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WIDE ANGLE X-RAY SKY MONITORING FOR CORROBORATING NON-ELECTROMAGNETIC COSMIC TRANSIENTS

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ABSTRACT

Gravitational waves (GWs) can be emitted from coalescing neutron star (NS) and black hole–neutron star binaries, which are thought to be the sources of short hard gamma-ray bursts (SHBs). The gamma-ray fireballs seem to be beamed into a small solid angle and therefore only a fraction of detectable GW events are expected to be observationally coincident with SHBs. Similarly, ultrahigh energy neutrino signals associated with gamma-ray bursts could fail to be corroborated by prompt γ-ray emission if the latter is beamed into a narrower cone than the neutrinos. Alternative ways to corroborate non-electromagnetic signals from coalescing NSs are therefore all the more desirable. It is noted here that the extended X-ray tails (XRTs) of SHBs are similar to X-ray flashes (XRFs), and that both can be attributed to an off-axis line of sight and thus span a larger solid angle than the hard emission. It is proposed that a higher fraction of detectable GW events may be coincident with XRF/XRT than with hard γ-rays, thereby enhancing the possibility of detecting it as a GW or neutrino source. Scattered γ-rays, which may subtend a much larger solid angle than the primary gamma-ray jet, are also candidates for corroborating non-electromagnetic signals.

Key words: X-rays: bursts – gamma-ray burst: general

1. INTRODUCTION

Short hard γ-ray bursts (SHBs) are now suspected to be caused by the merging of two compact objects, such as neutron stars (NSs) or black holes (BHs), which would release large amounts of energy over short time intervals (e.g., Goodman 1986). Collapse of a single object has also been proposed to give rise to a similar situation (Berezinsky & Prilutsky 1987). Eichler et al. (1989) suggested that gamma-ray bursts (GRBs) could be observed in coincidence with gravitational wave (GW) signals when two NSs merged.

The huge isotropic equivalent energy requirements implied by the BATSE observations of GRB isotropy and submaximal $V/V_{\rm max}$ suggested that GRBs might be highly collimated (e.g., Levinson & Eichler 1993), and this would make them a bad bet to corroborate GW signals from such mergers, as gravitational radiation is unlikely to be strongly collimated. This might be fatal (e.g., Guetta & Stella 2009) to the original proposal that LIGO signals would be coincident with GRBs. It is now accepted that GRBs are indeed highly collimated. Alternative ways to confirm LIGO signals from coalescing NSs (and, according some suggestions (van Putten 1999a, 1999b), unstable collapsing disks) are therefore all the more desirable.

The horizons of first generation LIGO and Virgo for NS–NS and BH–NS mergers are ∼20 and 43 Mpc, respectively, while advanced LIGO/Virgo should detect them out to a distance of ∼300 and 650 Mpc (for a review see Cutler & Thorne 2002). GW signals from NS–NS mergers are expected at a rate of one in 10–150 years with Virgo and LIGO and one every 1–15 days with advanced LIGO/Virgo class interferometers (Berezinsky et al. 2002, 2007). The BH–NS and BH–BH merger rates in the Galaxy are highly uncertain. Berezinsky et al. (2007) estimate 1% and 0.1% of the NS–NS merger rate, respectively, implying that BH–NS and BH–BH mergers contribute marginally to the GW event rate, despite the greater distance out to which they can be detected.

Ultrahigh energy (UHE) neutrinos may come from nearby supernova (SN) even if an associated GRB is shaded from our view or entirely smothered by the envelope of the host star (Eichler & Levinson 1999). A fluence F of 10^{-4} erg cm^{-2} in muon neutrinos at 10^{12} eV $\leqslant E_\nu \leqslant 10^{14}$ eV yields roughly a single neutrino detection in a gigaton detector such as ICECUBE, the exact expectation value depending somewhat upon the energy. A UHE neutrino signal from a nearby SN or SN/GRB could therefore be detectable at a distance of $D \sim 10^2 E_{{\rm iso},\nu,50}^{1/2}$ Mpc. Note that $E_{\rm iso}$ for γ-rays can be as high as 10^{54} erg ($E_{{\rm iso},\gamma,50} = 10^4$). We face the following interesting possibility: if the UHE neutrinos from GRB are beamed into a wider beam than the γ-rays, then even if the neutrino efficiency is high, the value of $E_{{\rm iso},\nu}$ may be too low to be seen from any given burst unless it is close. More importantly, most UHE neutrino events from GRB sources would not coincide with observed GRBs, as the latter would be most likely beamed away from us. For corroborating UHE neutrino signals, as is the case for GW corroboration, we seek electromagnetic signals that have broader angular reach than the primary γ-rays, even at the expense of $E_{\rm iso}$.

