Before and after merger: Multi-messenger searches for compact binaries

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A Golden Era for Astrophysics

Post-merger searches

Short GRB / GW follow-up with ZTF

Eclipsing White Dwarf Binaries

LSST

TESS

LIGO/Virgo

IceCube
Many detections are coming
A New Era

Many detections are coming

PC: Jonah Kanner

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![Graph showing strain vs. frequency with various noise sources labeled: Initial LIGO design specification, Advanced LIGO design specification, Quantum noise, Mirror coating thermal noise, Suspension thermal noise, Gravity gradient noise, Seismic noise.](image)
Newtonian Noise

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Seismometer and Tiltmometer Array

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Seismometer and Tiltmeter Array

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Low-Frequency Noise

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DeepClean

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LHO O2 Subtraction Comparison

ASD [strain Hz^{-1/2}]

Frequency [Hz]

DeepClean
Wiener Filter
H1:DCS-CALIB STRAIN

with Ormiston, Nguyen, Vajente, Adhikari
DeepClean

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with Ormiston, Nguyen, Vajente, Adhikari
Neutron Star Remnants

There are a variety of possibilities for post-merger scenarios, depending on the remnant mass and equation of state!

Can constrain the neutron-star equation of state as well as the initial compact binary that created the post-merger NS.
Post-merger searches

Short Duration: 10 - 100 ms

Intermediate Duration: 1 - 1000 s

Long duration: 100 - 10,000 s

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Improving the clustering

Post-merger searches

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with Schale, Coughlin, Clark and Bauswein

with Banagiri and Sun
Parameter estimation

\[ h_0(t) = \frac{4\pi^2 GI\epsilon}{dc^4} f_0^2 \left( 1 + \frac{t - t_0}{\tau} \right)^{\frac{2}{1-n}} \]

with Banagiri, Clark and others

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GW170817

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Follow-up

Localization

Counterpart

August 17, 2017
Follow-up

Many open questions:

- Why was GW170817 so bright and blue early?
- Is this blue emission ubiquitous in neutron-star binary mergers?
- How does the emission evolve in the first few hours post merger?
- Do all neutron-star mergers generate relativistic ejecta?
- Can these systems reproduce the heavy element abundance pattern observed in the Solar System?
GW-EM constraints

- \( q \lesssim 1.29 \) with 90% confidence.
- \( 279 \lesssim \Lambda \lesssim 822 \) with 90% confidence

with Coughlin, Dietrich, Margalit and Metzger
Many surveys: ZTF, PTF, CRTS, ATLAS, Pan-STARRS, LSST, Gaia, TESS, Kepler, ASAS-SN, etc

The largely unexplored galactic plane is being included in many of the more recent surveys
GW Sky Localizations

Post-merger searches
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Initial Skymaps
Final Skymaps
Counterpart Identification

- Wide Field of View Surveys
- Galaxy Targeted Followups
- Candidates
- Photometry
- Spectroscopy
- Identification
- Characterization

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Counterpart Identification

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LLAMA

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Palomar Telescopes

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P48 Discovery

P200 Spectroscopy

P60 Confirmation

B, g, r, i

IFU
The Kitt Peak EMCCD Demonstrator (KPED)

Post-merger searches

Short GRB / GW follow-up with ZTF

Eclipsing White Dwarf Binaries

Instrument breakdown exploded view

- Instrument Standoff Plate
- Barlow Cell
- Filter Wheel to Barlow Cell Adapter
- FLI Filter Wheel
- Spherical Bearing Stack
- Filter Wheel to Andor Adapter
- Tip/Tilt/Piston Plate
- Adjustment Bolt

with Feeney, Reed, Kulkarni and others
• ZTF covered 61.6% of the probability region
  • 2900 square degree coverage with its 47 square degree FOV
  • Somewhat poorer localization than average

with Ahumada, Cenko, Ghosh, Kaplan and others
Non-detection limits

Post-merger searches

Short GRB / GW follow-up with ZTF

Eclipsing White Dwarf Binaries

Do not pass the filter

175423 Sources

Pass the filter

107809

ToO

67614

50240

Positive subtraction

17374

5257

Real

12117

11430

No point underneath

687

18

No bright star nearby

669

372

Not moving object

297

with Ahumada, Cenko, Ghosh, Kaplan and others
Requirements for a counterpart candidate are minimal:
- Not a variable star or moving object
- $R_b > 0.3$
- Away from bright stars
- Within ToO fields

