Unveiling the violent Universe with gravitational wave astronomy

Eric Howell

In collaboration with Kendall Ackley, Antonia Rowlinson & David Coward
Gamma-ray bursts (GRBs)

- 10keV-GeV photons
- $10^{51}$ to $10^{54}$ ergs in few seconds
- γ-rays - ultra-relativistic energy flow converted to radiation

Formation of a gamma-ray burst could begin either with the merger of two neutron stars or with the collapse of a massive star. Both these events create a black hole with a disk of material around it. The hole-disk system, in turn, pumps out a jet of material at close to the speed of light. Shock waves within this material give off radiation.

| long-soft LGRB | < 2s |
| short-hard SGRB | > 2s |

Number of GRBs as a function of redshift.
Satellites for GW/GRB coincidence detection

**Fermi** (2008-)
- **GBM**: keV-30 MeV; 70% sky
- **LAT**: 0.02-300 GeV; 20% sky;
  - 240 GRBs/yr (40s sGRBs)
  - >10GeV photons detected

**Swift** (late 2004-)
- **BAT**: 15-150 KeV; 10% sky
- **XRT**: arc min localisation
  - >1000 GRBs (13% sGRBs)
  - > 200 redshifts

**INTEGRAL** (2002-)
- **IBIS (Imager)**; 15keV-10MeV
- **SPI (Spectrometer)**
- **SPI-ACS (AntiCoincidence Shield)** surrounds SPI
  - 75–2000 keV; all sky > 75 keV;
  - 20 sGRBs/yr
GW170817/GRB170817A
The merger of two Neutron Stars generated 976 Australian media items: 436 radio references, 353 television clips, 87 online articles, 10 print articles, & 2906 YouTube plays.

The EM follow-up campaign was ground breaking.
GRB 170817A

what puzzled us

what do we know
GRB170817A

- **Distance:** 42.5 Mpc (2nd closest GRB – GRB980425)
- **Peak Flux:** 3.6 +/- 1.1 ph s^{-1} cm^{-2} [median 7.3 ph s^{-1} cm^{-2}]
- **Luminosity:** 1.4e47 erg/s [average 10^{52} erg s^{-1}]
- **Energy (isotropic):** 4.3x10^{46} erg
- **No early X-ray observed**
- **Spectrum:** main pulse – $E_{\text{peak}} \sim 185$ keV weak tail – softer black body (not seen in Fermi data before)
Swift early Follow-up

- Swift FoV was occulted by earth at time of fermi trigger
- After 1h XRT imaged 90% of GW skymap – no bright sources
- 12h Swope reported NGC 4993 – no XRT detection

- Delayed onset of X-ray (9 days) and Radio (15 days) strongly we were viewing from a wide angle (not an on-axis jet)

VLA ruled out a slightly off-axis jet
Luminosity (isotropic) : $1.4\times10^{47}$ erg/s

Swift data

![Graph showing luminosity vs redshift with data points for IGRBs, sGRBs, GRB170817A, and LGRBs.](image)
1. Off-axes cocoon model

Matter ejected into circum-merger medium (UVOIR evidence)

Jet drills through ejector it converts fraction of its energy to matter enveloping the jet.

Inflates forming a hot mildly relativistic ($\Gamma \sim 2-3$) expanding cocoon

**Narrow jet ($\sim 10^\circ$)** - drills out leaving $E \sim 10^{48-49}$ erg in cocoon

**Wide jet ($\sim 30^\circ$)** - choked and deposits all energy in cocoon

Both scenarios predict weak gamma ray emission over wide opening angles.

2. Structured jet

- **Top hat**: constant emission and lorentz factor across jet
- **Structured jet**: luminosity per solid angle decreases smoothly with θ outside a narrower ultra-relativistic core
- 2 popular profiles - Power law or Gaussian
Cocoon (choked jet)/structured jet scenarios can be discriminated by late observations

- indistinguishable until the peak time (~ 200-300 days)
- post-peak slopes are expected to differ – i.e. cocoon will have a shallower decay than jet models
- more about this later

Troja et al. 2018 (astro-ph:1801.06516)
New VLBI observations

Mooley, Adam Deller et al, 2018, astro-ph:1806.09693

Observations (> 150 days) suggest successful jet breakout from a cocoon (consistent with structured jet models)
Structured jets from EM constraints

Take parameters from late time EM observations and convert to prompt phase

Howell, Ackley et al. 2018 in prep
A GRB170817 model favouring the lower $\theta_v$ edge would have had to be closer than 40Mpc if viewed $\theta_v > 20$ deg.

At the other extreme (higher $\theta_v$ edge) Fermi limits cause tension.

Howell, Ackley et al 2018 in prep
Fermi detection distance to SJ model

Less extreme Lazzati 2017 cocoon-jet breakout model (dashed) consistent with low $\theta_v$ edge up to around $\theta_v = 20$

Howell, Ackley et al 2018 in prep
What about joint detection rates looking forward?

