Discovery of gravitational waves and light from merging neutron stars: implications and open questions

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Neutron star mergers for non-experts: GW170817 in the multi-messenger astronomy and FRIB eras
What happened?

- Fate of the remnant unknown, but likely a BH
- A short gamma-ray burst was launched. How?
- Synchrotron emission at late times: radio to X-ray Cocoon? Structured jet?
- Radioactive of neutron rich ejecta powers (~0.05 $M_\odot$ of ejecta)
  UV/optical/infrared

From Metzger & Berger 2012
and the g and r images taken 1 day later; the optical counterpart of GW170817 is at R.A., decl. 197.450374, 23.381495 deg.

GW170817
DECam observation
(0.5–1.5 days post merger)

GW170817
DECam observation
(>14 days post merger)

Multiple components!

\[ k = 0.1 \text{ cm}^2 \text{g}^{-1} \]

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

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

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

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

Error bars are given at the 1σ level in all panels, but may be smaller than the points.

From Cowperthwaite et al., ApJL 848:L17 (2017)
observations acquired at later times, when the UV emission from the transient was no longer present in the images (Swift ID 07012979003). The systematic effect from the host light contamination is \( \approx 3\% \) (see e.g., Brown et al. 2009).

3. Light Curves and Spectral Energy Distributions

3.1. Light Curves

Our UV/optical/NIR light curves are shown in Figure 1. The data span from 0.47 to 18.5 days post-merger, with bluer bands fading below the detection limits at earlier times. The light curve coverage was truncated by the proximity of the source to the Sun. We first note that the light curves are not well described by a power law, indicating minimal contribution from a GRB optical afterglow over the timescale of our observations. This is consistent with modeling of the afterglow based on X-ray and radio observations (Margutti et al. 2017; Alexander et al. 2017).

The light curves exhibit a rapid decline in the bluest bands (ug), an intermediate decline rate in the red optical bands (rizY), and a shallow decline in the NIR (HKs). However, while the u- and g-band light curves decline by \( \approx 2 \) mag day\(^{-1} \) starting with the earliest observations, the redder optical bands exhibit a more complex behavior: they exhibit a comparatively slow decline (\( \approx 0.3 \) mag day\(^{-1} \)) over the first 1.5 days, develop a shoulder at about 4 days, and subsequently begin to decline at about 8 days.

We find a similar rapid evolution in the colors of the transient (Figure 2). In particular, the \( u - g \) and \( g - r \) colors become redder by about 1 mag between about 1.5 and 3.5 days. The colors in the redder optical bands exhibit slower evolution, with \( r - i \) \( \approx 0.5 \) mag, \( i - z \) \( \approx 0 \) mag, and \( z - Y \) \( \approx 0.3 \) mag. These colors are significantly redder than those of known supernovae near explosion (e.g., Folatelli et al. 2010; Bianco et al. 2014; Galbany et al. 2016).

3.2. Spectral Energy Distribution

We construct SEDs from photometry at several epochs from about 0.6 to 10 days post-merger (Figure 2). The SEDs exhibit rapid evolution from an initial peak at \( \sim 3500 \) Å to a final peak at \( \sim 15000 \) Å by 10 days. Moreover, the SED at 1.5 days appears to consist of two components, as indicated by the changing slope in the NIR emission. The same rapid evolution and structure are apparent in the optical and NIR spectra at comparable epochs (Chornock et al. 2017; Nicholl et al. 2017).

The SED at 0.6 days is well described by a blackbody with \( \sim T_{8300} \) K and \( \sim R_{4.5} 10^{14} \) cm, corresponding to an expansion velocity of \( \sim v_{c0.3} \). This is somewhat larger than the velocities observed in broad-lined SNe Ic (for which \( \sim v_{c0.1} \); Modjaz et al. 2016), but is consistent with expectations for ejecta resulting from a BNS merger (Metzger 2017). The SEDs at later times are not well described by a blackbody curve, instead exhibiting strong flux suppression at...
Strong and weak r-process

![Graph showing final abundances of nucleosynthesis calculations for different electron fractions and baryon numbers.](http://stellarcollapse.org/lippunerroberts2015)

WhiskyTHC


- Full-GR, dynamical spacetime*
- Nuclear EOS
- Effective neutrino treatment
- High-order hydrodynamics
- Open source!

* using the Einstein Toolkit metric solvers
Neutron rich outflows

See also Wanajo+ 2014, Sekiguchi+ 2015, 2016, Foucart+ 2016

DR, Galeazzi+ MRAS 460:3255 (2016)
Neutron rich outflows: model

- **Geometry** and **composition** of the outflows from simulations
- Multiple ejecta components
- Ejecta masses from fitting AT2017gfo

Kilonova modeling

Light curves for best fits: near-IR bands

See also: Chornock et al. 2017; Cowperthwaite et al. 2017; Drout et al. 2017; Nicholl et al. 2017; Rosswog et al. 2017; Tanaka et al. 2017; Tanvir et al. 2017; Villar et al. 2017
Kilonova modeling

- ~0.05 $M_\odot$ of ejecta
- Final disk mass $\gtrsim 0.08 M_\odot$
- Mergers could explain all of the r-process elements in the Universe
- However exact nucleosynthetic yields are unknown; more data/theory needed

See also: Chornock et al. 2017; Cowperthwaite et al. 2017; Drout et al. 2017; Nicholl et al. 2017; Rosswog et al. 2017; Tanaka et al. 2017; Tanvir et al. 2017; Villar et al. 2017

Perego, DR, Bernuzzi, arXiv:1711.03982
Fate of the remnant

From Margalit & Metzger 2017

See also Bauswein+, Rezzolla+, Shibata+, Ruiz+ (2017)
Prompt collapse?

