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Short gamma-ray bursts from SGR giant flares and neutron star mergers: two populations are better than one

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ABSTRACT

There is increasing evidence of a local population of short duration Gamma-ray Bursts (sGRB), but it remains to be seen whether this is a separate population to higher redshift bursts. Here we choose plausible Luminosity Functions (LF) for both neutron star binary mergers and giant flares from Soft Gamma Repeaters (magnetars, SGR), and combined with theoretical and observed Galactic intrinsic rates we examine whether a single population alone of progenitors can reproduce both the overall BATSE sGRB number counts and a local population, or whether a dual progenitor population is required. In addition we compare the predicted redshift distribution from our best fit models with the sGRB redshift distribution from the *Swift* era. We find that only a bimodal population consisting of lower and higher luminosity populations can reproduce both the overall BATSE sGRB number counts and a local population, as well as being consistent with *Swift* redshifts. Furthermore, the best fit luminosity parameters agree well with the known properties of SGR giant flares and classic short GRBs.

Key words: Gamma-ray Burst, magnetar, SGR

1 INTRODUCTION

Results from the Burst and Transient Source Experiment (BATSE) onboard the *Compton Gamma-Ray Observatory* showed that Gamma-ray Bursts (GRBs) divide observationally into two classes based primarily on their duration (Kouveliotou et al. 1993): long GRBs have durations $>$ 2 seconds, and short GRBs $\leqslant$ 2 seconds. Short GRBs (sGRBs) seem to be associated with a variety of host galaxies with no apparent restriction on galactic properties (Prochaska et al. 2006; Berger 2007; Levan et al. 2007b), although host identification is not always trivial (Levan et al. 2007a). Additionally, a handful of recently detected sGRBs have localisations consistent with origins in nearby galaxies (Ofek et al. 2006, 2007a; Frederiks et al. 2007; Mazets et al. 2007; Levan et al. 2007b). Overall, the *Swift* redshift distribution of sGRBs (Berger 2007) peaks closer than that of long GRBs (Jakobsson et al. 2006), though there is evidence that some sGRBs may occur at higher redshifts (Levan et al. 2006a), and that there may be a local population of underluminous long GRBs (Chapman et al. 2007).

The leading progenitor model for sGRBs is the merger of two compact objects, neutron star-neutron star (NS-NS) or neutron star-black hole (Nakar 2007) binaries. The Luminosity Function (LF) of BATSE sGRBs has been investigated previously assuming a single progenitor population (e.g. Guetta & Piran (2005, 2006); Schmidt (2001)) in order to determine the intrinsic rate and most likely LF parameters. In a refinement to this work, Guetta & Piran (2006) noted that a second population of bursts may be necessary to explain some features of their model fits and the comparison with *Swift* bursts, particularly at lower redshifts. Salvaterra et al. (2007) again considered only NS-NS mergers but found that the *Swift* cumulative redshift distribution could be better encompassed by considering two formation routes (still of the same binary merger progenitors) with different time delays and hence different abundances above and below $z \sim 0.3$.

However there are other possible progenitors for sGRBs as well. At much lower redshifts still, the initial spike in a giant flare from a Soft Gamma Repeater (SGR) in a relatively nearby galaxy would also appear

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as a sGRB. For example, the December 27th 2004 event from SGR1806-20 would have been visible by BATSE out to ≈ 50 Mpc (Hurley et al. 2005; Palmer et al. 2005; Taylor & Granot 2006; Nakar 2007). Thus it is entirely plausible that some fraction of sGRBs are extragalactic SGR giant flares.

Previously we demonstrated that between 10 and 25 per cent of BATSE sGRBs were correlated on the sky with galaxies within ≈ 113 Mpc (Tanvir et al. 2005), and we have now extended this work out to ≈ 155 Mpc. Can this nearby population ($z \leqslant 0.03$) be produced by a suitable LF describing a single progenitor population, or is it necessary to include an intrinsically lower luminosity population as well?

Here we attempt to answer this question by considering first single, and then dual population LFs. The intrinsic rates in the models will be assumed from both the observed Galactic SGR flare rates and the modelled NS-NS merger rates in order to investigate the LF parameters. Obviously there are significant uncertainties in these rates: the Galactic giant flare rate in particular is estimated from only 3 observed events. Regardless of these uncertainties and the exact form of luminosity functions chosen, we find that a single progenitor population described by a unimodal (i.e. with a single peak or knee) LF cannot produce sufficient local events, whereas a dual population reproduces the likely local sGRB distribution as well as the overall number counts[1].

2 METHODS

The number of sGRBs, N, observed above a threshold p in time T and solid angle Ω is given by Equation 1, where $\Phi(L)$ is the sGRB LF, $R_{GRB}(z)$ is the comoving event rate density at redshift z, $dV(z)/dz$ is the comoving volume element at z and z_{max} for a burst of luminosity L is determined by the detector flux threshold and the luminosity distance of the event.

$$N(>p) = \frac{\Omega T}{4\pi} \int_{L_{min}}^{L_{max}} \Phi(L) dl \int_0^{z_{max}} \frac{R_{GRB}(z)}{1+z} \frac{dV(z)}{dz} dz \tag{1}$$

We are of course dealing with detector limited and not bolometric luminosities. Following Schmidt (2001) and Guetta & Piran (2005) we assume a constant median spectral index of -1.1 in the BATSE energy range of 50-300 keV to derive a simplified K correction and conversion to photon flux.

