Implications of GW observations for short GRBs

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What are Gamma Ray Bursts?
What are short GRBs?
Open Questions:
Central engine of sGRBs
Progenitors of sGRBs
GW diagnosis can seal the debate
Gamma Ray Bursts

- Short (a few seconds) flashes of γ-rays (~ MeV)
- Typical energy release ~ $10^{48} - 10^{52}$ ergs
- Non-repetitive, from random directions in the sky
- 1 event/day (on an average)
- Extra-galactic, Cosmological (0.0085 - $z$ - 9.4)
- Longer lasting low-frequency counterparts
Zooming into a GRB location
Relativistic jets in GRBs

Large optical depth to pair production

But non-thermal spectrum

Relativistic bulk motion

Most conclusive: VLBI image of resolved GRB jet

Fig. 23. A typical Band-function spectrum of GRB 990123. From Briggs et al. (1999).
Fireball Model

- Central engine
- Internal dissipation
- External dissipation
- Relativistic outflow
- Burst photons
- Afterglow
- Progenitor
Short GRBs

- Predominantly two classes of GRBs
- Short Hard & Long soft

$T < \sim 2s$

$T > \sim 2s$
Progenitor Types

- In the torus: 0.01 - 0.1 M☉

- Accretion ends within a few seconds (disk ends & collapses into the BH)
DCO binaries

- 8 confirmed DNS systems in our Galaxy
- Rate: 6 - 100 Myr$^{-1}$
- No NS-BH system known till now
## Duration: The iceberg’s Tip

<table>
<thead>
<tr>
<th>Long GRBs</th>
<th>Short GRBs</th>
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<tbody>
<tr>
<td>Association with supernovae</td>
<td>No confirmed SN association so far</td>
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<tr>
<td>Origin in star forming galaxies</td>
<td>Occurs in both in late &amp; early type</td>
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<tr>
<td>Close to the bright UV regions</td>
<td>Relatively larger offsets</td>
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<tr>
<td>of host</td>
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Burst Offset

- In DCO model
- The NS/BH receives a kick due to SN explosion
- Translates to binary linear momentum (Podsiadlowski+95)
- Binary wanders in the galactic potential
- Till it merges ($\tau_{gw}$)

Figure 1. HST observations of ten short GRBs with robust associations to a host galaxy $y$

$P_{cc} y < \delta_{R} \approx 65 - 9 - 65 - 8 z$ based on previous ground-based observations.

The afterglow positions are represented by a $8\sigma$ error circle in each frame except for GRBs 5, 5, 69B and 5/50651 where the afterglow positional uncertainties are larger and the circles correspond to $6\sigma$. For GRB 5, 597/B1, the position of the X-ray afterglow from Swift 4XRT is shown (red circle). For GRB 685.58B, the image after PSF subtraction of the point source associated with the GRB is shown. All images are oriented with North up and East to the left.

We measure $\sigma_{GRB}$ from each afterglow image, where the centroiding accuracy depends on the size of the PSF and the signal-to-noise ratio of the afterglow detection using SExtractor and find values of $\sigma_{GRB} \approx 65 - 65 - 65 - 65 - 65 - 65 - 65 - 65 - 65 - 65$ mas. The second source of uncertainty is the astrometric tie between the afterglow and host galaxy HST images, which is determined using the same method described in Section 7. We use a range of 0 - 675 common point sources depending on the depth of the image and source density and find values of $\sigma_{GB \rightarrow HST} \approx 75 - 75 - 75 - 75 - 75 - 75 - 75 - 75 - 75 - 75$ mas. The number of astrometric tie objects and resulting RMS values are listed in Table 7. The final source of uncertainty is the centroiding accuracy of the host in the HST images. To determine this uncertainty, we again use SExtractor and find values of $\sigma_{gal} \approx 6 - 68$ mas. This is generally the smallest source of uncertainty.

