Implications of GRB Source Scenarios on the Triggered GW Burst Search

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I. Introduction

In the search for gravitational wave bursts (GWBs) for the triggered case, we consider sources of GWBs which are closely connected in time to gamma-ray burst (GRB) triggers. This category of triggers is attractive for two reasons. First, the astrophysical sequence which creates the GRB is also likely to produce GWBs. Second, a GWB search confined to a short time interval near the GRB results in an improved S/N relative to an untriggered search.

In this note, we attempt to connect current astrophysical ideas for GRB/GWB sources with search parameters or waveform injection parameters.

II. Models of coincident GRBs and GWBs

We consider the following classes of potential GWB sources which also produce GRBs, according to the current literature. We will refer to these classifications throughout.

1. Collapsar model (the "standard" scenario) [1].
   These are rapidly rotating massive stars whose cores collapse to black holes. The BH formation coincides with the creation of an accretion disk. Accretion onto the newly formed BH produces a relativistic ($\gamma \sim 10^2$) fireball. The remaining stellar shell (already lacking H) is blown off, resulting in a SN-like explosion. The fireball interacts with the expanding stellar material (via internal shocks in the standard scenario), giving rise to the photon production which, when boosted to our reference frame, is the observed GRB. The large angular momentum induces asymmetries in (perhaps) both the fireball and SN, which collimates the fireball, thus producing a beamed GRB with beaming angle on order $\theta \sim 0.1$ rad. Collapsars are sometimes further categorized as follows:
2. Type I. For progenitor mass greater than about $40M_\odot$, the collapse goes directly to a BH.
3. Type II. For masses roughly $20-40M_\odot$, there is an initial collapse to a proto-neutron star. Not all stellar material is ejected in the explosion however, and after a time on the order minutes to hours, this material falls back to the core, resulting in the final collapse to a black hole. Since the second collapse is thought to have the strongest potential GW emission [2], one ignores the initial collapse for current analyses. With this choice, the type I and type II events have essentially the same GRB-GWB timing.
4. Cannonball model [3].
   The GRBs arise from ordinary core-collapse SNe. An inner shell of stellar material remains behind after the explosion. Blobs of this material fall to the newly-formed core, resulting in a pair of oppositely directed cannonballs which, after interaction with the stellar ejecta, gives the GRBs. Each infalling blob produces a peak in

observed GRB lightcurves. GRB duration corresponds to the exhaustion of the shell material. The cannonballs are highly relativistic, with $\gamma \approx 10^3$ (compared to $\sim 10^2$ for fireballs in the collapsar model). A key parameter is the viewing angle θ between the cannonball direction and viewing direction, which is typically larger than the tightly collimated cannonballs (opening angle $1/\gamma$). This is used to explain the observed ratio of GRBs to SNe events and the vagaries of total gamma ray flux, as well as afterglow characteristics.

5. GW emission from the jets themselves. [4]
   The GW strain from a relativistic burst with Lorentz boost γ and mass m is
   $$h = \left(\frac{G}{c^2}\right)\frac{4\gamma m}{d}$$
   at a distance d. So for a cannonball with $\gamma = 10^3$ and $m = 10^{25}$ kg viewed at an angle $\theta \approx 1/\gamma$ with respect to the GRB axis, the strain magnitude can be non-negligible. Now comes the funny part... This produces a so-called "burst with memory", some kind of step-function in strain. Detectability was discussed by Braginsky and Thorne [5].
   I do not claim to understand yet how this manifests itself in modern LIGO.
6. Binary mergers.[6]
   Compact mergers under study by LIGO can lead to GRBs in a scenario where the merger produces a BH with an accretion disk. In this case, a GRB would follow in analogy to the collapsar model, assuming formation of a suitable accretion disk with sufficient angular momentum. The current prejudice is that compact binary mergers correspond to the short-duration (<2s) class of GRBs. The pertinent question perhaps is whether the S/N of the standard LIGO inspiral search improves if association with a GRB trigger set to the time of BH formation is assumed. For now, we do not pursue this further.

III. Parameters and waveforms for triggered search

The triggered search technique[7] is based on the cross-correlation (CC) statistic[8], comparing "on-source" (GRB-GWB coincident) CC distributions to "off-source" (non-coincident) distributions. The two main CC parameters, which we wish to connect to astrophysical expectations are:

T, CC integration time, and
Δ, observed GWB-GRB time difference in LIGO proper frame

In addition, we wish to know as much as possible about expected waveforms. In this way we can perform signal injections for determining search efficiencies, where the injection parameters correctly characterize the corresponding astrophysical model.

1. <u>Collapsars</u>

- T and Δ

Generically, the time scale for GWBs is simultaneous with the core collapse to the BH on a dynamical time scale of order 1 ms. As stated above, a jet/fireball is produced when the accretion disk first forms, which is also said to be within a few ms of BH formation. The GRB is formed (perhaps by internal shocks) when the jet passes through the stellar material at radius r. In this scenario, Δ is dominated by the time t_1 it takes for the jet to turn into photons, which is (for $\gamma \gg 1$):

$$t_1 \approx \frac{r}{2c\gamma^2}$$

The maximum t_1 is about 0.2s (for $r = 10^{12}$ m and $\gamma = 10^3$). For a source at redshift z, then Δ is approximately

$$\Delta = (1+z)t_1$$

One might accommodate the collapsar model with the choices $\Delta = 0$ and $T < 1$ s. However, this does not take into account the possibly non-negligible Δ shown above, nor does it include longer values of T associated with GW emission mechanisms such as bar or torus instabilities (see below). Therefore, for the maximum allowed Δ a generic choice under the collapsar model is

$$\Delta = 0.2(1+z)\ \mathrm{s}$$

while the choice for T depends on the specific type of GW emission, as given below.

