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Joint gravitational wave - gamma-ray burst detection rates for advanced detectors and beyond

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The observational follow-up campaign of the gravitational wave (GW) multi-messenger event GW170817/GRB170817A has shown that the prompt γ-rays are consistent with a relativistic structured jet observed from a wide viewing angle. We model the structured jet profile of GRB170817A assuming a structured jet model to estimate the future joint GW/sGRB detection rates for LIGO and Virgo detectors. We show that, if the jet structured profile of GRB170817A is a relatively common feature of sGRBs, then there is a realistic probability of another off-axis coincident detection during the third aLIGO/Virgo observing run (O3). We also find that up to 4 yr^{-1} joint events may be observed during the advanced LIGO run at design sensitivity and up to 10 yr^{-1} by the upgraded advanced LIGO configuration A+. We show that the detection efficiencies for wide-angled sGRB emissions will be limited by GRB satellites as the GW detection range increases through proposed upgrades. Therefore, although the number of coincident detections will increase with GW detector sensitivity, the relative proportion of detected binary neutron stars with γ-ray counterparts will decrease; 11% for O3 down to 2% during A+.

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1. Introduction

The first gravitational wave observation of a system of coalescing binary neutron stars (BNSs) GW170817, and the coincident detection by Fermi [1] and INTEGRAL [2] of a short-duration gamma-ray burst (sGRB) within 1.7 s, firmly established that these two types of events are associated [3]. Although predictions for the association of sGRBs with the merger of NSs have existed for several decades [4], the relative close proximity of GRB170817A and the dimness of the prompt gamma-ray emission was unexpected. The luminosity of $\sim 10^{47}$ erg sec^{-1} was 2 orders of magnitude below the generally accepted lower limits on the sGRB luminosity function and several orders of magnitude below the average luminosity for sGRBs [5].

A resolution was provided by monitoring in the radio [6], optical [7] and X-ray bands [8] which suggested Fermi/INTEGRAL detected the prompt emission from a wide-angle ($\theta_j \sim 20°$– $30°$), which would be significantly weaker than one viewed along the jet axis. Long baseline interferometric (VLBI) observations of GW170817/GRB170817A showed super-luminal motion, demonstrating that a successful jet core with an opening angle of $< 5°$was launched and that the early emissions were from a successful structured jet viewed $\sim 20°$from the jet axis [9].

2. The structured jets profile of GRB170817A

In a recent paper [10] we executed a MCMC analysis to determine the posteriors of the model parameters for a Gaussian structured jet profile for GRB170817A taking the form [11]:

$$L(\theta_{\rm V}) = L_{\rm c} \exp\left(-\frac{\theta_{\rm V}^2}{2\theta_{\rm c}^2}\right) , \tag{2.1}$$

with $L(\theta)$ the luminosity per unit solid angle, $\theta_{\rm V}$ the viewing angle and $L_{\rm c}$ and $\theta_{\rm c}$ structure parameters that define the angular profile.

Using a likelihood function based on the observed luminosity we used a uniform flat prior distribution for $\theta_{\rm c}$ in the range 1-9°and a Gaussian distribution around $\theta_{\rm v} = 20 \pm 5°$ based on the observations of [9]. For the prior on $L_{\rm c}$, we use the fact that the maximum detection distance of GRB170817A is relatively local in comparison with known cosmological GRB redshifts. Therefore, it is a reasonable assumption that the majority of sGRBs have been observed at small viewing angles close to the jet core. A reasonable prior is therefore a lognormal distribution with a mean observed sGRB isotropic equivalent luminosity $< L_{\rm ISO} > \approx 2 \times 10^{52}$erg sec^{-1} [5]. We found a structured jet profile defined by parameters $L_{\rm c} = 1.0 \pm 0.3 \times 10^{52}/\Omega$ erg s^{-1} sr^{-1}, $\theta_{\rm c} = 4.7 \pm 1.1°(0.08 \pm 0.02$ rad) and a viewing angle of $\theta_{\rm v} = 21.2 \pm 4.9°(0.37 \pm 0.09$ rad).