(1.44 + 1.39) $M_\odot$ — B1913 + 13

Prompt collapse?

$(1.44 + 1.39) M_\odot — B1913 + 13$

GW170817: not a prompt collapse

See also Bauswein+ 2017 ApJL 850:L34

What About Magnetic Fields?
Magneto-turbulence effects

• MHD instabilities are known to operate at a scale of few meters or less.

• Resolution in global simulations is orders of magnitude too low.

• Previous approach: neglect these effects or use unrealistically large B-fields, and/or idealized configurations.

• Our approach: explicit subgrid-scale modeling with large-eddy simulations.

See also: Shibata & Kiuchi 2017, Kiuchi, Kyutoku+ 2017

From Siegel+ 2013
Angular momentum transport

\[ t_{\text{visc}} = \infty \quad \text{and} \quad t_{\text{visc}} \sim 15 \text{ ms} \]

\[ t - t_{\text{mg}} \approx 0.1 \text{ ms} \]

See also: Shibata & Kiuchi 2017; Kiuchi, Kyotoku+ 2017
Angular momentum transport

\[ t_{\text{visc}} = \infty \quad \text{and} \quad t_{\text{visc}} \sim 15 \, \text{ms} \]
Angular momentum transport

$$t_{\text{visc}} = \infty$$

$$t - t_{\text{MB}} \simeq 0.1 \text{ ms}$$

$$t_{\text{visc}} \sim 15 \text{ ms}$$

$${\ell}_\text{mix} = 0$$

$${\ell}_\text{mix} = 50 \text{ m}$$

Delayed collapse!
Rotational profile

\[ \langle \Omega \rangle_{xy} \text{ [rad ms}^{-1}] \]

\[ r \text{ [km]} \]

\[ t - t_{\text{mrg}} \approx 10 \text{ ms} \]

See also Shibata & Taniguchi 2006; Kastaun+ 2015, 2016; Hanauske+ 2016

Rotational profile

Slowly rotating core

$t - t_{\text{mrg}} \sim 10 \text{ ms}$

See also Shibata & Taniguchi 2006; Kastaun+ 2015, 2016; Hanauske+ 2016

Rotational profile

Slowly rotating core
Rotationally supported envelope

$\langle \Omega \rangle_{xy}$ [rad ms$^{-1}$]

$r$ [km]

$t - t_{\text{mrg}} \approx 10$ ms

See also Shibata & Taniguchi 2006; Kastaun+ 2015, 2016; Hanauske+ 2016
Rotational profile

\[ \langle \Omega \rangle_{xy} \text{ [rad ms}^{-1}] \]

- Blue line: \( l_{\text{mix}} = 0 \)
- Red line: \( l_{\text{mix}} = 5 \text{ m} \)

\[ t - t_{\text{mrg}} \simeq 10 \text{ ms} \]

See also Shibata & Taniguchi 2006; Kastaun+ 2015, 2016; Hanauske+ 2016
Rotational profile

See also Shibata & Taniguchi 2006; Kastaun+ 2015, 2016; Hanauske+ 2016
Rotational profile

See also Shibata & Taniguchi 2006; Kastaun+ 2015, 2016; Hanauske+ 2016
Gravitational waves

See also: Shibata & Kiuchi 2017; Kiuchi, Kyotoku+ 2017
Gravitational waves

- How large is the turbulent viscosity?
- How do merger remnants evolve over many viscous timescales?

See also: Shibata & Kiuchi 2017; Kiuchi, Kyotoku+ 2017
Future prospectives: long-lived remnants
Long-lived remnants (I)

$DD2 - (1.35 + 1.35) M_{\odot} - M_0$

See also Fujibayashi, Kiuchi+ (2017)
Long-lived remnants (II)

- Low-mass NS binaries exist* and likely form stable remnants
- Long-lived remnants are found to be unstable over the viscous timescale
- Smoking gun: a very bright kilonova with a blue component

* PSR J1411+2551; PSR J1946+2052

DR, Perego, Bernuzzi, Zhang, arXiv:1803.10865
Conclusions

• GW170817 *probably* made a BH, but not immediately

• Using *numerical relativity* to bridge the gap between EM and GW observations: starting to constrain the NS EOS

• The postmerger evolution of NS mergers is affected by *turbulent angular momentum transport*

• The next GW event might look very differently!