Multi-messenger exploration of the transient radio sky

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Transient Astronomy

◆ A **transient** astronomical event is an astronomical object or phenomenon whose **duration may be from seconds to days, weeks or even several years**.

◆ These timescales are much shorter than the millions or billions of years during which galaxies and their component stars in our universe have evolved.

◆ I will focus on transient astronomy in connection with **ground-based** GW detectors, and on electromagnetic (EM) counterparts of **“CATASTROPHIC” events marking the birth of NSs or BHs**.
Laser Interferometer GW Observatory (LIGO)

\[ h \sim \frac{G \epsilon E}{c^4 d} \approx \frac{\Delta L}{L} \sim 10^{-43}! \]
A ZOO of GW sources

Modeled Waveform

Unmodeled Waveform

Short Duration

Long Duration
BBHs are nice but NS matter...
Welcome to the era of GW astrophysics!

LIGO, Virgo, and partners make first detection of gravitational waves and light from colliding neutron stars

Why multi-messenger astrophysics?

GWs
- Directly probe progenitors!
- Masses.
- Spins.
- Rates and implications on progenitor formation scenarios.
- Geometric properties of the progenitor:
  - “Position”
  - Distance
  - Inclination angle
  - …

EM
- Nucleosynthesis.
- Ejecta properties:
  - Energetics
  - Velocity
  - Geometry
- Redshift.
- Environment properties (especially density).
- Enhance confidence of low-SNR GW detections
- …
Gravitational waves!

(Short) Gamma-ray Burst (seconds), X-rays (secs-days) if on-axis or not too far off-axis

Interaction with ISM (optical and radio afterglow, days to months)

Kilonova R-process nucleosynthesis: optical-IR (∼ 1 day).

Courtesy: Varun Bhalerao
GW astronomy makes the BIG leagues!

Abbott et al., ApJL, 848:L13, 2017

Credit: I. Bartos
Combination of LIGO, Virgo, Fermi, and Integral localizations for GW170817: \(~30 \text{ deg}^2\) in area.

Optical observations reveal a host galaxy \(\text{@ 40 Mpc!}\)
OH, hang on, this is kind of dim??

Abbott et al., ApJL, 848:L13, 2017

 ERC1E (1 keV - 10 MeV) (erg)

Redshift (z)
Discovery of a delayed radio glow

Hallinan, Corsi et al. 2017, Science, 358, 1579
Lazzati et al. 2017, arXiv1712.03237
Margutti et al. 2018, arXiv1801.03531
An off-axis “top-hat” jet?

Kasliwal et al., Science, 2017, 358.1559

Nakar & Piran 2003
Instead of bright gamma-rays from an on-axis relativistic jet, just a red kilonova, and a relatively prompt radio/X-ray afterglow, we saw:

- gamma-rays $\sim 10^3$ times weaker than ordinary short GRBs;
- early blue kilonova;
- late radio/X-ray emission.

OH, hang on, radio light rises too slowly!
A more complex outflow: to jet or not to jet?

Anatomy of NS-NS outflows: Stokes I radio continuum

1. Jet signature
   - “Off-axis” Emission
   - Energy injection $t^{0.8}$
   - A very weak jet that doesn’t influence the observed light curve

2. No late energy injection
   - jet or a cocoon with low energy
   - 120 days

3. Continuous energy injection
   - energetic cocoon or dynamical ejecta

Regular “on-axis” afterglow

Log($F_{\nu}$) vs. Log(t)

Nakar & Piran 2018, arXiv:1801.09712
**Anatomy of NS-NS outflows: Linear polarization**

- In a structured jet model, the required asymmetry is built into the jet structure: energy and speed of ejecta components depend on polar angle.

- Emitting surface never completely symmetric for misaligned observers: magnetic field appears to have some degree of “order” or alignment, resulting in an appreciable degree of polarization in the received radiation.

Gill & Granot, arXiv: 1803.05892
Anatomy of NS-NS outflows: VLBI mapping
Why do we care? Geometry Matters

Successful jet+cocoon
(a.k.a. structured jet)

- After years of circumstantial evidence, we now have direct proof that short GRBs are related to binary NS mergers.
- After 20 years of searching, we have found an off-axis GRB jet.
- Rate of short GRBs traces NS/NS rate.
- Viewing angle constrains orbital inclination → Breaks $H_0$ degeneracy!

Cocoon only (choked jet)

- There is a diversity of central engine outcomes. Some launch jets, others fail.
- Rate of short GRBs < NS/NS rate.
- Expect a larger number of EM counterparts than off-axis jet:
  - Wide-angle ejecta are visible over a wider solid angle.
  - Cocoon may boost early UV/blue kilonova brightness.
How common is GW170817?

Is relativistic outflow launched in the absence of BH collapse?

Prompt collapse to BH may suppress blue kilonova (due to lack of neutrino flux preventing formation of heavy r-process elements)? Possibly, relativistic jets escape cleanly without interacting with polar ejecta, precluding cocoon formation?

GW170817-like events: blue and red kilonovae and cocoons. Fraction of such mergers where the jets escape through the polar ejecta yet to be determined.

Credit: JAGWAR team
What’s next?

Abbott et al., Living Reviews in Relativity 19, 1 (2016)

16th Synthesis Imaging Workshop
Conclusion

- LIGO-Virgo have made first measurements of GWs!

- Merging binary black hole and neutron star systems have been observed for the first time!
  
  ‘a scientific revolution’

- Plans are underway to improve LIGO’s sensitivity for O3 and beyond.

STAY TUNED!
TEXAS TECH UNIVERSITY
Graduate Study in Physics and Astrophysics Research

Extreme and Explosive Astrophysics
- Radio/X-ray follow-up of core-collapse supernovae and other transients.
- Observational studies of dynamics of dense star clusters.
- Accretion onto black holes and neutron stars, jets, GRBs.

Stellar Populations in Nearby Galaxies
- X-ray binary populations of nearby galaxies.

Gravitational-Wave Physics and Astronomy
- Gravitational waves from GRBs, pulsars, magnetars with LIGO.
- Radio, optical, and X-ray follow-up of gravitational waves.
- Theoretical studies of neutron stars and black holes.

Instrumentation and Collaborations
- STROBE-X – X-ray Timing and Spectroscopy on Dynamical Timescales from Microsecs to Yrs.
- Small telescopes for photometric follow-up of targets from exoplanet transit surveys.
- We are part of: CTA, DLT40, GROWTH, LIGO, ngVLA, ZTF.

QUESTIONS? Contact us:

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WHERE? Lubbock, (West) Texas - USA

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