We note that several wide-angle manifestations of nearby GRBs have been proposed. Eichler & Levinson (1999) have suggested both high-energy neutrino signals and scattered photons (i.e. scattered off material moving at Lorentz factor less than the intrinsic opening angle of the primary emission; see also Eichler & Manis 2007), each of which could corroborate LIGO events, at large viewing offsets. Levinson et al. (2002) have suggested orphan afterglows, though there might be some problem establishing uniqueness via coincidence because of their long timescales.

As it happens, evidence for a high degree of collimation is more convincing for the long GRBs, while SHBs are the ones now believed to be associated with mergers. SHBs frequently show a lower $E_{\rm iso}$, a somewhat broader $V/V_{\rm max}$ distribution, and less evidence of a narrow opening angle from jet breaks. This could be understood, for example, if the giant envelope in the case of long bursts provides better collimation than when it is absent.

The presence or absence of the envelope may be responsible for other differences between short and long GRBs. For example, it may be that there is intrinsic spread in the timescales of the central engines accretion timescale, and that only long bursts are sustained enough to break through a massive envelope, whereas mergers, perhaps for different reasons, also produce a spread in timescales while allowing all of them to be observed, though this would explain neither spectral differences nor differences in spectral lags and sub-pulse timescales between short and long GRBs. Neither would by itself explain why the short duration, hard emission of short GRB lie off to one side of the Amati relation, while long bursts, X-ray flashes (XRFs), and the X-ray tails (XRTs) of short GRB obey it.

Eichler & Manis (2007, 2008) and Eichler et al. (2009, EGM) noted that the unusually hard spectrum displayed by SHBs, their unusually soft XRT (as compared to the emission of long GRBs), and their short duration were consistent with a smaller Lorentz factor at the time the short, hard emission is last scattered, and a larger viewing angle. The larger viewing angle is, a priori, statistically expected if the line of sight is not obscured by an extended stellar envelope which is known to exist in the case of long GRBs, and which would be less likely in the case of NS–NS mergers. Less collimation and larger allowed viewing offset angle make a coincidence with a GW signal more likely. While larger viewing angle and/or less collimation means smaller $E_{\rm iso}$ and therefore less $V_{\rm max}$, that is not a problem for LIGO collaboration, where the sources would in any case be very close.[3]

Admittedly, the typical viewing angle for SHBs, though perhaps larger than for long GRBs, is uncertain and could be small compared to unity. There exists by now some evidence that SHBs are beamed, like long GRBs, into a modest solid angle. Fox et al. (2005) interpreted the steepening of the optical afterglow light curve of GRB 050709 and GRB 050724 in terms of a jet break that translates into a beaming factor $f_b^{-1} \sim 50$, with f_b being the fraction of the 4π solid angle within which the GRB is emitted. Soderberg et al. (2006) found a beaming factor of ∼130 for GRB 051221A. Therefore, with the present data the beaming angles of SHB seem to lie in the range of ∼0.1–0.2 radian.

The discovery that XRFs are a class of long GRBs was made by the Wide Field Camera (WFC) on *BeppoSAX* (Heise et al. 2001). The XRFs are GRBs characterized by no or faint signal in the γ-ray energy range, isotropically distributed in the sky and have an average duration of ∼100 s like long GRBs. There is strong evidence that classical GRBs and XRFs are closely related phenomena, and understanding what makes them differ could yield important insights into their origin. The redshift distribution of XRFs is very similar to normal GRBs and therefore the high redshift hypothesis, which might otherwise justify the softness of the burst, cannot account for all XRFs. D'Alessio et al. (2006) have concluded that the off-axis hypothesis seems to be the best hypothesis for now.

