r-Process nucleosynthesis and kilonovae from neutron star mergers

Jonas Lippuner
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Multi-Messenger Astrophysics in the Gravitational Wave Era
YITP, Kyoto, Japan
1. Very brief nucleosynthesis overview
2. The SkyNet nuclear reaction network
3. r-Process in neutron star mergers
4. Observational signature and first detection
Solar system abundances

Data sources:
Solar system abundances

Data sources:
The s-process

slow neutron capture

\[ \tau_{\beta^-} \ll \tau_n \sim 10^2 - 10^5 \text{ yr} \]
The s-process

slow neutron capture

\[ \tau_{\beta^-} \ll \tau_n \sim 10^2 - 10^5 \text{ yr} \]

isotopes involved in the s-process:

- \( ^{65}\text{Cu} \)
- \( ^{66}\text{Zn} \)
- \( ^{67}\text{Zn} \)
- \( ^{68}\text{Zn} \)
- \( ^{70}\text{Zn} \)
- \( ^{65}\text{Cu} \)
- \( ^{66}\text{Zn} \)
- \( ^{67}\text{Zn} \)
- \( ^{68}\text{Zn} \)
- \( ^{70}\text{Zn} \)
- \( ^{70}\text{Ge} \)
- \( ^{72}\text{Ge} \)
- \( ^{73}\text{Ge} \)
- \( ^{74}\text{Ge} \)
- \( ^{76}\text{Ge} \)
- \( ^{75}\text{As} \)
- \( ^{76}\text{Se} \)
- \( ^{77}\text{Se} \)
- \( ^{78}\text{Se} \)
- \( ^{80}\text{Se} \)
- \( ^{82}\text{Se} \)
- \( ^{79}\text{Br} \)
- \( ^{81}\text{Br} \)
- \( ^{82}\text{Kr} \)
- \( ^{83}\text{Kr} \)
- \( ^{84}\text{Kr} \)
- \( ^{85}\text{Rb} \)
- \( ^{86}\text{Kr} \)
- \( ^{87}\text{Rb} \)
- \( ^{89}\text{Y} \)
- \( ^{90}\text{Zr} \)
- \( ^{91}\text{Zr} \)
- \( ^{92}\text{Zr} \)

closed neutron shell
The r-process

rapid neutron capture

\[ \tau_n \ll \tau_{\beta^-} \sim 10 \text{ ms} - 10 \text{ s} \]
The r-process

rapid neutron capture

\( \tau_n \ll \tau_{\beta^-} \sim 10 \text{ ms} - 10 \text{ s} \)
Double peaks due to closed neutron shells

**s-process**: $\tau_{\beta^-} \ll \tau_n \sim 10^2 - 10^5$ yr

**r-process**: $\tau_n \ll \tau_{\beta^-} \sim 10$ ms – 10 s
Double peaks due to closed neutron shells

s-process: $\tau_{\beta^{-}} \ll \tau_{n} \sim 10^{2} - 10^{5}$ yr

r-process: $\tau_{n} \ll \tau_{\beta^{-}} \sim 10$ ms – 10 s

Los Alamos National Laboratory
UNCLASSIFIED
Double peaks due to closed neutron shells

s-process: $\tau_{\beta^{-}} \ll \tau_{n} \sim 10^{2} - 10^{5}$ yr

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r-process: $\tau_n \ll \tau_{\beta^-} \sim 10$ ms – 10 s
Solar system abundances

Data sources:

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Outline

1. Very brief nucleosynthesis overview
2. The SkyNet nuclear reaction network
3. r-Process in neutron star mergers
4. Observational signature and first detection
• General-purpose nuclear reaction network
• $\sim 8000$ isotopes, $\sim 140,000$ nuclear reactions
• Evolves temperature based on nuclear reactions
• Input: $\rho(t)$, initial composition, entropy
• Open source

Define abundance

\[ Y_i = \frac{n_i}{n_B}. \]  

