The Gemini Perspective on Neutron Star Mergers

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on behalf of many, many others...
• On August 17, 2017, Advanced LIGO/Virgo triggered on a low-mass merger consistent with being a binary neutron star merger

• Followed 1.7 s later by a spatially coincident weak burst of gamma rays
The optical counterpart, SSS17a, was independently found by 6 optical followup teams, first by the 1M2H collaboration using the Swope.

More than 70 telescopes participated in the followup effort.

LVC/EM partners 2017
Fig. 3. Near-infrared spectrum of EM170817 at 4.5 days after merger. For display purposes, the data have been smoothed using a Savitzky-Golay filter (solid black line), and the unfiltered data are shown in grey. A predicted model macronova spectrum assuming an ejecta mass of $M_{ej} = 0.05 M_{\odot}$ and a velocity of $v = 0.1 c$ at a phase of 4.5 days post merger is shown in red. The spectra have been corrected for Milky Way extinction assuming reddening $E(B-V) = 0.1$ (10). Regions of low signal-to-noise ratio from strong telluric absorption by the Earth's atmosphere between the near-infrared $J$, $H$, and $K$ spectral windows are indicated by the vertical dark grey bars. The light grey shaded band is the blackbody which best fits the photometric measurements at 4.5 days (10).
What happens in a BNS merger?
What we actually see

Dark Energy Camera / CTIO
i-band
Time Relative to 2017 August 17

+0.5 days

Credit: P. S. Cowperthwaite / E. Berger
Harvard-Smithsonian Center for Astrophysics
Two Emission Processes

- Optical through IR dominated by “thermal” kilonova component
- Underlying X-ray to radio power law from synchrotron emission (jet)

Margutti et al. 2018
Kilonova components

Different ejecta components will have different compositions and colors.

Material with $Y_e \leq 0.23$ will experience strong $r$-process and be “red”.

Kasen et al. 2017
**r-process Nucleosynthesis**

- Universal abundance ratios for “heavy” *r*-process, more scatter for the “light” *r*-process
- Mounting evidence that rare, high production events are responsible for the *r*-process
- Detailed BNS merger simulations reproduce the solar pattern
This matters for the opacity

- Atoms/ions with open $f$-shells have many more available states compared to iron-peak elements

Kasen et al. 2013

<table>
<thead>
<tr>
<th>Ion</th>
<th>Configurations</th>
<th>Number of levels</th>
<th>Number of lines</th>
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<tbody>
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<td>Nd</td>
<td>4$^{f}4^{6}s^{2}$, 4$^{f}4^{6}s(5d, 6p, 7s)$, 4$^{f}4^{5}d^{2}$, 4$^{f}4^{5}d6p$, 4$^{f}4^{5}d6s^{2}$, 4$^{f}4^{5}d2(6s, 6p)$, 4$^{f}3^{5}d6s6p$</td>
<td>31,358</td>
<td>70,366,259</td>
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Tanaka et al. 2018
Ingredient #2: Expansion

- The effects of weak lines are greatly enhanced in material with strong velocity gradients.
The first KN models using enhanced $r$-process opacities (from 2013) showed a shift of flux to the NIR.
Basic Observations of GW170817

- Very fast fading in blue, slower in near-IR
- Color temperature of ~2500K after a week
- Luminosity/timescale consistent with ~few×10^{-2} M_{\odot} of r-process ejecta
Light curve fits

Normal SN material does not provide a good fit to the light curve shape or match the spectra and NIR excess

Cowperthwaite et al. 2017
Kilonova fits

• Best-fit model has two components

• Low opacity “blue” kilonova with \( \sim 0.01-0.02 \, M_\odot \) and \( v \sim 0.25c \) that dominates in optical at early times

• High opacity “red” kilonova component has \( \sim 0.04 \, M_\odot \) and \( v \sim 0.1c \) that peaks in the NIR on longer timescales

Cowperthwaite et al. 2017; Villar et al. 2017
GW170817
SOAR + Gemini

Credit: M. Nicholl / R. Chornock / E. Berger
Harvard-Smithsonian CfA / Ohio University

1.5 days after merger

Spectral luminosity

Wavelength (Å)

4000  6000  8000  10000  12000  14000  16000  18000
Evidence for $r$-process

1. That there was anything at all to see in the optical/NIR!

- Some models now invoke other sources of heating at early times for the “blue” emission (e.g., shocks), but all still agree that the long-lasting IR emission requires some input heating from radioactive decay

2. Spectral energy distribution peaks near ~1 micron are a consequence of lanthanide opacity
Amazing NIR Agreement!

GW170817
+4.5 d

Kasen et al. 2017
red kilonova model

$M = 0.04 \, M_\odot$
$v = 0.1c$
$X_{\text{lanthanide}} = 10^{-2}$

Chornock et al. 2017
Blue kilonova

- The blue kilonova component can only accommodate light r-process (much lower lanthanide abundances)
- But the velocities are very high (~0.3c)

Nicholl et al. 2017
Nucleosynthesis

- There is a production threshold below $Y_e \approx 0.23$ in merger calculations: lanthanide fraction is not really a free knob.
2D kilonova simulations

- Reprocessing of one component by another may be very important, as is the fundamentally aspherical nature of the kilonova.

Kawaguchi et al. 2018
Galactic nucleosynthesis

With order-of-magnitude uncertainties, the $r$-process production in this event is about right to generate MW abundances.

Hotokezaka et al. 2018

Côté et al. 2018
Present & Future

- Binary neutron star mergers produce a range of ejecta material with various compositions and velocities
- Optical and NIR observations are sensitive to different components of the ejecta
  - Spectroscopy is key, although many theoretical uncertainties in the interpretation
- What is the range of kilonova properties?
  - Intrinsic (Range of ejecta masses, nucleosynthetic outputs)
  - Extrinsic (viewing angle)
- Rapid ToO observations with Gemini will be a valuable part of this future
- Thanks to everybody at the observatory for all the work to obtain the observations of GW170817, pointing into the setting sun at twilight and up to airmass 3 for three weeks
Backup slides
Can we actually constrain detailed abundances?

- Maybe?
- In the future?

Kasen et al. 2017