[3] The suggestion of Eichler & Manis (2007, 2008) and EGM that viewing angle affects the perceived durations both of the SHBs hard emission and XRT is compatible with an additional intrinsic spread in durations of central engine activity for mergers (van Putten 1999b). The long duration of GRB 060614 can be attributed to the prolonged activity of a rotating BH (van Putten 2008). The hypothesis of EGM can also accommodate events such as GRB 060614, which was of long duration while resembling SHBs in other respects. Also, an XRT that lasts 10^2 s in observer time can result from a SHB whose intrinsic duration is only 1 s. In this paper, however, we are concerned only with the angular spread of the XRT, not the intrinsic duration of the central engine activity that causes it, and consider the possibility that the XRTs of SHBs may have broader angular spreads and encompass more observers than the short, hard emission.

Many SHBs show a bright XRT that follows the short prompt γ-ray emission and lasts for ∼100 s (e.g., Nakar 2007). This X-ray component is evident in SHBs 050709 and 050724, where the X-ray energy is comparable to or even larger than the energy in the prompt γ-rays. It seems that XRTs, though not detected in all SHBs, are rather common among them. Extrapolation of the late afterglow back to early times suggests that these tails cannot be interpreted as the onset of the afterglow emission (Nakar 2007). These XRTs have spectra and durations that are similar to those of the known XRFs, and may be both can be attributed to an off-axis line of sight. In this case, they could encompass more observers than the hard emission of the SHB, and could thus be more opportune for corroborating non-electromagnetic manifestations of mergers and/or core collapses. EGM made rough estimates of order 0.1–0.2 radian offset from the periphery of the primary fireball, but with large uncertainties.

In this paper, we consider the possibility that a wider opening angle of XRTs, relative to the hard SHB emission, enhances their likelihood of corroborating non-electromagnetic signals from merger and collapse events. In Section 2, we report all the properties of the XRTs. In Section 3, we present a method to determine the XRFs rate. In Section 4, we compare this rate with the XRT rate and discuss our results.

2. X-RAY TAIL PROPERTIES

We have considered all the short bursts detected by *Swift* from its launch (2004 November) until 2009 August. This constitutes a sample of ∼40 bursts of which ∼25 have reported X-ray detection at 100 s after the trigger. In Table 1, we report the observed data for these 25 GRBs. We report the properties of SHB prompt and XRT emission as detected by the *Swift* X-ray telescope and *HETE-2*. The X-ray flux is estimated at 60–100 s after the burst and is given in the 0.3–10 keV energy range. In the last column, we also report what the X-ray flux would be if the SHBs were at a distance of LIGO (advanced version) detectability (300 Mpc if SHBs come from NS–NS mergers).

In order to give an estimate of the GW events expected from XRFs, XRTs, and SHBs, their cosmic event rates per unit volume and their beaming factors must be known. Measuring the relative detection rates and distribution of distances of each of the categories of events reduces the number of parameters. The universal central engine hypothesis discussed in EGM, in its simplest and most naive form, together with the offset viewing hypothesis for XRFs posit that SHBs and long GRBs have the same energetics and that they present XRTs to offset observers the same way long GRBs display XRFs to such observers.

3. THE RATE PER UNIT VOLUME OF XRFs IN THE LOCAL UNIVERSE

A burst is classified as an XRF when the softness ratio (SR) of the fluences in the 2–30 KeV band to the 30–400 KeV band is greater than unity (Lamb & Graziani 2003).

In this section, we give a method to estimate the rate of XRFs (by which we mean rate per unit volume) following Pelangeon et al. (2008). This method is valid both for the WFC that works in the 2–28 keV energy range and for WXM on *HETE-2* that works in a similar energy range. Moreover, the sensitivity of the WFC $\sim 4 \times 10^{-9}$ erg cm^{-2} s^{-1} (De Pasquale et al. 2006) is comparable to that of WXM $\sim 9 \times 10^{-9}$ erg cm^{-2} s^{-1} (Ricker et al. 2002).