3. Joint GW/sGRB detection rates

To produce joint GW/sGRB detection rates we assumed that all BNSs can produce a sGRB and based our modeling using the LIGO/Virgo rates of 1540^{+3200}_{-1220} Gpc^{-3} yr^{-1}yr^{-1} determined from the O2 observation run [12]. To convert from intrinsic BNS rates to detection rates we folded in GW and sGRB detection efficiency functions to produce the fraction of sources detected by the instrument with increasing source redshift. For a sGRB detection efficiency function we assumed Fermi-GBM and used well cited parameters for the sGRB LF [5], folding in the geometric dependence based on our model parameters of a structured jet. For the GW detection efficiency functions we used the framework of [13] for a range of aLIGO sensitivities and proposed upgrades.

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O2 † (2016-17)	O3 (2019-20)	aLIGO 2021-	A+ ‡ 2024-	Voyager ‡ 2030-
$0.8^{+1.7}_{-0.6}$	$5.3^{+11.1}_{-4.2}$	$17.9^{+37.2}_{-14.2}$	$128.2^{+266.3}_{-101.5}$	$1822.5^{+3787.1}_{-1443.8}$

Table 1: LIGO BNS rates calculated assuming a 50% double coincidence duty cycle. †- 9 month estimate ‡best estimated observing schedule.

O2 † (2016-17)	O3 (2019-20)	aLIGO 2021-	A+ ‡ 2024-	Voyager ‡ 2030-
$0.14^{+0.30}_{-0.11}$	$0.58^{+1.21}_{-0.46}$	$1.23^{+2.55}_{-0.97}$	$3.10^{+6.45}_{-2.46}$	$7.53^{+15.66}_{-5.97}$
-	11%	7%	2%	0.4%

Table 2: Joint sGRB/GW rates calculated assuming a double coincidence 50% duty cycle for two aLIGO type detectors and a Fermi-GBM instrument with a 60% duty cycle. The bottom row shows the percentage of BNS detections that are detected with a sGRB; we see that the fraction decreases with GW detector sensitivity. †= 9 month estimate; ‡= best estimated observing schedule.

Table 1 shows the derived BNS detection rates. To verify of our modelling, we found that our derived BNS detection rate were consistent with a single detection in O2. Furthermore, applying the sGRB detection efficiency curve to the intrinsic BNS source rate model we found a median Fermi-GBM detection rate of 38.74, compatible with the expected rate of 39.8 sGRBs/yr detected by Fermi-GBM since 2008.

Our estimates of the joint GW/sGRB detection rates are shown in Table 2. The range of our joint rates for the 2019-20 observing run (O3) are 0.1 - 1.8 detections per year and around 0.3–4 per year at design sensitivity. Our modelling suggests that 70% of Fermi-GBM detections are from sGRBs viewed within a half opening angle of 10°, most likely from sources $z \gtrsim 0.4$. Thus, such observations will require more sensitive GW detectors; we find that around 1-4 such joint observations could be achieved during A+ and up to 10 during Voyager.

We find that the fraction of coincident GW/sGRB events will decrease as the sensitivity of GW detectors increase; our results in Table 2 show that the joint detection percentage of BNS will be 11% during O3, decreasing to less than 1% by the time of the Voyager aLIGO upgrade. This projection is due to emissions further from the jet-axis being increasingly more difficult to detect by Fermi-GBM at greater distances.

For the remainder of the era of advanced GW interferometers, joint GW/sGRB detections will most likely be from sGRBs observed at wide-viewing angles. At the increased GW detection ranges of planned or proposed detector upgrades, flux-limited GRB detectors will be unable to detect the wider angled emissions; sGRB detections will start to be dominated by emissions closer to the jet axis. This pattern will continue into the era of 3G interferometers such as ET and Cosmic Explorer. Thus, consideration of the sensitivity of potential GRB/X-ray instruments that will be available in the future (e.g.THESEUS;[14]) will become increasingly important for studies of GRBs.

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