The Cosmic Origin of the Heavy Elements: Implications from the Neutron Star Merger GW170817

Daniel M. Siegel

NASA Einstein Fellow

Center for Theoretical Physics & Columbia Astrophysics Laboratory, Columbia University

CIPANP, Palm Springs, May 30, 2018
The origin of the elements

How are the heavy elements formed?
GW170817 and the firework of EM counterparts

- unique event in astronomy, maybe most important observation since SN 1987A
- unprecedented level of multimessenger observations
- confirms association of BNS to SGRBs
- kilonova provides strong evidence for synthesis of r-process material
The kilonova of GW170817

**blue** kilonova properties:
- $M_{ej} \sim 10^{-2} M_{\odot}$
- $v_{ej} \sim 0.2 - 0.3c$
- $Y_e > 0.25$
- $X_{La} < 10^{-4}$

**red/purple** kilonova properties:
- $M_{ej} \sim 4 - 5 \times 10^{-2} M_{\odot}$
- $v_{ej} \sim 0.08 - 0.14c$
- $Y_e < 0.25$
- $X_{La} \sim 0.01$

- two (“red-blue”) or multiple components expected from merger simulations
- single component models might be possible, but require fine-tuning of $Y_e$
Mass ejection generates kilonovae

neutron rich ejecta from NS-NS or NS-BH mergers ($Y_e \approx 0.1-0.4$)

- $\sim 1$ s decompression
- rapid neutron capture (r-process)

heavy radioactive elements

- $\sim$ days alpha, beta decay
- nuclear fission
- further expansion

thermal emission (kilonova)
- (quasi isotropic, long lasting: $\sim$ days)

Most simple kilonova model:

\[
\frac{dE_v}{dt} = -\frac{E_v}{t} - \frac{E_v}{t_{\text{diff}}} + \dot{Q}_v
\]

- adiabatic losses
- radiative luminosity (kilonova)
- radioactive heating (r-process)

The cosmic origin of the heavy elements: implications from GW170817
Sources of ejecta in NS mergers

dynamical ejecta (~ms)

Hotokezaka+ 2013, Bauswein+ 2013

winds from NS remnant (~10ms-1s)

Dessart+ 2009
Siegel+ 2014
Cioffi, Siegel+ 2017

accretion disk (~10ms-1s)

Siegel & Metzger 2017, 2018

**tidal ejecta**

shock-heated ejecta

\[ M_{\text{tot}} \lesssim 10^{-3} M_\odot \]

\[ v \gtrsim 0.2c \]

**neutrino-driven wind**

\[ \dot{M}_\text{in} \sim (10^{-4} - 10^{-3}) M_\odot \text{s}^{-1} \]

**magnetically driven wind**

\[ \dot{M}_\text{in} \sim (10^{-3} - 10^{-2}) M_\odot \text{s}^{-1} \]

**thermal outflows**

\[ M_{\text{tot}} \gtrsim 0.3 - 0.4 M_{\text{disk}} \]

\[ v \sim 0.1c \]

Overall ejecta mass per event:

\[ \lesssim 10^{-3} - 10^{-2} M_\odot \]

strongly depends on EOS and mass ratio

Bauswein+ 2013
Radice+ 2016, 2017
Sekiguchi+ 2016
Palenzuela+2015
Lehner+2016
Cioffi, Siegel+2017

Siegel & Metzger 2017, 2018

lower limit
Sources of ejecta for kilonova in GW170817

- **dynamical ejecta (~ms)**
  - $M_{\text{tot}} \lesssim 10^{-3} M_\odot$
  - $v \gtrsim 0.2c$

- **winds from NS remnant (~ms-1s)**
  - $\dot{M}_{\text{in}} \sim (10^{-3} - 10^{-2}) M_\odot s^{-1}$
  - $v \lesssim 0.1c$

- **accretion disk (~10ms-1s)**
  - $M_{\text{tot}} \gtrsim 10^{-2} M_\odot$
  - $v \sim 0.1c$

**blue KN in GW170817**
- → requires large amount of shock
- → heated ejecta to obtain high $Y_e > 0.25$
- → requires metastable NS phase
- → requires EOS with small NS radius (~12 km)

**red KN in GW170817**
- → produces the heavy r-process elements in GW170817 ($Y_e < 0.25$)
Disk outflows

Siegel & Metzger 2018

$Y_e \approx 0.1 - 0.3$

$E_{\text{kin}}/E_{\text{bind, tot}}$

$v_\infty \approx 0.1c$

$\nu e \gg 0.1c$

The cosmic origin of the heavy elements: implications from GW170817

---

$\nu_{1000\text{Km}}$, unbound

$\nu_{1000\text{Km}}$, total

$\nu_{\infty}$, unbound

---

$\nu$ absorbing BB sphere

$\nu$ absorbing BB ring

---

$\log(M/M_\odot)$

$0.1$ $0.2$ $0.3$

$Y_{e, 5\text{GK}}$

$\log(E_{\text{kin}}/E_{\text{bind, tot}})$

$0.05$ $0.10$ $0.15$ $0.20$ $0.25$

$v/c$

$\nu_{\infty}$, corresponds to $\sim 8\text{MeV}$ per baryon in nuclear binding energy release
Why are the disk outflows neutron-rich?