In order to estimate the rate of XRFs, we need to know the redshift of the sources; therefore, we select only the XRFs that

Table 1
Properties of SHBs Prompt and Afterglow Emission as Detected by *Swift* X-ray Telescope and *HETE-2*

GRB	z	S_γ (10^{-7} erg cm^{-2})	$E_{\gamma,\rm iso}$ (10^{49} erg)	F_x (10^{-11} erg cm^{-2} s^{-1})	$E_{x,\rm iso}$ (10^{49} erg)	F_x (@ 300 Mpc) (10^{-11} erg cm^{-2} s^{-1})
050709*+	0.16	3 ± 0.38	1.4	800	3.9	3.9×10^3
050724+	0.258	6.3 ± 1	7.2	1200	14.6	1.4×10^4
051210+		1.9± 0.3		90		
051221+	0.546	22.2 ± 0.8	84	20	0.9	923
060313 +		32.1 ± 1.4		30		
071227+	0.383	2.2 ± 0.3	4.0	46	1.1	1.1×10^3
050509B	0.225	0.23 ± 0.09	0.2	0.06	5.6×10^{-4}	0. 55
050813	0.7	1.24 ± 0.46	5.2	0.6	0.042	42
050906		0.84 ± 0.46		<0.007		
050925		0.92 ± 0.18		<0.003		
060502B	0.287	1 ± 0.13	1.15	0.1	0.001	1.4
060801		0.8 ± 0.1		0.1		
061201	0.11	3.3 ± 0.3	0.7	10	0.02	23
061217	0.827	0.46 ± 0.08	2.4	0.1	0.005	9.1
070429B	0.904	0.63 ± 0.1	3.5	0.11	0.006	10.4
070724	0.45	0.3 ± 0.2	0.6	0.05	0.0012	1.7
070729	0.904	1.0 ± 0.2	5.6	0.024	0.001	2.5
070809		1.0		0.179		
071112B		0.48		<0.02		
080426		3.7 ± 0.3		0.91		
080702A		0.36 ± 0.1		1.0		
080905A		1.4 ± 0.2		31		
081226A		0.99 ± 0.18		0.047		
090305A		0.75 ± 0.13		0.55		
090426	2.6	1.8 ± 0.3	71	1.2	0.48	470
090621B		0.7 ± 0.1		0.045		

Notes. *HETE-2* has been indicated by the "*," and the "+" sign indicates possible detection by the WFC. The X-ray flux is estimated at 60–100 s after the burst and is given in the 0.3–10 keV energy range. In the last column, we report what the X-ray flux would be if the SHBs were at a distance of LIGO (advanced version) detectability (300 Mpc if SHBs come from NS–NS mergers).

Table 2
Properties of the XRFs Detected by WXM on *HETE-2*

XRF	T_{90} (s)	S (10^{-7} erg cm^{-2})	z
011130	39.5	5.9	0.5
020317	7.14	2.2	2.11
020903	10	0.8	0.25
030429	12.95	4.7	2.68
030528	62.8	62	0.782
040701	11.67	5.44	0.214

Notes. S is the fluence in 2–25 keV

have determined redshift. These are only the XRFs detected by the WXM, as no XRF of the WFC has a known redshift. Our sample contains six long bursts, and we report the relevant information about these bursts in Table 2.

The steps to compute the rate are as follows.

1. To determine the maximum redshift $z_{\rm max}$ at which the source, an XRF, could have been detected by the instruments, by first comparing the measured flux with the threshold flux of the instrument for an XRF with known distance (z): $F_x/F_T = (D_{\rm max}(z_{\rm max})/D(z))^2$.
2. To assume that the GRB rate follows the star formation rate. For this, we have adopted the model SFR$_2$ of Porciani & Madau (2001) that reproduces a fast evolution between $z=0$ and $z=1$ and remains constant beyond $z \geqslant 2$:

$$R_{\rm SFR_2}(z) \propto 0.15 h_{65} \frac{\exp(3.4z)}{\exp(3.4z)+22}. \quad (1)$$