For each galaxy filter combination, we use the afterglow and host position to measure angular offsets, and for the galaxies with known redshifts, we also calculate physical offsets (Table 7). We assume $z \leq 6$ for host galaxies without known redshift, taking advantage of the relatively flat value of the angular diameter distance at $z \gtrsim 5.03$. Finally, we use the effective radii ($r_e$) determined from surface brightness profile fits (Section 7.3 and Table 8) to calculate host-normalized offsets. The offsets and accompanying combined uncertainties are listed in Table 7.

For GRBs 5, 5, 5/ and 5/50651 where we do not have the afterglow discovery images, we use the published uncertainties of 5.9′′ and 5.7′′ respectively (Perley et al, Nicuesa Guelbenzu et al), which dominate over all other sources of uncertainty.

73.3 Surface Brightness Profile Fitting

We use the IRAF ellipse routine to generate elliptical intensity isophotes and construct one-dimensional radial profiles. Also Arun, Ajith, Resmi, Misra (In preprn)
1. Delay times ($\tau_{GW} \propto a^4/\mu\text{M}^2$): span a wide range → Possible in both Spirals & Ellipticals

2. Natal kicks & delay time → high offsets
Others

Redshift distribution

- Redshift distribution
- $E_{\text{bol}} \sim (1/100)$ of SGRBs
- Systematically lower AG flux compared to IGRBs
Background

1. Distinct bimodality in GRB population ⇒ Two different progenitor classes.

2. Existence of DCO systems in our Galaxy.

3. Conjecture: DNS or NS-BH binary coalescence due to energy & angular momentum loss to GW.

4. A stellar mass BH + (short lived) Torus system ⇒ short GRB

sGRB : GW source
Important Questions

1. What are the central engines of short GRBs?
2. Are all short GRBs from binary compact object mergers?
short GRB central engine

- Should launch an
  - energetic \(10^{48}-10^{51}\) erg,
  - clean \((E/N_b >> m_p c^2)\) jet
- Be active for the burst duration

sub second duration \(\Rightarrow\) formation of prompt BH
short GRB central engine

 Should launch an
  ‣ energetic ($10^{48} - 10^{51}$ erg),
  ‣ clean ($E/N_b \gg m_p c^2$) jet
 Be active for the burst duration

Continued central engine activity

1. Extended emission
2. Flares
3. Plateau phase
1. Extended Emission

- 25% has short EE \(\sim 100\text{ s}\) (Fong + 2013)
- Energies equal to or larger (\(\sim 30\) times) than initial spike (Sakamoto+ 2011, Perley+ 2009)

Norris & Bonnell 2006
2. X-ray Flares

- Flares similar to γ-ray burst (spectral & temporal)
- SGRBs show weaker (2 orders of mag. dimmer) ones compared to LGRBs
- But similar Flare/Prompt intensity
3. Plateaus

Long GRB, swift XRT repository

typical AG slope
3. Plateaus

Figure 8 – continued
Central engine: prompt-BH

- Accretion timescale too less for EE, flares, plateaus
- For BH-NS merger, tidal disruption of NS throws matter out to highly eccentric orbits [Rosswog 2007]
- This material falls back: EE?, Flares?
Central engine: magnetar

- Highly magnetized ($10^{10}-10^{11}$ T)
- Neutron star
- Proposed to explain SGRs and AXPs in our galaxy
- Like pulsars, relativistic wind of charged particles
Central engine: magnetar

- A millisecond proto-magnetar is formed [Metzger + 2007]
  - AIC of WD
  - Merger: WD-NS
  - Merger: NS-NS
- Prompt spike: Accretion onto magnetar
- Flares: late magnetar activity (Metzger; Giannios 2006)
- EE: powered by relativistic wind from magnetar
- Plateau: powered by spin down of magnetar (Zhang & Meszaros, 2001, Rowlinson+ 2013)

Magnetar: Difficult to produce jets
Feasibility of magnetar formation after merger

DNS merger can result in an NS (Shibata+ 2006, Morrison + 2004)

- Depends on EOS, total mass of binary, rotation

Discovery of 1.97 M_{\text{sun}} NS (Demorest 2010): high mass NS are possible
GW diagnosis

Figure 1. Schematic diagram of the evolution of compact binary coalescences. The frequency of the emitted GW is indicated for the different stages.

