Studies of r-process nucleosynthesis based on recent hydrodynamical models of NS-NS mergers

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The $r$-process: observational request

- many r-rich Galactic halo stars show remarkable agreement with solar pattern
- $r$-process must occur in the early Galaxy
- astrophysical events must reproduce this common pattern ($Z>40; A>90$)

→ suggests existence of “main” $r$-process sites producing a (solar-like) common pattern

Sneden+ (2008) ARAA
Dynamical ejecta of supernova explosion?

- neutrino-driven proto-neutron star wind
- supernova ejecta $\rightarrow$ iron group elements including $^{56}\text{Ni}$
- EC-SNe are exception? (c.f., Wanajo+ 2011)
  But, not enough to produce heavy r-process elements


→ needs other components of SNe?
needs for neutron-rich ejecta (and failure of PNS wind)

condition for r-process 3rd peak

based on Hoffman et al. (1997)

hight entropy
  → high T
  → low seed
  → high n /seed

→ needs other astronomical sites

Wanajo 2013

Fischer et al. 2010, Hüdepohl et al. 2010 etc.
NS-NS mergers

collaboration with
S. Wanajo (NAOJ)

Y. Sekiguchi, K. Kiuchi and M. Shibata (YITP, Kyoto U)
K. Kyutoku (UW-Milwaukee)

Wanajo et al., ApJL 789, 2014
Sekiguchi et al. (in prep.)
Nishimura et al. (in prep.)
Astronomical sites/scenarios for r-process

- only lighter r-process elements (see e.g., Wanajo 2013)
- non-standard SNe associated with magnetar formation jets (Nishimura+ 2006, Winteler+ 2012)
Big problem: too neutron-rich?

Goriely + 2011 (e.g., Korobkin + 2011, Rosswog + 2013)

tidal ejection of “pure” n-rich matter with $Y_e \ll 0.1$

$Y_e = Y_p = 1 - Y_n$

strong r-process with fission recycling

severe problem: only $A > 130$ with fission recycling
Solution?: wind ejecta driven by neutrino

see also, talks by A. Perego and O. Just last week

Rosswog 2014+

- wind ejecta has enough mass?
- two different components can explain “universality”?
- modeling dynamical ejecta has physical uncertainties
  - general Relativistic (GR) hydrodynamics
  - nuclear equation of state (EOS)
  - neutrino transport

dynamical ejecta
(Ye < 0.1)
+
neutrino-driven wind
(Ye > 0.3)
‘Robustness’ of r-process in NS-NS merger?

- **Korobkin et al. 2012**: Newtonian SPH simulations
- **Bauswein et al. 2013**: Relativistic SPH simulations with multiple EOS but weak interactions are not implemented
- **This Study**: Full GR, rad-hydro simulation with SFHo(Steiner) and Shen EOS

**Shen EOS: ‘Stiffer’**
- Larger NS radius
- Mass ejection is driven mainly by Tidal force

**SFHo (Steiner) EOS: ‘Softer’**
- Smaller NS radius
- Tidal effects are less important in mass ejection
- Stronger bounce

\[
F \sim k_{\text{EOS}} \Delta x \sim M_{\text{NS}}, \\
E \sim k_{\text{EOS}} (\Delta x)^2 \sim M_{\text{NS}}^2 k_{\text{EOS}}^{-1}
\]

Figure by Evan O’Connor
Einstein's equations: Puncture-BSSN/Z4c formalism

GR radiation-hydrodynamics (Sekiguchi + 2013)
- Advection terms: Truncated Moment scheme (based on Shibata et al. 2011)
  - Fully covariant and relativistic
  - Gray or multi-energy but advection in energy is not included
  - M-1 closure
  - EOS: any tabulated EOS with 3D smooth connection to Timmes EOS
- Source terms: two options
  - Implicit treatment: Bruenn’s prescription
  - Explicit treatment: trapped/streaming \( v \)'s
    - \( e \)-captures: thermal unblocking/weak magnetism; NSE rate
    - Iso-energy scattering: recoil, Coulomb, finite size
    - \( \eta \)-annihilation, plasmon decay, bremsstrahlung
    - Diffusion rate (Rosswog & Liebendoerfer 2004)
    - Two (beta- and non-beta) EOS method
NEW NS-NS simulation