Previously – use sGRB data to determine GW (and GW-GRB) detection rates

Now we know the BNS connection, let's go the other way
BNS rate evolution model

- Star formation rate – *Madau & Dickinson (2014)*
- Delay time distribution – $P(t_d) \propto 1/t_d$; 20 Myr min
- Flat $\Lambda$ cosmology: $\Omega_M=0.31$, $\Omega_{\Lambda}=0.69$, $H_0=67.8$ km s$^{-1}$Mpc$^{-1}$ (*Planck Collab et al. 2015*)
- BNS rates – *Abbott et al, 2017*
- $1680^{+3050}_{-1310}$ Gpc$^{-3}$ yr$^{-1}$
- Assume that all BNSs can produce a sGRB

Howell, Ackley et al 2018 in prep
BNS rate evolution model

GW BNS detection rate - fold a GW detection efficiency model into a BNS source rate evolution model

Howell, Ackley et al 2018 in prep
Future BNS detection rates

O3 Observation run 2019-20
Detection range = 120 Mpc

A+ Observation run 2023-26
Detection range = 355 (z=0.08)

Howell, Ackley et al 2018 in prep
BNS rate to Fermi sGRB rate

Joint on-axis GW-BNS detection rate - fold a GRB detection efficiency model based on the assumed beaming angle, luminosity function, detector sensitivity, FoV, DC etc

Howell, Ackley et al 2018 in prep
Future joint on-axis sGRB-BNS rates

O3 Observation run 2019-20
Detection range = 120 Mpc

A+ Observation run 2023-26
Detection range = 355 (z=0.08)

Howell, Ackley et al 2018 in prep
### Projected event rates

<table>
<thead>
<tr>
<th>Epoch</th>
<th>Detection range/ Horizon</th>
<th>BNS Detection rate (yr-1)</th>
<th>BNS+sGRB On-axes / yr</th>
</tr>
</thead>
<tbody>
<tr>
<td>O3 (2019-20)</td>
<td>117 Mpc  270 Mpc</td>
<td>2-18 (7)</td>
<td>0.05-0.5 (0.3)</td>
</tr>
<tr>
<td>Design (2021-)</td>
<td>173 Mpc  413 Mpc; z~0.1</td>
<td>5-65 (23)</td>
<td>0.13-1.6 (0.6)</td>
</tr>
<tr>
<td>A+ (2023-2026)</td>
<td>354 Mpc  933 Mpc; z~0.2</td>
<td>49-622 (221)</td>
<td>0.4-4.9 (1.7)</td>
</tr>
<tr>
<td>Voyager (2.5G) 2027-2030</td>
<td>736 Mpc; z<del>0.15 2.4Gpc; z</del>0.4</td>
<td>500-6750 (2400)</td>
<td>1-13 (5)</td>
</tr>
</tbody>
</table>

- Wide angled event should increase number by few ([WTS](#))
- Fermi will be running sub-threshold pipelines
- The BNS detection range may exceed that of the GRB
- Kilonova and late EM searches for most BNS

Howell, Ackley et al 2018 in prep
Outlook for O3 & beyond (2017-18)

• Chance of first on-axes GW-sGRB at design
• Clues to X-ray plateaus, extended emissions, GeV photons
• More off-axes prompts – further constraints on cocoon/structured jet emission
• For off-axes GRB emission – joint detection may be limited by GRB instrument (not GW-IFO)
• Great opportunities for kilonova/macronova and prompt and late EM follow-ups
• Fermi low threshold searches could play an important role (triggers for LIGO)
• First BH/BNS ?
THANK YOU FROM OzGrav
EXTRA SLIDES
Multimessenger pathways and end products

<table>
<thead>
<tr>
<th>GWs</th>
<th>0s</th>
<th>1s</th>
<th>10s</th>
<th>100s</th>
<th>1000s</th>
<th>10000s</th>
<th>days</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inspiral</td>
<td>Merger/Ringdown</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gamma</td>
<td></td>
<td>GRB</td>
<td>Plateau/Afterglow</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>X-ray</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Optical/IR</td>
<td>Optical Flash</td>
<td>Afterglow</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Kilonova</td>
</tr>
<tr>
<td>Radio</td>
<td>FRB</td>
<td>FRB</td>
<td>Reverse Shock</td>
<td>Afterglow</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>


See Nikhil Sarins talk on Friday
The Low luminosity of GRB170817A
On-axes low-luminosity burst

- A dimmer LF lower limit requires a rate increase of 100.
- For consistency with the O2 BNS rate upper limit requires an average on-axis beaming angle of > 24 deg.
- sGRB Sample with observed jet breaks [3 – 8]deg.
The Low luminosity of GRB170817A
GRB observed slightly off-axis