Consider reaction

\[ p + ^7\text{Li} \rightarrow 2^4\text{He} \]  

with rate \( \lambda = \lambda (T, \rho) \). Then

\[ \dot{Y}_{\text{He}} = 2\lambda Y_p Y_{\text{Li}} + \cdots, \]
\[ \dot{Y}_p = -\lambda Y_p Y_{\text{Li}} + \cdots, \]
\[ \dot{Y}_{\text{Li}} = -\lambda Y_p Y_{\text{Li}} + \cdots \]  

Need to solve big, stiff, non-linear system of ODEs
SkyNet features

Science
- Extended Timmes equation of state (EOS)
- Calculate nuclear statistical equilibrium (NSE)
- NSE evolution mode
- Calculate inverse rates from *detailed balance* to be consistent with NSE
- Electron screening with smooth transition between weak and strong screening (reactions and NSE)

Code
- Adaptive time stepping
- Python bindings
- Modularity
- Extendible reaction class (currently REACLIB, table, neutrino)
- Make movies
Initial conditions: NSE with $T = 6.1$ GK, $\rho = 7.4 \times 10^9$ g cm$^{-3}$, $Y_e = 0.07$, screening and self-heating on*
Fixed $\rho = 10^7 \text{ g cm}^{-3}$, initial $T = 3 \text{ GK}$, initial $X_C = X_O = 0.5$, screening and self-heating on
Fixed \( \rho = 10^8 \text{ g cm}^{-3} \), initial NSE with \( T = 5.5 \text{ GK} \), \( Y_e = 0.1 \), screening and self-heating off
Outline

1. Very brief nucleosynthesis overview
2. The SkyNet nuclear reaction network
3. \textit{r-Process in neutron star mergers}
4. Observational signature and first detection
Merger ejecta: Dynamical

Tidal tails or collision interface

NS–NS: $M_{ej} \sim 10^{-4} - \text{few} \times 10^{-2} M_{\odot}$, $Y_e \sim 0.05 - 0.45$
NS–BH: $M_{ej} \sim 0 - 10^{-1} M_{\odot}$, $Y_e \lesssim 0.2$

Bauswein+13, Hotokezaka+13, Foucart+14, Sekiguchi+15, Kyutoku+15, Radice+16
Merger ejecta: Disk outflow

Neutrino-driven wind or outflow due to MHD, viscous heating, and $\alpha$ recombination

$M_{ej} \sim \text{few} \times 10^{-3} M_\odot$, $Y_e \sim 0.2 - 0.45$

Surman+08, Wanajo+11, Fernández+13, Perego+14, Just+15, Foucart+15, Siegel+17, Siegel+18, Miller+19
Parametrized r-process


Parameters

\[ 0.01 \leq Y_e \leq 0.50 \]  
\[ 1 \text{ } k_B \text{ baryon}^{-1} \leq s \leq 100 \text{ } k_B \text{ baryon}^{-1} \]  
\[ 0.1 \text{ ms} \leq \tau \leq 500 \text{ ms} \]

initial electron fraction  
initial specific entropy  
expansion time scale

Density profile

\[
\rho(t, \tau) = \begin{cases} 
\rho_0 e^{-t/\tau} & \text{ if } t \leq 3\tau \\
\rho_0 \left(\frac{3\tau}{te}\right)^3 & \text{ if } t \geq 3\tau
\end{cases}
\]

Initial conditions

- Choose initial temperature \( T_0 = 6 \text{ GK} \)
- Find \( \rho_0 \) by solving for NSE at \( T_0 \) and \( Y_e \) that produces specified \( s \)
http://jonaslippuner.com/skynet/SkyNet_Ye_0.010_s_010.000_tau_007.100.mp4
http://jonaslippuner.com/skynet/SkyNet_Ye_0.250_s_010.000_tau_007.100.mp4

Temperature = 3.65E+08 K
Density = 3.13E+01 g / cm³
Heating rate = 8.74E+18 erg / s / g
Entropy = 1.94E+02 kB / baryon
Ye = 0.316
Final abundances vs. entropy

\[ s_{kB} = 1 \]
\[ s_{kB} = 3.2 \]
\[ s_{kB} = 10 \]
\[ s_{kB} = 100 \]

