Nucleosynthesis of heavy elements: r-process and its astrophysical site

Cas A (Chandra X-Ray observatory)

Rezzolla et al.

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Helmholtz Young Investigator Group
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Nuclear processes and solar abundances

- **r-process**
- **s-process**
- Iron peak
- Big Bang: H, He
- Burning in stellar interiors
- Neutron capture burning
- Nuclear processes and solar abundances

Key Elements:
- **Silver**
- **Gold**
- **Uranium**

Masses measured at the ESR will be measured with CR at FAIR.

Stable nuclei nuclides with known masses.
r-process

Rapid neutron capture compared to beta decay

Neutron density: \( N_n \sim 10^{27} - 10^{20} \text{ cm}^{-3} \)
Temperature: \( T \sim 10^{10} - 10^8 \text{ K} \)
Where does the r-process occur?

- Core-collapse supernovae
- Neutron star mergers

rapid process → explosions
high neutron densities → neutron stars
core-collapse supernovae
r-process in core-collapse supernovae? \( (B^2FH \ 1957) \)

- prompt explosion (Hillebrandt 1978, Hillebrandt et al. 1984)
- neutrino-driven wind (Meyer et al. 1992, Woosley et al. 1994)
- shocked surface layers (Ning, Qian, Meyer 2007)
- neutrino-induced in He shells (Banerjee, Haxton, Qian 2011)
- jets (e.g., Winteler et al. 2012)
Core-collapse supernova: ONeMg

ONeMg core: $P_e$ reduced as $e^-$ captured $\rightarrow$ collapse (electron-capture supernova)

Prompt explosion (Hillebrandt 1978, Hillebrandt et al. 1984) not confirmed by modern supernova simulations (Kitaura, Janka, Hillebrandt 2006)

Delayed neutrino-driven explosion works for this progenitor even in 1D (Kitaura et al. 2006, Fischer et al. 2010)

Prompt explosion excluded as r-process site
Core-collapse supernova: ONeMg

r-process in the shocked surface layers (Ning, Qian, Meyer 2007):

- very high velocity (c/3)
- high entropy
- slightly neutron rich is sufficient
Core-collapse supernova: ONeMg

r-process in the **shocked surface layers** (Ning, Qian, Meyer 2007):
- very high velocity (c/3)
- high entropy
- slightly neutron rich is sufficient

not found in simulations

Core-collapse supernova: ONeMg

r-process in the **shocked surface layers**
(Ning, Qian, Meyer 2007):
- very high velocity (c/3)
- high entropy
- slightly neutron rich is sufficient

**One model** for low mass progenitors: $8.8M_{\odot}$ (Nomoto 1984, 1987)

Promising scenario for the r-process, requires further investigation
Eichler, Arcones, Thielemann 2012
Supernova-jet-like explosion

3D magneto-hydrodynamical simulations: rapid rotation and strong magnetic fields

matter collimates: neutron-rich jets

right r-process conditions

Winteler, Käppeli, Perego et al. 2012
Neutrino-induced r-process in He shell

at low metallicity $Z < 10^{-3}Z_{\text{sun}}$ → low seed abundance
neutral- and charged-current neutrino reactions on He → few neutrons

cold r-process
relative low neutron density
lasts ~20s
peaks shift to high $A$ (between r- and s-process)

Banerjee, Haxton, Qian 2011
Epstein, Colgate, Haxton 1988, Woosley, Hartmann, Hoffman, Haxton 1990
Nadyozhin, Panov, Blinnikov 1998
Neutrino-driven winds

NSE $\rightarrow$ charged particle reactions / $\alpha$-process

T $= 10 - 8$ GK $\rightarrow$ r-process

T $< 3$ GK

for a review see Arcones & Thielemann (2013)
Neutrino-driven wind parameters

r-process $\Rightarrow$ high neutron-to-seed ratio ($Y_n/Y_{\text{seed}} \sim 100$)

- Short expansion time scale: inhibit $\alpha$-process and formation of seed nuclei
- High entropy: photons dissociate seed nuclei into nucleons
- Electron fraction: $Y_e < 0.5$

![Diagram showing the relationship between $S[k]$ and $\tau_{\text{dyn}}[\text{sec}]$ with labels for $L=10^{52}$, $L=9\times10^{51}$, $L=7\times10^{51}$, $L=5\times10^{51}$, $L=10^{51}$, $2.0 M_\odot$, $1.7 M_\odot$, $1.4 M_\odot$, $1.2 M_\odot$, $Y_e=0.45$, and Otsuki et al. 2000]
Neutrino-driven wind parameters

**r-process ⇒ high neutron-to-seed ratio** ($Y_n/Y_{seed} \sim 100$)

- **Short expansion time scale**: inhibit $\alpha$-process and formation of seed nuclei
- **High entropy**: photons dissociate seed nuclei into nucleons
- **Electron fraction**: $Y_e < 0.5$


- $S_{\text{wind}} = 50 - 120 \, k_B/\text{nuc}$
- $\tau = \text{few ms}$
- $Y_e \approx 0.4 - 0.6$?