3. To derive for each burst the number of GRBs per year within its visibility volume:

$$N_{\rm Vmax} \propto \int_0^{z_{\rm max}} dz \frac{dV(z)}{dz} \frac{R_{\rm SFR_2}(z)}{1+z}. \quad (2)$$

In this equation, $dV(z)/dz$ is the commoving element volume, described by

$$\frac{dV(z)}{dz} = \frac{c}{H_0(1+z)^2} \frac{4\pi\, dl^2(z)}{[\Omega_M(1+z)^3 + \Omega_K(1+z)^2 + \Omega_\Lambda]^{1/2}}, \quad (3)$$

where H_0 is the Hubble constant, Ω_K is the curvature contribution to the present density parameter ($\Omega_K = 1 - \Omega_M - \Omega_\Lambda$), Ω_M is the matter density, and Ω_Λ is the vacuum density. Throughout this paper, we have assumed a flat ΛCDM universe where (H_0, Ω_M, Ω_Λ) = ($65\, h_{65}$ km s^{-1} Mpc^{-1}, 0.3, 0.7).

This procedure allows us to give each burst a weight (W_b) inversely proportional to $N_{\rm Vmax}$. The rationale of weighting each burst by $1/N_{\rm Vmax}$ is that the visibility volume is different for each XRF of our sample. Moreover, each XRF observed is randomly taken from all the bursters present in its visibility volume. In this way, rare bright XRFs, having a large visibility volume, will have low weights, while faint local XRFs will have higher weights. This procedure also takes into account the fact that the XRF rate evolves with redshift, leading to the fact that XRFs are about 10 times more frequent at $z \sim 1$ than at present.

This study also allows us to derive the rate of XRFs detected and localized by *HETE-2* ($R_0^{\rm H2}$). For this purpose, we consider that each XRF in our sample contributes to the local rate in proportion to

$$h_b = \frac{N_{\rm Vloc}(z = 0.1)}{N_{\rm Vmax}(z = z_{b,\rm max})} \quad (4)$$

with $N_V(z)$ being computed according to Equation (2), and we obtain the number per unit volume of *HETE-2* GRBs during the mission,

$$\tau = \frac{1}{V_{\rm loc}} \sum_{b=1}^{n_{\rm burst}} h_b, \quad (5)$$

the value of which we calculated to be 7.7 $\rm Gpc^{-3}$, similar to what found by Pelangeon et al. (2008).

In order to normalize this in terms of the rate per year, we took into account the effective monitoring time of the WXM, obtained from

$$T_m = \frac{T_{\rm mission} \times T_\epsilon}{4\pi} \times S_{\rm cov}, \quad (6)$$

where T_m is the effective monitoring time of the WXM, $T_{\rm mission} = 69$ months is the duration of the mission, $T_\epsilon = 37\%$ is the mean observation efficiency during $T_{\rm mission}$, and $S_{\rm cov} = 2\pi(1 - \cos 45^\circ) = 1.84$ sr is the sky coverage of the WXM.[4]

The effective monitoring time of the WXM is hence $T_m = 0.31$ yr. Using this, the rate of detectable XRFs in the Local Universe per $\rm Gpc^3$ and per year can be found to be $\sim$25 $\rm Gpc^{-3}\ yr^{-1}$. This result is a lower limit because *HETE-2* missed the bursts with intrinsic peak energy E_p lower than 1 or 2 keV as well as bursts occurring at very high redshifts (Pelangeon et al. 2008).

Note that the main contribution to the rate comes from XRF 020903, which has a maximum detectability redshift $z_{\rm max} \sim 0.3$, implying a small visibility volume and therefore a large weight.

3.1. *Swift* XRFs

Because the *Swift* Burst Array Telescope (BAT) instrument, which provides the trigger conditions, has an energy band (15–150 keV) narrower than WXM+Fregate on *HETE-2*, we have to find another way to define an XRF. Sakamoto et al. (2008) define an XRF to be a burst with the ratio of the fluence in the 25–50 KeV band to that in the 50–100 KeV band greater than 1.32, and we use this definition to construct a sample of XRF with redshift. The relevant properties are given in Table 3.

