Connection of Galactic r-process enrichment with merger event rates of NS-NS & BH-NS binaries

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1. Light *r*-process nucleosynthesis

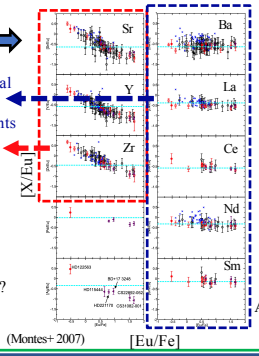
I. Supernovae produce light r-process elements??

r-process features for Galactic halo field stars

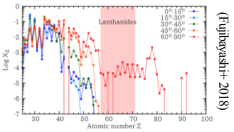
The uniformity of elemental ratios exists only for heavy *r*-process elements

A nonuniform abundance pattern for light *r*-process may suggest that they are produced in the different site from heavy *r*-process

co-production of light *r*-process elements and Fe??



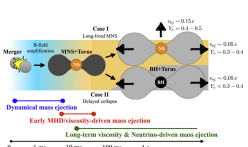
II. NS mergers can produce light r-process elements in the post-merger ejecta

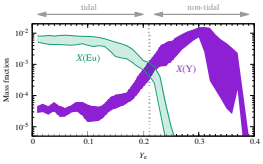


The post-merger wind from the torus surrounding a massive NS is characterized by moderate Ye values and dominantly produces light r-process elements.

A need to change the interpretation of [light *r*-process/Eu] variation

2. Nucleosynthesis in tidal and non-tidal ejecta





classification of ejecta

merger process	nucleosynthesis
dynamical	tidally-driven
post-merger	non-tidal

tidal ejecta

without experiencing significant shock heating nor neutrino irradiation

➡ low Ye

➡ production of heavy *r*-process elements

non-tidal ejecta

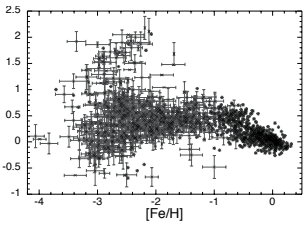
shock heated ejecta

➡ Ye increases

➡ production of light *r*-process elements

3. A large star-to-star variation in [Eu/Fe] for Galactic halo stars

A large star-to-star variation in the abundances of r-process elements, as seen in the [Eu/Fe] ratio for Galactic halo stars, is a prominent feature that is distinguishable from other heavy elements.



~three orders

can explain

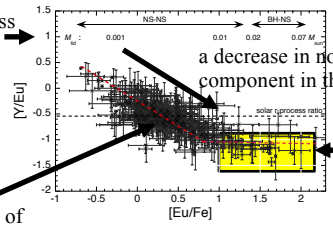
The mass of dynamical ejecta is predicted to vary very widely

$\sim 10^{-4} - 0.01\ M_\odot$: NS-NS mergers (e.g., Hotokezaka+2013)

as massive as $\sim 0.1\ M_\odot$: BH-NS mergers (Kyutoku+2015)

4. Observed correlation of [light *r*-process/Eu] with [Eu/Fe]

approximate mass of tidal ejecta



a decrease in no-tidal component in the dynamical ejecta

no Y production in the dynamical ejecta (dynamical=tidal)

the average mass of tidal ejecta from NS-NS mergers

a few × $10^{-3}\ M_\odot$

variable Y/Eu

small ⟷ large mass asymmetry

small ⟷ large M_{tidal}

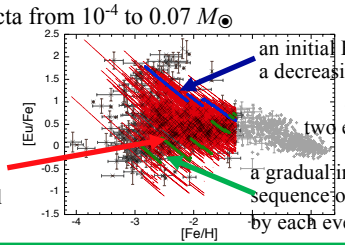
high ⟷ low Y/Eu

the lowest Y/Eu

Massive dynamical ejecta produce little light *r*-nuclides (Y) due to very low *Ye* as in the case of BH-NS mergers

5. Chemical evolution of *r*-process in the Galactic halo

- protogalactic fragments with a baryonic mass of $10^6\ M_\odot$ (the minimum baryonic mass at the epoch of galaxy formation)
- In each fragment, separate chemical evolutions proceed as building blocks of the halo
- an Eu ejection occurs at a rate of one per ~200 CCSNe (~6 events in fragment), randomly assigning the mass of tidally-driven dynamical ejecta from 10^{-4} to $0.07\ M_\odot$



chemical paths in 100 fragments, randomly selected

an initial Eu-boost, followed by a decreasing trend of [Eu/Fe]

two examples

a gradual increase in [Eu/Fe] via a sequence of mild Eu enrichment by each event

6. Merger Event Rate

I. NS-NS

from the solar composition of Eu and Mg

$$\frac{\mathrm{Eu}}{\mathrm{Mg}}\ (=5.2\times 10^{-7}) = \frac{\text{NS–NS rate}}{\text{CCSN rate}} + \text{Galactic CCSN rate} \rightarrow \text{NS-NS rate}$$

(2.3 SNe per century)

$$R_{\text{Milky Way}} \approx 20 \left(\frac{M_{tidal}}{0.01 M_\odot}\right)^{-1} \text{Myr}^{-1}$$

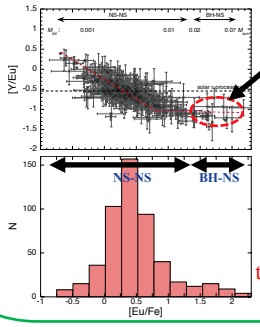
$$R_{\text{Local Volume}} \approx \mathbf{230} \left(\frac{M_{tidal}}{0.01 M_\odot}\right)^{-1} \text{Gpc}^{-3}\text{yr}^{-1}$$

⟨ + the density of a Milky Way equivalent galaxy

The event rate of NS-NS deduced from Advanced LIGO/Virgo Observing Runs 1 and gives 110-3840 $\text{Gpc}^{-3}\text{yr}^{-1}$ (the 90% confidence intervals) with the most probable value around **~1000 $\text{Gpc}^{-3}\text{yr}^{-1}$**

in good agreement if we adopt the average mass of tidally-driven dynamical ejecta of **a few times $10^{-3}\ M_\odot$**

II. BH-NS producing *r*-process elements



halo stars associated with enrichment by BH-NS mergers

Roughly,

$$\frac{N_{\text{stars with } [\frac{\mathrm{Eu}}{\mathrm{Fe}}]>1.4}}{N_{\text{stars with } [\frac{\mathrm{Eu}}{\mathrm{Fe}}]<1.4}} \approx \frac{\text{BH–NS rate}}{\text{NS–NS rate}}$$

~0.5-1% at maximum ~1000 $\text{Gpc}^{-3}\text{yr}^{-1}$

the event rate of BH-NS with the r-process ≈ a few per Gpc^3 per year

7. Summary

- Galactic *r*-process abundance feature demands the contributions from both NS-NSs and BH-NSs.
- There is no necessity of an astrophysical site for light r-process elements different from merger events.
- The typical mass of tidally-driven dynamical ejecta for double NS mergers is predicted to be a few times $10^{-3}\ M_\odot$.
- This implied relatively low ejecta mass is nicely supported by the NS-NS rate deduced from the gravitational-wave observations.
- There is a low probability that the gravitational-wave events originated from BH-NSs are accompanied by electromagnetic counterparts.