Additional ingredients: wind termination, extra energy source, rotation and magnetic fields, neutrino oscillations
neutron-star mergers
Ejecta from three regions:

- dynamical ejecta
- neutrino-driven wind
- disk evaporation
Neutron star mergers: robust r-process

1.2\( M_\odot \) – 1.4\( M_\odot \)
1.4\( M_\odot \) – 1.4\( M_\odot \)
2\( M_\odot \) – 1.4\( M_\odot \)

simulations: 21 mergers of 2 neutron stars
2 of neutron star black hole

nucleosynthesis of dynamical ejecta
robust r-process:
- extreme neutron-rich conditions (\( Y_e = 0.04 \))
- several fission cycles

Korobkin, Rosswog, Arcones, Winteler (2012)
see also Bauswein, Goriely, and Janka
Hotokezaka, Kiuchi, Kyutoku, Sekiguchi, Shibata, Tanaka, Wanajo
Neutron star mergers: robust r-process

1.2M⊙ — 1.4M⊙
1.4M⊙ — 1.4M⊙

Simulations: 21 mergers of 2 neutron stars
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Nucleosynthesis of dynamical ejecta
Robust r-process:
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$\rho \, (g \, cm^{-3})$

$T \, (GK)$
Korobkin et al. 2012

t : 1.15e+00 s / T : 0.56 GK / \( \rho_b : 3.98e+02 \text{ g/cm}^3 \)

robust r-process
Neutron star mergers: neutrino-driven wind

3D simulations ~100ms after merger disk and neutrino-wind evolution neutrino emission and absorption

Nucleosynthesis for few trajectories

see also Just et al. 2014, Sekiguchi et al.
Neutron star mergers: evaporation disk

2D simulations with simple neutrino treatment
outflows from accretion disk: black hole, super-massive neutron star
matter unbound: viscosity and alpha recombination

Fernandez & Metzger 2013

see also Just et al. 2014
Neutron star mergers: evaporation disk

2D simulations with simple neutrino treatment
outflows from accretion disk: black hole, super-massive neutron star
matter unbound: viscosity and alpha recombination

see also Just et al. 2014
Radioactive decay in neutron star mergers

r-process heating affects:
- merger dynamics: late X-ray emission in short GRBs (Metzger, Arcones, Quataert, Martinez-Pinedo 2010)
- remnant evolution (Rosswog, Korobkin, Arcones, Thielemann, Piran 2014)
Radioactive decay in neutron star mergers

Transient with kilo-nova luminosity (Metzger et al. 2010, Roberts et al. 2011, Goriely et al. 2011): direct observation of r-process, EM counter part to GW

Multi messenger (e.g. Metzger & Berger 2012, Rosswog 2012, Bauswein et al. 2013)
Where does the r-process occur?

Rare core-collapse supernovae

Neutron star mergers
Galactic chemical evolution

First stars: H, He \[\rightarrow\] Heavy elements \[\leftarrow\] New generation of stars

Interstellar medium (ISM)

The very metal-deficient star
HE 0107-5240
(Hamburg-ESO survey)

![Artist's View of Star Formation in the Early Universe](image1)

![Horsehead Nebula](image2)

![Sun](image3)

![Spectra of Stars with Different Metal Content](image4)
Trends with metallicity

Fe and Mg produced in the same site: core-collapse supernovae

Mg and Fe production is not coupled to r-process production

Significant scatter at low metallicities

r-process production rare in the early Galaxy

Sneden, Cowan, Gallino 2008
Fingerprint of the r-process

Oldest observed stars

Atomic number

Gold

Silver

Eu

Solar system abundances

Mass number

Sneden, Cowan, Gallino 2008
LEPP: Lighter Element Primary Process

Ultra metal-poor stars with high and low enrichment of heavy r-process nuclei suggest: at least two components or sites (Qian & Wasserburg):

Travaglio et al. 2004:
solar = r-process + s-process + LEPP

Montes et al. 2007:
solar LEPP ~ UMP LEPP → unique

Are Honda-like stars the outcome of one nucleosynthesis event or the combination of several?

\[ \log \varepsilon \]

or

\[ \log \varepsilon \]

or

\[ \log \varepsilon \]
Nucleosynthesis components

C.J. Hansen, Montes, Arcones 2014

LEPP and r-process components based on 3 methods:

M1: LEPP = Honda star
r-process = Sneden star

M2: LEPP = Honda - Sneden
r-process = Sneden

M3: iterative method (Li et al. 2013)
LEPP = LEPP - r-process
r-process = r-process - LEPP