In order to estimate the rate of XRFs from the *Swift* data, we can repeat the analysis described above taking the threshold of *Swift* in 15–150 keV of $\sim$0.25 ph $\rm cm^{-2}\ s^{-1}$ (Band 2006). We then consider 4.5 years of activity with a sky coverage of 0.17 sr and find a rate of $R \sim 130\ \rm Gpc^{-3}\ yr^{-1}$. Note again that the main contribution to the rate comes from XRF 060218, which has a maximum redshift $z_{\rm max} \sim 0.03$ implying a small visibility volume and therefore a large weight. This rate determined by XRF 060218 is similar to what found in Guetta & Della Valle (2007). The soft γ-rays of XRF 060218, which show a spectral evolution similar to many other GRBs and subpulses therein, may be photons scattered off relatively slow ambient material (Mandal & Eichler 2010).

Comparing this rate and the rate found with the XRFs of the WXM with the rate found by Guetta et al. (2005) and Guetta & Piran (2007) for long GRBs, $\sim$0.1–0.4 $\rm Gpc^{-3}\ yr^{-1}$, we infer that the population of γ-ray bursts is dominated by the XRFs at $z < 0.1$. This is understandable, as XRFs are soft but also faint in the observer frame, according to the hardness–intensity relation derived by Barraud et al. (2003). Therefore, if the rate of detected bursts is in fact higher for classical GRBs than for XRFs, we can guess that this is because the classical GRBs can be seen out to greater distances.

Table 3
Properties of the XRFs Detected by *Swift*

XRF	T_{90} (s)	S (10^{-7} erg $\rm cm^{-2}$)	z	F (ph $\rm cm^{-2}\ s^{-1}$)
050315	95.6	32.2	1.949	1.93
050319	152	13.10	3.24	1.52
050406	6.4	0.79	2.44	0.36
050416	3.0	3.7	0.6535	4.88
050824	26.6	2.7	0.83	0.5
051016	4.0	1.7	0.9364	1.3
060108	14.3	3.69	2.08	0.77
060218	2100	15.7	0.033	0.25
060512	9.7	2.3	0.44	0.88

Note. S is the fluence in 15–150 keV and F is the 1 s peak photon flux.

The fact that XRFs have a much higher rate per unit volume than classical GRBs, within the framework of our hypothesis that they are the same phenomenon viewed from different angles, suggests that the opening angle of XRF is significantly wider than that of the GRB. Significantly, the SN-associated GRB and XRF event rates are much larger not only than the classical GRB rate (Guetta & Della Valle 2007) but also than the estimated rate of NS merging. The main contribution to the SN-associated GRB event rate comes from GRB 980425 at $z = 0.0085$. This burst was detected by the *BeppoSAX* WFC (Pian et al. 1999) and BATSE (Kippen 1998). The peak flux in the 50–300 keV band was $F_{50-300} = 4.48$ ph $\rm cm^{-2}\ s^{-1}$. Given the threshold of BATSE, $\sim$0.25 ph $\rm cm^{-2}\ s^{-1}$, we find that $D_{\rm max} = 160$ Mpc. The *BeppoSAX* sky coverage was about 0.08 and the operation time $\sim$4 years. Therefore, the rate of 980425-like events is $R \sim 182\ \rm Gpc^{-3}\ yr^{-1}$ which is $\sim$10 times higher than the XRFs rate and more than 100 times higher than the high luminous "classical" GRB rate. This high rate suggests that if classical GRB emits GW, e.g., from an unstable protocollapsar tori (van Putten 1999a, 1999b), then combined signals from wide angle electromagnetic emission and GW might be the most common sort of electromagnetic plus non-electromagnetic multi-detections of mergers/collapses.

4. RATE OF XRTs AND DISCUSSION

The rate of XRFs is an upper limit to the rate of XRTs. For the lower limit, we can take one of the SHBs derived by Guetta & Stella (2009). In this paper, they find evidence in favor of a bimodal origin of SHB progenitors where a fraction of SHBs come from the merging of primordial NS–NS (BH), and a fraction come from the merging of dynamically formed binaries in galaxy clusters. In particular, they find that the redshift distribution of SHBs is best fitted when the incidences of primordial and dynamical mergers among the SHB population are 40% and 60%, respectively. In this case, the rate of SHB is $R_0 \sim 2.9\ \rm Gpc^{-3}\ yr^{-1}$.