- Observed solar r-process

Impact of electron fraction

$s = 10 \, k_B \, \text{baryon}^{-1}$

$\tau = 1 \, \text{ms}$
Full binary neutron star merger simulations

From Wanajo+14

See also Goriely+15
Accretion disk outflow

Jonah Miller at LANL performed accretion disk simulation using GW170817 parameters
• Full GRMHD
• Monte Carlo neutrino transport
• Using $\nu_{bhlight}$ (see Miller+19a)

Figure from Miller+19b
Final abundances from accretion disk outflow

Figure from Miller+19b
Nucleosynthesis in HMNS disk outflow

- $3 \, M_\odot$ central HMNS or BH, $0.03 \, M_\odot$ accretion disk
- Variable HMNS lifetime, neutrino leakage, $\alpha$ viscosity

Figure from Metzger & Fernández (2014)
Electron fraction distribution

\[ Y_e \]

\[ \tau = 0 \text{ ms} \]
\[ \tau = 10 \text{ ms} \]
\[ \tau = 30 \text{ ms} \]
\[ \tau = 100 \text{ ms} \]
\[ \tau = 300 \text{ ms} \]
\[ \tau = \infty \]
Ejected mass

$E_{\text{jected}} = 10^{-3} M_\odot$
Final abundances

![Graph showing final abundances](image)

- Observed solar r-process

Black hole–neutron star merger


1. Full GR simulation of BH–NS

2. Evolve ejecta in SPH code
   Matt Duez (WSU)

3. Nucleosynthesis with varying neutrino luminosity
   JL and Luke Roberts (MSU)

Figure credit: F. Foucart
BHNS: Final abundances vs. neutrino luminosity

Relative final abundance vs. Mass number $A$

- $L_{\nu_e,52} = 0.2$
- $L_{\nu_e,52} = 1$
- $L_{\nu_e,52} = 25$

Solar r-process
BHNS: Electron fraction distribution

The graph shows the electron fraction distribution $Y_e$ for different values of $L_{\nu_e,52}$:
- $L_{\nu_e,52} = 0.2$
- $L_{\nu_e,52} = 1$
- $L_{\nu_e,52} = 25$

The x-axis represents the electron fraction $Y_e$, and the y-axis represents the mass $M/M_\odot$. The distribution is shown for masses ranging from 0.00 to 0.30.
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Observational signature of r-process: Kilonova

Jet–ISM Shock (Afterglow)
Optical (hours–days)
Radio (weeks–years)

GRB
(t ~ 0.1–1 s)

θ_j

Ejecta–ISM Shock
Radio (years)

Kilonova
Optical (t ~ 1 day)

Merger Ejecta
Tidal Tail & Disk Wind
v ~ 0.1–0.3 c

BH

Impact of lanthanides
Impact of lanthanides

\[ s = 10 \, k_B \, \text{baryon}^{-1} \]
\[ \tau = 7.1 \, \text{ms} \]
\[ M = 0.01 \, M_\odot \]

\( Y_e = 0.01 \)
\( Y_e = 0.19 \)
\( Y_e = 0.25 \)
\( Y_e = 0.50 \)

Luminosity
Heating rate
Light curves vs. electron fraction

$s = 10 \, k_B \, \text{baryon}^{-1}$

$\tau = 1 \, \text{ms}$
First neutron star merger observation: GW170817

Lightcurve from Fermi/GBM (10 – 50 keV)

Lightcurve from Fermi/GBM (50 – 300 keV)

Gravitational-wave time-frequency map

GW170817: Hunt for electromagnetic counterpart

- LIGO/VIRGO localization: 31 deg$^2$
  $\sim$ 150 full moons
- Distance estimate: 40 $\pm$ 8 Mpc
- 49 galaxies in that volume
- Check all galaxies starting with most massive first

Kasliwal et al., 2017, Science 358, 1559
GW170817: Counterpart discovered in NGC 4993

- Discovered 10.9 hours after merger
- Host galaxy: NGC 4993, elliptical galaxy, constellation Hydra, 40 Mpc
  $\sim 130$ Mly

Credit: 1M2H Team / UC Santa Cruz & Carnegie Observatories / Ryan Foley
GW170817: Rapid color evolution

