Hirschegg 2017 "Neutron Star Mergers"

GCD–Evolution & the Origin of R–Process Elements

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Galaxy formed in 0.1 Gy, then First Star formed in a few My.

Cosmic Evolution

Last Photon Scatter: 3.8x10^5 y

Dark Age

Galactic Chemo-Dynamical Evolution

Galaxy Evolution & Sites of R-Elements?

13.8 Gy

1.3 Gly

Supernova

Binary BH Merger

Binary NS Merger

Quantum Fluct. of Space-Time

Cosmic Evolution
How to identify Astro. Sites for R-Elements, SNe or NSMs.

[1] Time-Scale Problem of NSMs in Galactic Chemical Evolution
⇒ Galactic Chemo-Dynamical Evolution

   — Nuclear Physics
   — Astron. Obs. of EMP☆ + Cosmochem. Analys. of Pre-Solar Grains

Binary Neutron–Star Mergers

100My ≤ τc ≤ 10Ty

Binary NS Mergers have arrived too late in cosmic history!
**Time Scale Problem**
Merging, too slow for GW rad.: $100\text{My} < \tau_c$

\[
\tau_c \approx 9.83 \times 10^6 \text{ yr} \left( \frac{P_b}{\text{hr}} \right)^{8/3} \times \left( \frac{m_1 + m_2}{M_\odot} \right)^{-2/3} \left( \frac{\mu}{M_\odot} \right)^{-1} (1 - e^2)^{7/2}
\]

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**Gal. Chem. Evolution (not Dynamical Simul.)**
Argast, et al., A&A 416 (2004), 997,

Larry M. Greenhill

\[\tau_c = 100 \text{ My} \]

Merger R–Process (Theory)

- $\tau_{life} (10-30M_\odot)$
  - $1\text{My}$
  - $10\text{My}$
  - $100\text{My}$
  - $10\text{Gy}$

**Orbital period (hours)**
- $100\text{My}$
- $10\text{Gy}$
- $10\text{Ty}$
Mixing of r-elements between Neighboring UFDGs is limited to $[\text{Fe/H}] < -3.5$ and only fractional 0.001-0.1%.

SUPERCOMPUTING of Galactic Chemo–Dynamical Evolution
Dwarf Galaxies = Building Blocks of Milky Way Galaxy

N–Body/SPH Simulation of DM+GAS+Star Particles with GAS MIXING in star forming region. SNe = Metals ; NSM ($\tau_c = 100$My) = r–process elements. ($n_H > 100$ cm$^{-3}$ $\rightarrow \sim 10$–100pc)

SPH code = ASURA (Saitoh et al., PASJ 60 (2008), 667; PASJ 61 (2009), 481)


$M_{\text{tot}} = 7 \times 10^8 M_\odot$, $N_i = 5 \times 10^5$ particles, $M_\star = 100 M_\odot$
Galactic Chemo-Dynamical (N-Body/SPH) Simulation

No need of introducing artificial parameters!


Time-scale for STAR FORMATION $\sim 1\text{--}2\text{Gy} (1000\text{My})$

Binary NSMs ($100\text{My}<\tau_C$) can contribute from the epoch of INHOMOGENEOUS mixing!

**Star Formation History**

![Graph showing star formation history with time and metallicity distributions for different models.](image-url)
SUPERCOMPUTING of Galactic Chemo-Dynamical Evolution of Dwarf Galaxies

N-Body/SPH Simulation of DM+GAS+Star Particles with GAS MIXING in star forming region.
SNe = Metals ; NSM (τ_c=100My) = r-process elements. (n_H > 100 cm^{-3} \rightarrow \sim 10-100pc)


Without GAS MIXING

With GAS MIXING

NSMs have arrived still too late !

Sun (obs.)
Core-Collapse Supernovae

\( \nu \)-Driven Winds \( \Rightarrow \) Up to 1st R-Peak


Long-GRBs (Collapsar) \( \Rightarrow \) Peculiar R-Pattern


MHD-Jet


Explosion Condition, still unclear?

\( \tau = 1 - 10 \text{My} \)

Underproduction, off R-Peaks?
UNIVERSALITY !

Early Galaxy !


UNIVERSALITY is explained by ONLY SN-MHD Jet !

Astron. Obs. Doesn’t separate ISOTOPES !

Atomic Number Z ELEMENTAL (Z)
Solar System r-Process Abundance

Early Galaxy!