Only 14 new candidates found within the 2900 deg$^2$ area to $r > 20.3$ ($g > 0.6$). None were found to be consistent with a short gamma ray burst afterglow. with Ahumada, Cenko, Ghosh, Kaplan and others
Non-detection limits

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with Ahumada, Cenko, Ghosh, Kaplan and others
Short GRB Follow-ups with ZTF (so far)

6 short GRB triggers from Fermi-GBM

- GRB180523B (2900 deg2, 60% coverage)
- GRB180626C (300 deg2, 87% coverage)
- GRB180715B (250 deg2, 37% coverage)
- GRB180728B (350 deg2, 90% coverage)
- GRB180913 (550 deg2, 72% coverage)
- GRB181126B (1400 deg2, 77% coverage)

Total time used: 15 hours
Number of counterparts: 0

with Ahumada, Cenko, Ghosh, Kaplan and others
Can we do better?

We can modify the probability maps to account for galaxy density.

Post-merger searches
Short GRB / GW follow-up with ZTF
Eclipsing White Dwarf Binaries

with Tao, Chatterjee, Ghosh and others

with Reed and Foley

We can modify the probability maps to account for galaxy density.
Looking at other kilonovae?

Post-merger searches

Short GRB / GW follow-up with ZTF

Eclipsing White Dwarf Binaries
LISA Verification Binaries

- EM
  - Orbital Period
  - Inclination Angle
  - Scaled radii
  - Mass ratio (radii + mass-radius)

- GW
  - Chirp mass + Distance (degenerate)
  - GW+EM
  - Distance from EM breaks degeneracy
  - Also possible from dP/dt

Post-merger searches
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Finding Periodic Objects

Post-merger searches

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Finding Periodic Objects

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Eclipsing White Dwarf Binaries

How do we find White Dwarf Binaries?

- Eclipses
- Ellipsoidal modulation
- Irradiation of companion

J0651, a 12.75 minute binary (Brown et al. 2011)
How do we find White Dwarf Binaries?

• Eclipses
• Ellipsoidal modulation
• Irradiation of companion

J0651, a 12.75 minute binary (Brown et al. 2011)
White Dwarf Binary Identification

- Wide Field of View Surveys
- HR Diagram/Gaia
- Candidates
- Photometry
- Spectroscopy
- Identification
- Characterization

Post-merger searches
Short GRB / GW follow-up with ZTF
Eclipsing White Dwarf Binaries
Eclipsing White Dwarf Binaries

Problem: Searching for short periods in long baseline data is computationally expensive!
Solution: GPUs!

Problem: How to actually identify them (outside of cross-matching)?
Solution: Eclipses, Ellipsoidal Modulation, Irradiation of the companion

J0651, a 12.75 minute binary (Brown et al. 2011)
• PTF1J162528.61-003545.8: an eclipsing white dwarf--red dwarf system (g=16.0) identified by PTF with an orbital period of 7.8 hr.

• Eclipse timing uncertainty: 0.2 s

• Sum of the scaled radii \(((R_1+R_2)/a)\) and the ratio of the radii: 1%

with Burdge, Prince, Kulkarni and others
Now, for some early ZTF results...

- We performed a global period search of the first set of ZTF data
- We quickly followed up candidates with KPED

with Burdge, Prince, Kulkarni and others
A 7 minute system

• Folded Lightcurve of the 7 minute binary from KPED

Two eclipses; 7 minute period

with Burdge, Prince, Kulkarni and others
A 7 minute system (continued)

- Folded Lightcurve of the 7 minute binary from Chimera

Two eclipses; 7 minute period

with Burdge, Prince, Kulkarni and others
Post-merger searches

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Eclipsing White Dwarf Binaries

A 7 minute system (continued)
A 7 minute system (continued)

Post-merger searches
Short GRB / GW follow-up with ZTF
Eclipsing White Dwarf Binaries

With Burdge, Prince, Kulkarni and others
LISA Verification Binaries (updated)

- Post-merger searches
- Short GRB / GW follow-up with ZTF
- Eclipsing White Dwarf Binaries

Graph showing characteristic strain against gravitational wave frequency. Points labeled:
- PTF Binary (~20 min)
- Eclipsing
- SDSS J0651 (12.75 min)
- ZTF Binary (~7 min)
- V407 Vul (9.5 min)
- HM Cnc (5.4 min)

with Burdge, Prince, Kulkarni and others
Many binaries coming?

