The cosmic origin of the heavy elements

Daniel M. Siegel
Center for Theoretical Physics & Columbia Astrophysics Laboratory
Columbia University

Einstein Fellows Symposium, Harvard-Smithsonian Center for Astrophysics, Oct 2-3, 2018
The origin of the elements

How are the *heavy elements* formed?
The r-process and s-process

Burbidge, Burbidge, Fowler, Hoyle (1957), Cameron (1957):

The heavy elements (A > 62) are formed by neutron capture onto seed nuclei

\[ n \rightarrow e^- \]

slow neutron capture (s-process):
timescale for neutron capture longer than for \( \beta \)-decay

rapid neutron capture (r-process):
timescale for neutron capture shorter than for \( \beta \)-decay

\[ \rightarrow \text{speculated that r-process requires explosive environment of supernovae} \]

\[ \rightarrow \text{NS mergers proposed by Lattimer & Schramm (1974) but not favored until recently} \]
The kilonova of GW170817

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

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

  heavy r-process elements!

- two (“red-blue”) or multiple components expected from merger simulations
- single component models might be possible, but require fine-tuning
The kilonova of GW170817

- **blue** kilonova properties:
  - $M_{\text{ej}} \sim 10^{-2} M_{\odot}$ (Kilpatrick+ 2017)
  - $v_{\text{ej}} \sim 0.2-0.3c$
  - $Y_e > 0.25$
  - $X_{\text{La}} < 10^{-4}$ (Kilpatrick+ 2017; Kasen+ 2017; Nicholl+ 2017; Villar+ 2017; Coughlin+ 2018)

- **red** kilonova properties:
  - $M_{\text{ej}} \sim 4-5 \times 10^{-2} M_{\odot}$ (Kilpatrick+ 2017)
  - $v_{\text{ej}} \sim 0.08-0.14c$
  - $Y_e < 0.25$
  - $X_{\text{La}} \sim 0.01$ (Kilpatrick+ 2017; Kasen+ 2017; Kasliwal+ 2017; Drout+ 2017; Cowperthwaite+ 2017; Chornock+ 2017; Villar+ 2017; Coughlin+ 2018)

Observed ejecta properties of red kilonova inconsistent with known classical ejection mechanisms in NS mergers

---

Daniel Siegel
The cosmic origin of the heavy elements
Post-merger accretion disk outflows

Siegel & Metzger 2017, PRL
Siegel & Metzger 2018a

The cosmic origin of the heavy elements

\[ t = 20.113 \text{ ms} \]
Disk outflows and the red kilonova

Siegell & Metzger 2017, PRL
Siegell & Metzger 2018

- Neutron-richness: self-regulation mechanism in degenerate inner disk provides neutron rich outflows ($Y_e < 0.25$)

- Production of full range of r-process nuclei, excellent agreement with observed r-process abundances (solar, halo stars)
Disk outflows and the red kilonova

Siegel & Metzger 2017, PRL
Siegel & Metzger 2018

- Neutron-richness: self-regulation mechanism in degenerate inner disk provides neutron rich outflows ($Y_e < 0.25$)
- Production of full range of r-process nuclei, excellent agreement with observed r-process abundances (solar, halo stars)
- Slow outflow velocities (~0.1c)
- Large amount of ejecta ($\gtrsim 10^{-2} M_\odot$)
But... what about galactic chemical evolution?