Credit: ESO / N.R. Tanvir, A.J. Levan and the VIN-ROUGE collaboration
GW170817: Huge observing campaign

GW
LIGO, Virgo

γ-ray
Fermi, INTEGRAL, Astrosat, IPN, Insight-HXMT, Swift, AGILE, CALET, H.E.S.S., HAWC, Konus-Wind

X-ray
Swift, MAXI/GSC, NuSTAR, Chandra, INTEGRAL

UV
Swift, HST

Optical
Swope, DECam, DLT40, REM-ROS2, HST, Las Cumbres, SkyMapper, VISTA, MASTER, Magellan, Subaru, Pan-STARRS1, HCT, T2AC, LSGT, T17, Gemini-South, NTT, GROND, SOAR, ESO-VLT, KMTNet, ESO-VST, VIRT, SALT, CHILESPE, TOROS, BOOTES-5, Zadko, iTelescope.Net, AAT, Pi of the Sky, AST3-2, ATLAS, Danish Tel, DFN, T80S, EABA

IR
REM-ROS2, VISTA, Gemini-South, 2MASS, Spitzer, NTT, GROND, SOAR, NOT, ESO-VLT, Kanata Telescope, HST

Radio
ATCA, VLA, ASKAP, VLBA, GMRT, MWA, LOFAR, LWA, ALMA, OVRO, EVN, e-MERLIN, MeerKAT, Parkes, SRT, Effelsberg

GW170817: Combined light curve

GW170817: One-component kilonova models fail

\[ {^{56}\text{Ni}, \kappa = 0.1 \text{ cm}^2 \text{ g}^{-1}} \]

\[ \text{Blue KN, } \kappa = 0.1 \text{ cm}^2 \text{ g}^{-1} \]

\[ \text{Red KN, } \kappa = 10 \text{ cm}^2 \text{ g}^{-1} \]

\[ \text{KN, } \kappa = 0.8 \text{ cm}^2 \text{ g}^{-1} \]

GW170817: Two-component models do better

Troja et al., 2017, Nature 551, 71

GW170817: Three-component model needed?

GW170817: Featureless optical spectrum

Nicholl et al., 2017, ApJL 848, L18

Swift 1.2d
HST 5.5d

1.5 days after merger
2.5d
3.5d
4.5d
7.5d
8.5d
9.5d

$F_\lambda (10^{-16} \text{ ergs cm}^{-2} \text{ cm}^{-1} \text{ Å}^{-1})$

Rest wavelength (Å)
GW170817: Infrared spectrum

GW170817: What we learned

- Confirmed neutron star mergers make short GRBs (but this was a weird GRB)
- Total ejecta mass larger than expected: $\sim 5 \times 10^{-2} M_\odot$
- Neutron star mergers can easily make all r-process material in the galaxy
- Blue (lanthanide-free) component larger than expected, maybe large disk wind or blue dynamical component
- Lanthanide-rich component is evidence for full r-process, tens of Earth masses of gold and platinum
- “Purple” kilonova component with $X_{\text{La}} \sim 10^{-3} - 10^{-2}$, $\kappa \sim 3 \text{ cm}^2 \text{ g}^{-1}$?
- Gravity propagates at the speed of light, rules out many alternative theories of gravity besides Einstein’s General Relativity
Summary

- s- and r-process create heavy elements beyond the iron peak
- r-process happens in dynamical and disk ejecta in a neutron star merger
- SkyNet is free and open source state of the art nuclear reaction network
  - Feature-rich
  - Checked against other existing reaction networks
- Dynamical ejecta (NS-NS and BH-NS) is generally neutron-rich enough for full r-process
- Disk outflow may have neutron-rich and neutron-poor components
- GW170817: First LIGO detection of neutron star merger accompanied by GRB and kilonova
  - Kilonova followed pretty well what we expected
  - Yet more work is needed to understand light curve in detail, purple component?
Solar system abundances

Data sources:
Letters to the Editor

Publication of brief reports of important discoveries in physics may be secured by addressing them to this department. The closing date for this department is five weeks prior to the date of issue. No proof will be sent to the authors. The Board of Editors does not hold itself responsible for the opinions expressed by the correspondents. Communications should not exceed 600 words in length.