Component abundance pattern: $Y_r$ and $Y_L$
Assumptions: Z range for components robust pattern
Abundance deconvolution

big sample of stars (Frebel et al. 2010)
remove s-process, carbon enhanced, and stars with internal mixing

fit abundance as combination of components: \( Y_{\text{calc}}(Z) = (C_r Y_r(Z) + C_L Y_L(Z)) \cdot 10^{\text{[Fe/H]}} \)

\[ BS16089-013 \]
\[ \text{[Fe/H]} = -2.82 \]
\[ \chi^2 = 0.15 \]

\[ CS29518-051 \]
\[ \text{[Fe/H]} = -2.65 \]
\[ \chi^2 = 3.98 \]
Abundance deconvolution

big sample of stars (Frebel et al. 2010)
remove s-process, carbon enhanced, and stars with internal mixing

fit abundance as combination of components: $Y_{\text{calc}}(Z)$

$2\chi^2 = 3.98$

$[\text{Sr/Fe}] = -1.0$
$X^2 = 0.15$

$Y_{\text{calc}}(Z) = C_{\text{r}(Z)} + C_{\text{L}(Z)} \cdot [\text{Fe/H}]$
Abundance deconvolution

big sample of stars (Frebel et al. 2010)
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fit abundance as combination of components: \( Y_{\text{calc}}(Z) = (C_r Y_r(Z) + C_L Y_L(Z)) \cdot 10^{[\text{Fe/H}]} \)
Abundance deconvolution

big sample of stars (Frebel et al. 2010)
remove s-process, carbon enhanced, and stars with internal mixing

fit abundance as combination of components:

$$Y_{\text{calc}}(Z) = (C_r Y_r(Z) + C_L Y_L(Z))$$

$$\chi^2 = \frac{1}{\nu} \sum_{Z_{\text{range}}} \left( \log Y_{\text{observed}}(Z) - \log Y_{\text{calc}}(Z) \right)^2 / \Delta(Z)^2,$$

0.32 dex (obs. + method)
LEPP in neutrino winds?

Arcones et al. 2007

Shock
Reverse shock
Neutron star
Lighter heavy elements in neutrino-driven winds

Overproduction at $A=90$, magic neutron number $N=50$ (Hoffman et al. 1996) suggests:

only a fraction of neutron-rich ejecta
(Wanajo et al. 2011)

(Arcones & Montes, 2011)
Electron capture supernova

Wanajo, Janka, Müller (2011): small neutron-rich pockets in 2D simulations
Lighter heavy elements in neutrino-driven winds

**Observation pattern reproduced!**
Production of p-nuclei

Overproduction at \( A=90 \), magic neutron number \( N=50 \) (Hoffman et al. 1996) suggests:
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Lighter heavy elements in neutrino-driven winds

Observations (Arcones & Montes, 2011)

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suggests:

only a fraction of neutron-rich ejecta (Wanajo et al. 2011)

Production of p-nuclei

\[ \nu_p \text{-process} \]

\[ \text{weak r-process} \]

\[ \begin{array}{cccccccc}
35 & 40 & 45 & 50 & 55 \\
10^{-12} & 10^{-11} & 10^{-10} & 10^{-9} & 10^{-8} & 10^{-7} & 10^{-6} & 10^{-5} \\
\end{array} \]

\[ \text{Entropy} \left[ \frac{k_B}{\text{nuc}} \right] \]

\[ \begin{array}{cccccccc}
40 & 50 & 60 & 70 & 80 & 90 & 100 & 110 \\
0.40 & 0.41 & 0.42 & 0.43 & 0.44 & 0.45 & 0.46 & 0.47 \\
\end{array} \]

\[ \begin{array}{cccccccc}
40 & 50 & 60 & 70 & 80 & 90 & 100 & 110 \\
40 & 41 & 42 & 43 & 44 & 45 & 46 & 47 \\
\end{array} \]

Arcones & Bliss (2014)
LEPP components: constraining conditions

LEPP abundance ratios:
- Sr/Y = 6.13 (//)
- Sr/Zr = 1.22 (∨∨)
- Sr/Ag = 48.2

![Logarithmic plots of Sr/Y and Sr/Zr ratios against entropy.](image-url)
LEPP components: constraining conditions

LEPP abundance ratios: Sr/Y = 6.13 (//)
Sr/Zr = 1.22 (\)
Sr/Ag = 48.2
LEPP components: constraining conditions

LEPP abundance ratios: Sr/Y = 6.13 (\)/Sr/Zr = 1.22 (\)/Sr/Ag = 48.2
Conclusions

How many r-processes? How many astrophysical sites?

heavy r-process: mergers: dynamical, wind, disk evaporation
jet-like supernovae
He shell

lighter heavy elements: neutrino-driven winds
mergers: wind, disk evaporation
constraints from observations: LEPP component

Needs

Observations: oldest stars, kilo/macronovae,
neutrinos, gravitational waves, ... 

Neutron-rich nuclei: experiments with radioactive beams, theory

Improved supernova and merger simulations

Chemical evolution models