$\text{Te}(52)$

$\text{Sn}(50)$ → $\text{Nd}(60)$

$\nu$-Driven Wind SN

Magneto-Hydrodynam. Jet Supernovae
Lorusso, Nishimura, Kajino et al. (2015), PRL 114, 192501.

Many contributors

Less abundant
We don’t care in Elemental!

Abundant

R-process path

128, 130 Te(r)

Sn (50)

Nd (60)
**C staying Nuclei: Magneto-Hydrodynamic Jets**


**Possible Solutions**

Underproduction → Possible Solutions

Nucl. Phys. – Shell Quenching?

or

Another Site (NSM)!

S.S. abundance has no Time-Scale Problem.
RIKEN–RIBF : Decay Spectroscopy around $A = 100–145$

G. Lorusso et al., PRL 114 (2015), 192501.

No clear evidence for shell quenching on N=82!

H. Watanabe et al., PRL111 (2013)
No clear evidence for shell quenching on N=82!

$^{128}\text{Pd}$ is the progenitor parent of the 2nd r-peak element $^{128}\text{Te}$
MHD–Jet SNe vs. Binary Neutron Star Mergers

$^{236}$U & others
Theory vs. Exp.

Fission fragment $n$

Bimordial or Trimodal FFD:

$$f(A, A_p) = \sum_{A_i} \frac{1}{\sqrt{2\pi\sigma}} W_i \exp \left( -\frac{A - A_i}{2\sigma} \right)$$

$A_H = (1 + \alpha)(A_p - N_{loss})/2$

$A_L = (1 - \alpha)(A_p - N_{loss})/2$

$A_M = (A_H + A_L)/2$

Neutron capture ($n,\gamma$) plays important roles!

Neutron Star Mergers

Fission Region

Numerical result
Solar r-element


Oe, France, (2007).
**Fluid-Dynamical Model for Neutron Star Merger**

**Binary Neutron Star Merger**


**SPH Simulation: (Adiabatic Expansion)**

Newtonian gravity, Neutrino Leakage scheme

**Entropy, Ye, T, ρ Evolution:** *(Fission is a strong heat-source: S ∼ \( \dot{q}/T \))*

We solved thermodynamic evolution of each trajectory from the initial conditions.

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![Graph showing mass fraction Ye against neutron number N](attachment:image.png)

Ye \( \sim 0.03 \)

Extremely n-rich!
Solar System $r$-Process Abundance


Neutron Star Mergers

(0.1 Gy = 100 My < $\tau$)

v-Driven Wind SN

Magneto-Hydrodynam. Jet Supernovae

Asymmetric Fission Recycling

ISOTOPIC–MASS (A)
Ejected Mass [Msun] x Event Rate [/Galaxy/Century]

<table>
<thead>
<tr>
<th>Ejected Mass</th>
<th>Event Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>νSN (Weak r)</td>
<td>$7.4 \times 10^{-4}$</td>
</tr>
<tr>
<td>MHD Jet SNe</td>
<td>$0.6 \times 10^{-2}$</td>
</tr>
<tr>
<td>Binary NSMs</td>
<td>$(2 \pm 1) \times 10^{-2}$</td>
</tr>
</tbody>
</table>

**Observations**

- a $1.9 \pm 1.1$ Diehl, et al., Nature 439, 45 (2006).
- b $0.03 \pm 0.02$ Winteler, et al., ApJ 750, L22 (2012).

Galactic Evolution including Binary Evolution
Kajino, Mathews et al. (2017)

\[
\frac{dM_i}{dt} = P_t(t) + E_i(t) + X_m f_{m}(t) - X_i f_{m}(t) + B(t)
\]

Ejection rate of species $i$ into the ISM

\[
E_i(t) = \int_{m_{t}}^{m_{\infty}} \frac{(m_{t}X_i(t - t_{\infty})(m - m_{t} - m_{m}))q(m)q(t - t_{\infty})dm}{t_{\infty}}
\]

Production rate of newly synthesized species $i$ into the ISM

- $P_t(t) = m_{T_{\infty}}R_{T_{\infty}} + m_{T_{\infty}}R_{R_{T_{\infty}}}$
- $P_{\nu S N}(t) = m_{\nu S N}R_{\nu S N}$
- $P_{\nu S N}(t) = m_{\nu S N}R_{\nu S N}$
- $P_{M D}(t) = m_{M D}R_{M D}$
- $P_{M D}(t) = m_{M D}R_{M D}$

\[
R_{N S M} = \int_{m_{t}}^{m_{\infty}} dM_3 \psi \left( M_3 \right) \int_{m_{t}}^{m_{\infty}} dM_2 \psi \left( M_2 \right) \int_{m_{t}}^{m_{\infty}} dM_1 \psi \left( M_1 \right) y(t - t_{m2} - t_{m3})
\]

\[
R_{S N S M} = \int_{m_{t}}^{m_{\infty}} q(m)q(t - t_{m})dm
\]
Strong Universality in Ultra-Faint Dwarf Ret. II

Which is likely r-process site, MHD-Jet SN or Binary NSM?