Galactic chemical evolution models, merger-only r-process enrichment

late-time galactic r-process enrichment (Eu/Fe decrease) inconsistent with NS merger paradigm  
Côté+ 2017, 2018, Hotokezaka+ 2018a

There should be another significant source of r-process enrichment...
GW170817 points to *collapsars* as main r-process source

Siegel, Barnes, Metzger 2018

- BH-accretion disk from *collapse of rapidly rotating massive stars* (M > 20 M\(_{\text{sun}}\))
  - “failed explosion” (direct collapse to a BH)
  - “weak explosion” (proto-NS collapses due to fallback material)

- *Angular momentum* of infalling stellar material leads to circularization and formation of accretion disk around the BH

- Widely accepted model to generate *long GRBs* and their accompanying GRB SNe (*hypernovae, broad-lined Type Ic*)

jet punches through infalling material, generates GRB
GW170817 points to **collapsars** as main r-process source

Siegel, Barnes, Metzger 2018

Neutron-richness:

\[ e^- + p \rightarrow n + \nu_e \]

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

Low disk densities (low \( \dot{M} \)):

\[ Y_e \sim 0.5 \]

Outflows produce \( ^{56}\text{Ni} \)

**accretion rate**

- \( r \)-process
- Light \( r \)-process
- \( ^{56}\text{Ni} \)
- \( ^4\text{He} \)
- Black hole formation
- Gamma-ray burst

**nucleosynthesis in disk outflow**

- \( ^{4}\text{He} \)
- \( ^{56}\text{Ni} \)
- \( \dot{M}_1 \)
- \( \dot{M}_2 \)
- \( \dot{M}_3 \)
- Solar r-process

**degeneracy**

**Neutron-richness:**
GW170817 points to *collapsars* as main r-process source

Siegel, Barnes, Metzger 2018

Neutron-richness:

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

Low disk densities (low \( \dot{M} \)):

\( Y_e \sim 0.1 \)

Outflows produce r-process nuclei
Collapsars: r-process yield

Relative r-process contribution:

• assume accreted mass proportional to gamma-ray energy (same physical processes in both types of bursts, similar observational properties!)

\[
\frac{m_{r,\text{coll}}}{m_{r,\text{merger}}} \sim \frac{m_{\text{acc}}^{\text{LGRB}}}{m_{\text{acc}}^{\text{SGRB}}} \int R_{\text{LGRB}}(z)dz = \frac{E_{\text{iso}}^{\text{LGRB}} R_{\text{LGRB}}(z = 0)}{E_{\text{iso}}^{\text{SGRB}} R_{\text{SGRB}}(z = 0)} \approx 4 - 30
\]

→ dominant contribution to Galactic r-process relative to mergers

Independent absolute r-process estimate:

• assume collapsars as main contribution to Galactic r-process:

\[
m_{r,\text{coll}} \sim X_r f_Z^{-1} \rho_{\text{SF}}(z = 0) f_b R_{\text{LGRB}}(z = 0) \approx 0.08 - 0.3 M_\odot \left( \frac{f_Z}{0.25} \right)^{-1} \left( \frac{X_r}{4 \times 10^{-7}} \right) \left( \frac{f_b}{5 \times 10^{-3}} \right)
\]

→ consistent with relative estimate, using r-process yield from GW170817 (~0.05 M_\odot)
Dominant contribution to the Galactic r-process from collapsars dramatically improves evolution of r-process enrichment at high metallicity (MW disk)!

Collapsars: galactic chemical evolution

Siegel, Barnes, Metzger 2018
Conclusions

- **GW170817**: heavy elements & red kilonova most likely originate from outflows of post-merger accretion disk
  - can produce entire range of r-process nuclei
  - ubiquitous phenomenon

- **NS mergers inconsistent with r-process enrichment** of Milky Way disk

- **Collapsars** likely provide dominant contribution to Galactic r-process
  - similar physics as in NS post-merger disks
  - lower event rate overcompensated by higher yield (calibrated relative to GW170817)

- **Collapsars help alleviate observational challenges** of merger models
  - reproduce r-process enrichment at high metallicity (track star formation history)
  - don’t require very short delay times and small kicks to explain enrichment in UFDs
Appendix
GW170817 points to collapsars as main r-process source

Siegel, Barnes, Metzger 2018

(a) $L_{\text{bol}}$ (erg s$^{-1}$)

(b) $AB$ Mag.

(c) Norm. flux + offset