- Waveforms

These are very uncertain. We attempt below to classify the possibilities encountered in the literature.

a) DFM-type core collapse GWBs.
One perhaps imagines "scaled-up" versions of DFM [9] calculations. Apparently, there are preliminary calculations from Fryer [10] along these lines. But for now there is little guidance. For T, one expects at most ≈ 10 ms for ordinary core collapse. Lacking specific knowledge of how to extrapolate this to collapsar core collapse, we conservatively choose 100 ms. Thus

$$T < 0.1(1+z)\ \mathrm{s}.$$

b) Bar instabilities.
Given the large angular momentum in this model, this is plausible. It is an interesting possibility, since strains can be large. However, there is no certainty that collapsars give rise to bars, or, if they do, exactly what are their characteristics. In general, one gets a sinusoidal strain, but the number of coherent cycles is not known. For now, we can use the estimate from Fryer et al.[11] for bars from core collapse SN, for which the frequency range is estimated to be 100-1000 Hz with a number of cycles 10-100. So in this case,

$$T < 1(1+z)\ \mathrm{s}.$$

c) Core fragmentation.
In collapse, the core breaks up and the pieces can effectively orbit each other for some short time. One might crudely model this as a binary inspiral [6], resulting in a familiar chirp. But presumably the waveforms can be arbitrarily complicated.

Presumably, characteristic frequencies are similar to the previous case, as is the integration time.

d) GW emissions from BH toroid [12].
The large progenitor angular momentum drives emission from a rapidly rotating toroid orbiting the BH. Here we get large strains, with modulated sinusoidal waveforms and long coherence times. Frequency range is about 200-1200 Hz. GW signal duration is given by BH spin-down timescale, which is matched to the (long) GRB duration, thus approx 10-100 s. Therefore,

$$T < 100(1+z)\,\mathrm{s}$$

It is probably worth considering whether T should be explicitly tied to the observed GRB duration for this model.

2. Cannonball model
This is relatively straightforward, since the GWBs result from ordinary core-collapse SNe, for which we are guided by the DFM [9] waveforms. These are apparently still considered to be the best estimates on the market, or at least nothing clearly better is available.

- T and Δ

From DFM, $T \ll 1\,\mathrm{s}$, and 10 ms is reasonable. In the original cannonball papers, Δ was on order 1 day. This is being revised presently [13] to be on the order “seconds to minutes.” Reflecting this current uncertainty, we choose a range 1 to 100 s.

- Waveforms: DFM

3. GW emission from the jets/fireballs which produce the GRBs.
We need to understand this.

4. Binary mergers.
One imagines that if the binary system has sufficient mass and angular momentum, then its merger will produce a BH and accretion disk system superficially similar to that of the collapsar case. Hence, one might also expect a similar GRB production. This scenario for GWB-GRB events is discussed in Ref [6], and we use the same CC parameters as were used in this reference, which were chosen primarily to accommodate the inspiral case[2]. For a variety of astrophysical reasons, mergers are generally considered to be the leading candidates for the short-duration GRBs (<2 s). The timing of chirp signal relative to GRB would be rather well determined. [Has there been a LIGO study of whether one gets improved S/N in a triggered search using the usual matched filter technique?] In any case, we leave this to the Inspiral Group for now.

IV. Possible waveform parameterizations for injections

- DFM for core collapse waveforms. Since these waveforms are not to be taken too literally, we assume that a mixture of gaussian (G) and sine-gaussian (SG) waveforms with time-frequency characteristics similar to the DFMs can be used as legitimate surrogates, representing the underlying physics of the DFMs. The coverage of the DFM waveforms in the CC parameter space has been studied by Mohanty [14]. In the best case, the surrogate "suite" of G and SG waveforms overlap closely with those of the untriggered bursts analysis.
- Sinusoids. Presumably we can use SG waveforms, with the gaussian σ used to model the duration time or coherence time of the expected signals. Hence we characterize the sinusoidal waveforms with two parameters (other than amplitude): the central frequency f_0, and σ.
- Bursts with memory. Not yet clear how to model this.

V. Possible strategy for matching models to injections.

In the table below, we attempt to summarize the connections between various models and search or injection parameters. Note the abbreviations wf=waveform, G=Gaussian, and SG=sine-gaussian. The model identifier can be found be referring to Section III.

Model*	Δ (s)	T (s)	wf type	wf parameters range
1-a	$[0,0.2](1+z)$	$0.1(1+z)$	G and SG	The DFM suite
1-b	$[0,0.2](1+z)$	$[0.01,1](1+z)$	SG	$100 < f_0 < 1000$ Hz; $\sigma: 10-100$ cycles
1-c	$[0,0.2](1+z)$	$[0.01,1](1+z)$	chirp (SG) ?	see discussion
1-d	$[0,0.2](1+z)$	$[10,100](1+z)$ $\propto$ GRB duration	SG	$200 < f_0 < 1200$ Hz; $10 < \sigma < 100$ s
2	$[1,100]$	$0.01(1+z)$	G and SG	The DFM suite
3	$[1,100]$	~ 0.01 ?	?	see discussion
4	0 ?	$[0,10]$?	chirp	Leave to Inspiral Group ?

* refer to Section III

VI. References

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