- NS-NS inspirals are observable for a few seconds to minutes. Upon the merger of the NS system, a binary with total mass $M_{\text{binary}} \gtrsim 3M_\odot$ promptly collapses into a BH. For non-equal-mass binaries, the forming BH will be surrounded by an accretion disk. NS-NS binaries with total mass $M_{\text{NS,max}} < M_{\text{binary}} < 3M_\odot$ will form a hypermassive NS with strong differential rotation, which assumes a non-axisymmetric ellipsoid shape. The hypermassive NS survives for milliseconds to a second, eventually collapsing into a BH potentially with an accretion disk. Very low mass NS-NS binaries ($M_{\text{binary}} < M_{\text{NS,max}}$) can leave a stable NS behind.

- BH-NS binaries after an inspiral phase observable for seconds to minutes, the NS either gets tidally disrupted (if tidal disruption at radius $R_{\text{tidal}} < R_{\text{ISCO}}$) or it plunges into the BH (if $R_{\text{tidal}} \geq R_{\text{ISCO}}$). Tidal disruption results in a BH with an accretion disk, while no accretion disk forms upon plunge. This merger phase, along with the ringdown of the BH after plunge, lasts for milliseconds.

- The location and inclination of the sources is $\sim y \pi D_h / w^6 n^3 \left[ y^6 \right] s$. Using the current best guess rates of mergers, this gives tens of NS-NS and a few NS-BH binaries detected with advanced detectors each year. Additional advanced detectors, such as KAGRA or LIGO India, can significantly increase this range. Third generation detectors are expected to reach an order of magnitude farther than advanced detectors, ises to several Gpc and hence will be able to observe tens of thousands of events a year.

2.1.2. Merger phase — Depending on the binary system, the merger can progress in multiple distinct directions with qualitatively different GW and gammaray emissions.
GW diagnosis

- Detection of GW chirp signal
- Different between prompt-BH & magnetar
- “ring down” signal
- extended GW due to secular bar-mode instability

(Baiotti+ 2008)
Progenitor of sGRB

- Magnetar model $\Rightarrow$ AIC of WD can also form a sGRB

- Merger time delay distribution from theory $\Rightarrow$ fit to all sGRB data (Virgili+ 2011)
Summary

~ Short duration GRBs were conventionally believed to be DCO mergers

~ Model can explain (i) burst nature (ii) host population (iii) offset, but difficulty reproducing central engine longevity (plateau, Flares & EEs)

~ Magnetar CE proposed to explain continuous powering of CE. But has difficulties producing collimated jets

~ GW signal can conclude the debate

~ sGRB population may have massive star candidates? Again GW signal can be conclusive

~ Inclination angle measurement (Arun+ 2014) & orphan AGs
Additional slides
Magnetar-nova

~ Interaction of e+/e- wind with the merger remnants
~ Brighter than kilonova
~ Metzger 2014, Zhang 2012
Orphan AGs

- LSST
- SKA

Inclination angle measurement (Arun+ 2014): angle btn angular mom. axis and l.o.s
Central engine

- Should launch an
  - energetic \((10^{49}-10^{55} \text{ erg})\),
  - clean \((E/N_b \gg m_p c^2)\) jet
- Should be intermittent

\[
L_{\text{GRB}} = \zeta m c^2 = 1.8 \times 10^{51} \text{ erg/s} \quad \zeta \sim \frac{m}{(M_\odot \text{ s}^{-1})}
\]

\[
E_{\text{rot}} = \frac{1}{2} I \Omega^2 = 2 \times 10^{52} \text{ erg} \quad \left[ \frac{M}{1.4 M_\odot} \right] \left[ \frac{R}{10 \text{ km}} \right]^2 \left[ \frac{P}{1 \text{ ms}} \right]^{-2}
\]