- This scenario is disfavoured by the geometry
- Steep drop-off suggests low-probability
- Similar scenario exists when considering $E_{\text{peak}}$
VLA data rules out slightly off-axes jet

- Slightly off-axes jet requires radio AG within days
- $E_{\text{ISO}}$, $\theta_{\text{JET}}$ (25 deg), $\theta_{\text{VIEW}}$ (30 deg) fixed – Vary ISM density $n$
  - $n = 10^{-3}$ cm$^{-3}$ (low end of sGRB AG observations) – too bright
  - $n = 10^{-7}$ cm$^{-3}$ – too low (more consistent with IGM)

G. Hallinan et al., Science 10.1126/science.aap9855 (2017)
Localisation

1100 deg² => 600 deg² => 190 deg² => 31 deg²
An Ordinary Short Gamma-Ray Burst with Extraordinary Implications: 
Fermi-GBM Detection of GRB 170817A

1 Science and Technology Institute, Universities Space Research Association, Huntsville, AL 35805, USA; Adam.M.Goldstein@nasa.gov
2 Center for Space Plasma and Aeronomic Research, University of Alabama in Huntsville, 320 Sparkman Drive, Huntsville, AL 35899, USA
3 NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA
4 Space Science Department, University of Alabama in Huntsville, 320 Sparkman Drive, Huntsville, AL 35899, USA
5 Astrophysics Office, ST12, NASA/Goddard Space Flight Center, Huntsville, AL 35812, USA
6 NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA
7 Max-Planck-Institut für extraterrestrische Physik, Giessenbachstrasse 1, D-85748 Garching, Germany
8 Physics and Astronomy, Carleton College, MN 55057, USA
9 Artemis, Université Côte d’Azur, Observatoire Côte d’Azur, CNRS, CS 34229, F-06304 Nice Cedex 4, France
10 Center for Relativistic Astrophysics and School of Physics, Georgia Institute of Technology, Atlanta, GA 30332, USA
11 Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138, USA
12 Istituto Nazionale di Fisica Nucleare, Sezione di Bari, I-70126 Bari, Italy
13 Politecnico di Bari, Via Edoardo Orabona, 4, I-70126 Bari, Italy
14 Jacobs Technology, Inc., Huntsville, AL 35805, USA
15 Los Alamos National Laboratory, PO Box 1663, Los Alamos, NM 87545, USA
16 School of Physics, University College Dublin, Belfield, Stillorgan Road, Dublin 4, Ireland

Received 2017 September 18; revised 2017 September 26; accepted 2017 September 26; published 2017 October 16
GW detections looking ahead

![Graph showing GW detections looking ahead. The graph plots redshift against total source frame mass in solar masses. Different lines and shaded areas represent various detection rates (10%, 50%) for different observatories (aLIGO, ET, Voyager, CE).]
GW-GRB rates for 2018-19

<table>
<thead>
<tr>
<th>BNS Rate (Gpc-3 yr-1)</th>
<th>On-axes / yr (120 -170 Mpc)</th>
<th>Off-axes /yr (80 Mpc)</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>1000</td>
<td>0.3-0.9</td>
<td>0.3</td>
<td>0.6 – 1.2</td>
</tr>
<tr>
<td>1680</td>
<td>0.6-1.6</td>
<td>0.4</td>
<td>0.9 – 2</td>
</tr>
<tr>
<td>4730</td>
<td>1.6-4.5</td>
<td>1.0</td>
<td>2.5 – 5.5</td>
</tr>
<tr>
<td>370</td>
<td>0.13-0.35</td>
<td>0.08</td>
<td>0.2 – 0.4</td>
</tr>
</tbody>
</table>

- Assume on-axes dominates for $\theta_{\text{VIEW}} < 16$ deg
- Off-axes emission 45 deg > $\theta_{\text{VIEW}} > 16$ deg and no angular dependency on luminosity – fix $10^{47}$ erg s$^{-1}$
- Assuming off axes cocoon – detection range limited by GRB detector rather than GW detector sensitivity
OBSERVATIONS OF GAMMA-RAY BURSTS OF COSMIC ORIGIN

RAY W. KLEBESADEL, IAN B. STRONG, AND ROY A. OLSON

University of California, Los Alamos Scientific Laboratory, Los Alamos, New Mexico
Received 1973 March 16; revised 1973 April 2

ABSTRACT

Sixteen short bursts of photons in the energy range 0.2–1.5 MeV have been observed between 1969 July and 1972 July using widely separated spacecraft. Burst durations ranged from less than 0.1 s to \( \sim \)30 s, and time-integrated flux densities from \( \sim 10^{-5} \) ergs cm\(^{-2}\) to \( \sim 2 \times 10^{-4} \) ergs cm\(^{-2}\) in the energy range given. Significant time structure within bursts was observed. Directional information eliminates the Earth and Sun as sources.