The Origin of Chemical Elements

R. A. Alpher*
Applied Physics Laboratory, The Johns Hopkins University, Silver Spring, Maryland

AND

H. Bethe
Cornell University, Ithaca, New York

AND

G. Gamow
The George Washington University, Washington, D. C.

February 18, 1948

As pointed out by one of us,¹ various nuclear species must have originated not as the result of an equilibrium corresponding to a certain temperature and density, but rather as a consequence of a continuous building-up process arrested by a rapid expansion and cooling of the primordial matter. According to this picture, we must imagine the early stage of matter as a highly compressed neutron gas (overheated neutral nuclear fluid) which

We may remark at first that the building-up process was apparently completed when the temperature of the neutron gas was still rather high, since otherwise the observed abundances would have been strongly affected by the resonances in the region of the slow neutrons. According to Hughes,² the neutron capture cross sections of various elements (for neutron energies of about 1 Mev) increase exponentially with atomic number halfway up the periodic system, remaining approximately constant for heavier elements.

Using these cross sections, one finds by integrating Eqs. (1) as shown in Fig. 1 that the relative abundances of various nuclear species decrease rapidly for the lighter elements and remain approximately constant for the elements heavier than silver. In order to fit the calculated curve with the observed abundances³ it is necessary to assume the integral of ρ₀ dt during the building-up period is equal to 5 × 10⁴ g sec./cm².

On the other hand, according to the relativistic theory of the expanding universe⁴ the density dependence on time is given by ρ²(t)/t. Since the integral of this expression diverges at t = 0, it is necessary to assume that the building-up process began at a certain time t₀, satisfying the relation:

\[ \int_{t_0}^{\infty} \frac{10^8}{t^2} dt \leq 5 \times 10^4, \tag{2} \]

which gives us t₀ ≤ 20 sec. and ρ₀ ≤ 2.5 × 10⁶ g sec./cm². This result may have two meanings: (a) for the higher densities existing prior to that time the temperature of the neutron gas was so high that no aggregation was taking place, (b) the density of the universe never exceeded the value
Synthesis of the Elements in Stars

E. Margaret Burbidge, G. R. Burbidge, William A. Fowler, and F. Hoyle

Kellogg Radiation Laboratory, California Institute of Technology, and Mount Wilson and Palomar Observatories, Carnegie Institution of Washington, California Institute of Technology, Pasadena, California

“It is the stars, The stars above us, govern our conditions”;

*(King Lear, Act IV, Scene 3)*

but perhaps

“The fault, dear Brutus, is not in our stars, But in ourselves,”

*(Julius Caesar, Act I, Scene 2)*

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NS–NS ejecta sources: Tidal tails

$Y_e \sim 0.05 - 0.45$

Credit: D. J. Price et al. (2006)
NS–NS ejecta sources: Collision interface

\[ Y_e \sim 0.05 - 0.45 \]

Credit: D. Berry, SkyWorks Digital, Inc.
NS–NS ejecta sources: Disk outflow

$Y_e \sim 0.2 - 0.45$

Credit: A. Bauswein et al. (2013)
Recent evidence for rare r-process

- Reticulum II: 1 in 10 highly r-process enhanced ultra-faint dwarf galaxy
- Recently discovered second UFD with r-process star: Tucana III

Ji et al., 2016, Nature 531, 610
Recent evidence for rare r-process

- $^{244}\text{Pu}$ is actinide (r-process only) with $\tau_{1/2} \sim 80$ Myr ($< \tau_{\text{mix}} \sim 300$ Myr)
- Interstellar material is swept up and deposited in deep-sea crust
- Measure abundance of $^{244}\text{Pu}$ in 25 Myr old deep-sea crust $\rightarrow$ $^{244}\text{Pu}$ abundance in ISM

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**From Wallner+15**

![Graph showing $^{244}\text{Pu}$ flux measurements and limits in crust and sediment](image)

**From Hotokezaka+15**

![Graph showing constraints on compact binary mergers and supernova explosions](image)