- LSST
- Gaia

Post-merger searches
Short GRB / GW follow-up with ZTF
Eclipsing White Dwarf Binaries
Many binaries coming?

Korol et al. 2017

Number of sources

Period

2min 6min 20min 1h 3h 10h 30h

ELM
Gaia
LSST
Many binaries coming?

• Can we successfully identify candidates?
  • For the shortest orbital period systems, we must account for orbital period decay
• Can we successfully follow them up?
  • LSST objects will likely be intrinsically faint (especially eclipsing!)
State of the Art Follow-up

Photometry - Chimera

Spectroscopy - ULTRASPEC

Post-merger searches

Short GRB / GW follow-up with ZTF

Eclipsing White Dwarf Binaries

Ives et al. 2008
A spectrograph with EMCCDs (SPEED)

Post-merger searches

Short GRB / GW follow-up with ZTF

Eclipsing White Dwarf Binaries

with Feeney, Reed, Kulkarni and others
Post-merger searches

Short GRB / GW follow-up with ZTF

Eclipsing White Dwarf Binaries

Conclusion

• We can find and use post-merger signals to understand the progenitor and the remnant.

• Searches for gravitational-wave counterparts are feasible (even when the objects are further away or fainter than GW170817) and are a unique opportunity to answer questions about the binaries (or other sources?) not possible from gravitational waves alone.

• The significant synergy between gravitational-wave and optical observations, particularly with LIGO and LISA, open many avenues to inform population synthesis, test general relativity, etc.
Thank you!

• Collaborators

  ● LIGO Scientific Collaboration and Virgo Collaboration (including Columbia!)
  ● Tomas Ahumada (Graduate Student; University of Maryland)
  ● Kevin Burdge (Graduate student; Caltech)
  ● Michael Feeney (Lead instrument engineer for KPED; COO)
  ● Jim Fuller (Assistant Professor of Theoretical Astrophysics, Caltech)
  ● Mansi Kasliwal (Associate Professor of Physics, Caltech)
  ● Shri Kulkarni (PI of ZTF; George Ellery Hale Professor of Astronomy and Planetary Science, Caltech)
  ● Tom Prince (Ira S. Bowen Professor of Physics; CO-I of ZTF, Caltech)
  ● Reed Riddle (Lead software engineer for KPED; COO)
  ● Leo Singer (Staff scientist; NASA Goddard)
  ● Jan van Roestel (postdoctoral scholar; Caltech)
What is a White Dwarf?

- Compact degenerate stellar remnant
- Masses range from 0.15-1.4 solar masses
- Radii typically a few thousand km

HR diagram from https://arxiv.org/abs/1804.09378
Landscape of Periodic Objects

Some early PTF Results

- Shortest Period HW Vir (sdB+MS) (P=92.4 min)

- Shortest Period Pre-CV (P=63.7 min)

- Three new WD-sdB Binaries
Proof of concept: A Detached 20 Minute Orbital Period Binary Discovered in PTF

Atmospheric fit (performed by Elena Cukanovaite, Pier-Emmanuel Tremblay)

(The first?) Helium Rich Extremely Low Mass WD

Atmospheric fit (performed by Elena Cukanovaite, Pier-Emmanuel Tremblay)
The Kitt Peak EMCCD Demonstrator (KPED)

**Photometric Performance**

- Relative Magnitude [mag]
- Probability Density Function
- CCD
- EMCCD

**Pointing / Distortion**

- Right Ascension
- Declination
- Full Width Half Max [pixels]
- Counts

- RA [arcsec]
- Destination [arcsec]

![Graphs and plots showing photometric performance and pointing/distortion results for the Kitt Peak EMCCD Demonstrator.](image-url)
A 7 minute system (continued)

- Low flux level during the eclipse prioritizes the use of the EMCCD, which is designed for low light level observations.