Neutron-rich conditions favor:

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

How can the overall \( Y_e \) of the outflow stay low (~0.1-0.2)?

(and produce 3rd peak r-process elements?)
Self-regulation: keeping a neutron-rich reservoir

**Neutrino-cooled accretion disks** self-regulate themselves to mild degeneracy (low \( Y_e \) matter):

- viscous heating via magnetic turbulence
- neutrino cooling

**charged-current processes:**

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

**pair annihilation:**

\[ e^- + e^+ \rightarrow \nu_e + \bar{\nu}_e \]
\[ e^- + e^+ \rightarrow \nu_{\mu,\tau} + \bar{\nu}_{\mu,\tau} \]

**plasmon decay:**

\[ \gamma \rightarrow \nu_e + \bar{\nu}_e \]
\[ \gamma \rightarrow \nu_{\mu,\tau} + \bar{\nu}_{\mu,\tau} \]

---

**Fig.: disk properties; contours: rest-mass density**

Beloborodov 2003, Chen & Beloborodov 2007, Metzger+ 2009

Siegel & Metzger 2017, PRL

Siegel & Metzger 2018
Neutrino-cooled accretion disks self-regulate themselves to mild degeneracy (low $Y_e$ matter):

- viscous heating via magnetic turbulence
- neutrino cooling

$\mu_e/k_T$ balance with feedback mechanism:

- higher degeneracy $\mu_e/k_T$
- fewer $e^-$, $e^+$ (lower $Y_e$)
- less neutrino emission, i.e., cooling
- higher temperatures
- lower degeneracy $\mu_e/k_T$

**direct evidence of self-regulation**

Fig.: disk properties; contours: rest-mass density

Siegel & Metzger 2017, PRL  Siegel & Metzger 2018

Beloborodov 2003, Chen & Beloborodov 2007, Metzger+ 2009
r-process nucleosynthesis in disk outflows

nuclear reaction network (SkyNet)
- neutron captures
- photo-dissociations
- $\alpha$, $\beta$-decays
- fission

Movie: r-process nucleosynthesis from NS merger remnant disks

Siegel & Metzger 2017, PRL
Siegel & Metzger 2018
• robust 2nd and 3rd peak r-process!

• including neutrino absorption: additional good fit to 1st & 2nd peak elements

→ production of all r-process elements!
Constraints on r-process nucleosynthesis

The cosmic origin of the heavy elements: implications from GW170817
Constraints on r-process nucleosynthesis

post-merger disk outflows are a promising site for the r-process!

Daniel Siegel
The cosmic origin of the heavy elements: implications from GW170817
Conclusions

- The **origin of the heavy elements** has been an **enduring mystery** for more than 70 years.

- **First-principle simulations key** to understand their formation (identify the site, production processes, abundance pattern etc.)

- **Simulations + GW170817 + EM (kilonova)** point to **post-merger accretion disk winds** as promising site (**ubiquitous phenomenon!**)
  - **red KN** in GW170817 consistent with winds from post-merger accretion disk
    - Self-regulation provides **neutron-rich outflows**
    - **Slow outflow velocities** \( \sim 0.1c \)
    - **Large amount of ejecta**

Relative abundances, total ejecta mass, measured BNS merger rate provide yet strongest evidence for NS mergers being the prime production site for the r-process
Appendix
Scenario for GW170817

- NS—NS
- SMNS / HMNS
- BH - torus
- GW170817
- long-lived NS
- BH - torus

- prompt collapse
- blue kilonova with $10^{-2} M_{\odot}$
- presence of red/purple kilonova
- absence of energy injection by NS

Margalit & Metzger 2017

The cosmic origin of the heavy elements: implications from GW170817

Appendix
r-process nucleosynthesis in disk outflows

Siegel & Metzger 2017a, PRL  Siegel & Metzger 2017b

Long $\beta$-decay times near magic neutron numbers $N=82, 126$ produce local abundance peaks

The cosmic origin of the heavy elements: implications from GW170817