“Production of all the r-process nuclides in the dynamical ejecta of neutron star mergers”

- fully general relativity
- approximate neutrino transport
- realistic EOS
  - Steiner’s EOS (2013, SFXo)
- 1.3 M⊙ NSs

ejected matter on the orbital plane
dynamics

density

temperature

Ye

entropy

Wanajo+ 2014
Impact of EOS (vs Shen EOS 1998)

- Steiner’s EOS makes compact NS
- compact NS
  \[ \rightarrow \text{less tidal disruption} + \text{strong collision} \]
Neutrino burst and $Y_e$

"Protonization" Burst

Ye changes due to positron capture and neutrino absorption

$$n + e^+ \rightarrow p + \overline{v}_e$$

Wanajo+ 2014
ejecta of NS-NS model

- mild neutron-rich
  
  \( Y_e = 0.1 - 0.4 \)

- low entropy
3D-geometry

Temperature

Ye

mass fraction

mass number

mass-averaged (x-y)

solar r-abundance

mass number

mass fraction

mass averaged (x-y)

abundance

mass averaged (x-y)

mass-averaged (x-y)
ejecta of NS-NS model

solar-like r-process pattern
NO strong fission cycling

Theoretical reaction rates are based on mass model HFB-21 (Goriely)
(fission properties are based on HFB-14, Goriely)
as a source for “kilonova”

main source (β-decay)

\(~1\) days

\((^{85}\text{Kr}, ^{89}\text{Sr}, ^{103}\text{Ru})\)

\(~10\) days

\((^{123}\text{Sn}, ^{125}\text{Sn})\)

※fission does not play significant role
NS-NS as a Galactic r-process source

- amount of ejecta
  - $\sim 0.01 \, M_\odot$

- estimated rate $10^{-5}$/year (agree with other estimation) (e.g., Dominik et al. 2012)

Goriely+ 2011

$Y_e \ll 0.1$
SFHo vs. Shen (high resolution): temperature

- SFHo: temperature is higher (as 1MeV) due to the shock heating, and produce copious positrons.
- Shen: temperature is much lower.

\[ n + e^+ \rightarrow p + \bar{\nu} \]

Higher T : more \( e^+ \)
Shock heating
more positron capture

Lower T : less \( e^+ \)
Mass ejection mainly driven by tidal effects
Higher $T$ : more $e^+$
higher $Y_e > 0.25$ region : less neutron rich

Lower $T$ : less $e^+$
smaller $Y_e < 0.25$ : neutron rich

SFHo vs. Shen (high resolution): $Y_e$

- SFHo: In the shocked regions, $Y_e$ increases to be $>> 0.2$ by weak processes
- Shen: $Y_e$ is low as $< 0.2$ (only strong r-process expected)
BH-NS merger?: extremely neutron-rich matter

Nishimura et al. (2013); NPA VI Conf.
ejected matter by strong tidal disruption:
BH (4M_☉) — NS (1.25M_☉)
→ maintaining initial Y_e (neutron rich)
Summary

- **NS mergers**
  - dynamical ejecta can produce full range of r-process nuclei
  - sophisticated EOS, GR, neutrino are significant impacts on the nucleosynthesis
  - the r-process study is a new probe to examine nuclear EOS and binary stars (NS-NS) evolution
  - (can make a precise predict for “kilonova”)

- **open question**
  - dependences on mass of NSs, EOS etc.
    (robustness of our present results)
  - BH-NS ?
  - needs to change galactic chemical evolution scenario?