For a fiducial value of $f_b^{-1} \sim 100$, we derive a beaming-corrected rate of $\rho_0 = f_b^{-1} R_0 \sim 290(f_b^{-1}/100)$. Therefore, the rate of XRTs is $2.9\ \rm Gpc^{-3}\ yr^{-1} < R < 130\ Gpc^{-3}\ yr^{-1}$. This

[4] Recall that throughout this study, we only consider the XRF localized by the WXM.

rate is left uncorrected for the beaming, as we do not know the beaming angle of this X-ray emission which can be the same or larger than the beaming angle of the γ-ray emission.

Another way to estimate the rate of the XRTs is to consider the XRTs detected by the *Swift* X-ray telescope that could be detected by the WFC if they were at a distance of 300 Mpc. These are four GRBs—GRB 050709, GRB 050724, GRB 051221, and GRB 071227. Considering the threshold of the detector that triggered them (Fregate for 050709 and BAT for the other three bursts) and using the same procedure described above for the XRFs rate, we find a rate of $\sim$7 Gpc^{-3} yr^{-1}.

Our suggestion that some XRTs of SHBs are XRFs, combined with the hypothesis that they correspond to offset viewing of a long burst in some other direction (Eichler et al. 2009), predicts that a large enough sample of XRFs, even if unbiased by any γ-ray trigger, should have a subset that correlates with SHBs. A careful analysis, however, shows that BATSE should have detected less than one SHB coincident with any XRF recorded by other contemporaneous detectors. A larger sample of XRFs detected while a SHB detector is operating would give tighter constraints.

In summary, we have considered the possibility that SHBs have larger opening angles than long GRBs, and that the XRT associated with the SHB has a wider angular extent than the harder emission. Very rough estimate of the opening angle of XRTs, based on their hypothesized similar to XRFs, is an opening angle of 0.1–0.2 radians (EGM), which may be somewhat larger than estimates of the opening angles for the hard emission, which are typically 0.03–0.1 radians (Bloom et al. 2003). While this does not constitute proof that the XRTs have larger opening angles than the hard γ-ray emission from the SHBs, the fact that extended soft emission is a reliable indicator for SHBs (Donaghy et al. 2006) suggests that the solid angle in which the soft photons are detectable by *HETE-2* is at least as large as that from which the hard γ-beam is detectable. On the other hand, our estimate for the rate per unit volume of XRTs that would be visible from the typical distance of an advanced LIGO source, $\sim$300 Mpc, is less than the estimated rate of NS mergers, which leaves open the possibility that even the XRTs are beamed and could not corroborate most LIGO signals. Further information on the relative detectabilities of XRTs and the corresponding short hard γ-ray emission could be obtained by a wide field X-ray camera and γ-ray detectors working together.

In any case, the rate of WFC-detectable XRTs per sphere of radius $300R_{300}$ Mpc is at least about $0.8R_{300}^3$ per year, meaning that a 2π detector would detect one per 2.5 years for $R_{300} = 1$. This is a non-negligible, if modest, fraction of the total expected rate of LIGO signals from mergers: about 3 per year with advanced LIGO. Including the other two WFC-detectable XRTs, though their redshift is unknown, would raise the estimate to about $1 \times R_{300}^3$ per year. This suggests that some fraction of LIGO signals, if not most or all, could be corroborated by wide field X-ray cameras.

Coincidentally, this rate of 1 per several years is about the rate of SN-associated GRB within 300 Mpc, as estimated from the prototypes GRBs 980425 and 060218, which could be looked for in coincidence with UHE neutrinos. We also find the event rate per unit volume for SN-associated GRBs and XRFs to be about 10^2 higher than for cosmologically distant GRBs. If GWs and/or neutrinos are emitted by such events, then nearby SN-associated GRBs, corroborated by wide angle electromagnetic emission such as XRFs or scattered γ-rays, may be the most frequent collapse events observed simultaneously in both electromagnetic and non-electromagnetic modes.

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