Product. Yield ~ $10^{-2} \, M_\odot$/event

1. Event Rate, too small?
   
   $(2.6 \pm 0.2) \times 10^3 M_\odot$ Ret. II baryon mass
   
   $\rightarrow \sim 10 \, \text{SNe}$ IMF
   
   $\rightarrow \sim (0.01 - 0.3) \times 10 \, \text{NSM/SN} \, (0.1\%)$
   
   $\text{SN} ! \quad \text{NSM} !$

2. Very old?
   
   $\text{SN} ! \quad \text{NSM} !$

3. Extended Universality?
   
   Dust forms?
   
   $\text{SN} ! \quad \text{NSM} ?$

4. Ejecta escape from shallow pot.?
   
   $\text{SN} ! \quad \text{NSM} ?$
Ret. II should be very old!
INTEGRAL Mission (γ-Ray Satellite) detects 511 keV Emission Line.

- Does e^+− come from DM-annihilation or Stellar Activity?
- No significant detection except for Reticulum II

Micro-quasar!
links to MHDJ-SN or NSM??

Exposure map

511 keV narrow line flux [10^{-4} ph cm^{-2} s^{-1}]

10^5 10^6 10^7
Exposure time at source position [sec]

Extended Universality

Ultra-Faint warp Galaxy: Ret. II

Astron. Observation


Theor. Calculation

NSM cannot produce enough $A < 50$!
Another DIFFICULTY for R–Process in Binary NSMs

Macronova (Kilonova)

Dust is hard to form for deficient Carbon and other lighter elements.

Dust formation becomes even more difficult when one includes more complete opacity table for heavy actinide elements.
**Milky Way Halo Stars**

- [Eu/Fe] > 1

- Error bars cover Th detected stars

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**EXTENDED UNIVERSALITY**

Honda, Aoki, Kajino, Beers, et al., (SUBARU-HDS Collaboration),


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**Extended Universality**

- Carbon
- Silicon
- Eu
- Th

**Strong Universality**

Error bars cover Th detected stars
**QUEST for Cosmo-Chemistry and Astronomy:**

**to find/confirm “EXTENDED UNIVERSALITY”**

**Supernova Grains e.g. Murchison Meteorite**

![SiC X-grains](image)

- Enhanced $^{12}\text{C}$ ($^{12}\text{C}/^{13}\text{C} > \text{Solar}$), Enhanced $^{28}\text{Si}$
- Deficient $^{14}\text{N}$ ($^{14}\text{N}/^{15}\text{N} < \text{Solar}$)
- Decay of $^{26}\text{Al}$ ($t_{1/2}=7\times10^5\text{yr}$), $^{44}\text{Ti}$ ($t_{1/2}=60\text{yr}$)

Pre-solar X-grains condense and form in SN/NSM ejecta.

- If SiC X-grain incl. much r-elements
- If extended Universality manifests in $[r/C-Si-Fe] = 0$
- If diversity in $[r/C-Si-Fe]$ exists

**Spectr. Astron. Obs.**

Direct detection of C, Si & r-elements simultaneously!

[EMP image]

+ [SN image] [SN-remnant image]
SUMMARY

★ TIME−SCALE PROBLEM of NSMs remains. Galactic Chemo−Dynamical Evolution can PARTIALLY resolve this problem.

★ UNIVERSALITY in EMP☆ is satisfied only by SNe (νDW+MHDJ).

★ S.S. r−elements need both SNe and NSMs.

→ Evolution of ISOTOPIC Abundances takes the key!
→ Pre−solar X−Grains (SiC+r nuclei) should be an evidence!

⇒ Quest for Astronomy, Astrophysics and Cosmology
⇒ Quest for Nuclear Physics

SYNERGY among Astronomy, Cosmochemistry and Nuclear Physics is highly desirable!