
<td>6</td>
<td>1</td>
</tr>
<tr>
<td>Mean</td>
<td>0.174</td>
<td>1.75</td>
<td>19.1</td>
<td>184</td>
<td>694</td>
</tr>
</tbody>
</table>

**[Eu/Fe] vs. [Fe/H] in sub-halos**

- Case 1: $SFR/M_{gas} \propto (M_\odot)^{0.3}$, $OFR/M_{gas} = const.$
- Case 2: $SFR/M_{gas} = const.$, $OFR/M_{gas} \propto (M_\odot)^{0.3}$

Because of high SFR, enhancement of Eu appears at $[Fe/H]=-2$

Some stars show extreme high $[r/Fe]$, because of high OFR

**Galactic Halo: sum of sub-halos**

Case 1 reproduce large scatters of $[r/Fe]$ in MPS. But the trend is rather flat.

Case 2 shows clear correlation of $[r/Fe]$ with $[Fe/H]$. But the dispersion is small for MPS, and high enhancement of $[Ba/Fe]$ is seen at $[Fe/H]=-2$. 

Stars in low mass sub-halos show strong enhancement of Eu!

Stars in massive sub-halos distribute on the average values.
Chemical evolution of the Galactic halo with NSMs

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The best fit model

\[
\frac{\text{SFR}}{M_{\text{gas}}} \propto (M_*)^{0.2} \quad \text{and} \quad \frac{\text{OFR}}{M_{\text{gas}}} \propto (M_*)^{-0.1}
\]

If the Galactic halo was formed from sub-halos with mass-dependent SFR & OFR,
NSMs with long coalescence time can well explain observed [r/Fe] of MPS!

Conclusions

If the Galactic halo are formed from clusterings of sub-halos with mass depend SFH, i.e.,
\[
\frac{\text{SFR}}{M_{\text{gas}}} \propto (M_*)^{0.2} \quad \text{and} \quad \frac{\text{OFR}}{M_{\text{gas}}} \propto (M_*)^{-0.1},
\]
NSMs with long coalescence time, \(\sim 100\text{Myr}\),
well explain [r/Fe] in MPS.

This scenario is also consistent with obs. of UfDs:

\~90%: (Almost) No r-process
\~10%: Strong r-enhanced stars such as Ret II.

These results strongly support NSMs as the site of r-process!

UfD: Reticulum II

\(10^3 - 10^{11} M_\odot\) sub halos
NSMs occur in 9 out of 138 SHs

In particular, this scenario predict
1 out of 10 UfDs (\~10^4 M_\odot) shows extremely high [r/Fe],
which is consistent with observational data of UfDs!