2.1 Intrinsic rates

The sGRB rate per unit volume, $R_{\mathrm{GRB}(z)}$ is given by Equation 2 where N_{GRB} is the number of sGRBs per progenitor, $\rho_{\mathrm{progenitor}}$ is the intrinsic ($z = 0$) progenitor formation rate and $F(z)$ describes the volume evolution of this rate with z.

[1] Throughout this paper we assume a flat cosmology with $H_0 = 71$km s^{-1} Mpc^{-1}, $\Omega_M = 0.27$ and $\Omega_\Lambda = 0.73$

$$R_{\mathrm{GRB}}(z) = N_{\mathrm{GRB}} \times \rho_{\mathrm{progenitor}} \times F(z) \ \mathrm{Mpc}^{-3} \tag{2}$$

For NS-NS mergers, a burst is produced only once at merger, and $N_{\mathrm{GRB}} = 1$. The intrinsic NS-NS merger rate is taken as 10^{-5} yr^{-1} per Milky Way equivalent galaxy (Star Formation Rate, SFR $\approx 4\mathrm{M}_\odot$ yr^{-1}, e.g. Diehl et al. (2006)) from the population synthesis models of Kalogera et al. (2007). Mergers, of course, occur some time after the formation of the binary itself. Thus the merger rate at redshift z, is dependent not on the SFR at the same z, but on the earlier SFR at higher redshift. $F(z)$ is therefore given by the convolution of the SFR as a function of redshift with a distribution of delay times from binary formation to merger. The population syntheses of Belczynski et al. (2006) suggest a relatively flat distribution (with respect to $\log(t)$) of delay times between 10^7 and 10^{10} years, with a narrow peak at the very lowest times. The orbital properties of the Galactic binaries (as listed for example in Champion et al. (2004)) seem consistent with this model, and thus we assume a delay time probability distribution constant between $\log(10^7)$ and $\log(10^{10})$ years and zero outside this range.

SFR as a function of z is parameterized according to the SF2 model of Porciani & Madau (2001), normalised to a local SFR of 1.3×10^{-2} $\mathrm{M}_\odot \mathrm{yr}^{-1} \mathrm{Mpc}^{-3}$ (Gallego et al. 1995) as given in Equation 3.

$$\mathrm{SFR}(z) = 1.3 \times 10^{-2} \left(\frac{23e^{3.4z}}{e^{3.4z} + 22} \right) \mathrm{M}_\odot \ \mathrm{yr}^{-1} \ \mathrm{Mpc}^{-3} \tag{3}$$

An alternative analysis is that the merger rate should be proportional to Stellar Mass Density (SMD), which must be representative of star formation history. We therefore also investigate merger rates which follow a simple single exponential fit to the SMD out to $z \sim 5$ derived from the FORS deep field (Drory et al. 2005) as:

$$\mathrm{SMD}(z) = 10^{8.75} \exp(-\ln(2)z) \ \mathrm{M}_\odot \ \mathrm{Mpc}^{-3} \tag{4}$$

Over the last 30 years of observations, there have been 3 giant flares from 4 known SGRs in the Milky Way and Magellanic Clouds. The observed local rate of giant flares per Galactic SGR is therefore $\approx 3 \times 10^{-2}$ yr^{-1}, and their short active lifetimes of $\sim 10^4$ years (Duncan & Thompson 1992; Kouveliotou et al. 1998; Kouveliotou 1999) imply $N_{\mathrm{GRB}} \sim 300$ in the SGR case. Magnetars are commonly believed to form in a fraction of core collapse supernovae, and hence their formation should follow the SFR as a function of z. Given the the association of the 4 known SGRs with young stellar populations, this therefore implies a formation rate via core collapse supernovae of 4×10^{-4} yr^{-1}.

However, it is also plausible that magnetars may form via the Accretion Induced Collapse (AIC) of White Dwarf (WD) binaries which contain at least one sufficiently massive and magnetized member (Levan et al. 2006b). In older galaxies with relatively little star formation, this would be the dominant formation route and therefore makes it possible for SGRs to be associated with all types of galaxies, not just those with a relatively high

SFR. Following Levan et al. (2006b), the rate of magnetar formation via WD-WD mergers in a Milky Way equivalent galaxy is estimated as 3×10^{-4} yr^{-1}. We therefore assume $F(z)$ for SGRs follows both SFR(z) for magnetar production from supernovae and either the delayed SFR or SMD to allow for production by WD binary mergers.

2.2 Luminosity functions

Luminosity functions for SGR giant flares and NS-NS mergers are not well known. A log-normal LF approximates the shape of the theoretical NS-NS merger luminosity distribution (Rosswog & Ramirez-Ruiz 2003), but other functional forms may be equally valid: for example Guetta & Piran (2005) assumed a broken power law for their LF calculations, and the luminosities of many other astronomical populations are well described by a Schechter function (Schechter 1976).

Given only 3 events, it is not possible to constrain the SGR giant flare LF to any great degree. The more common short duration bursts from SGRs, with luminosities up to 10^{41} erg s^{-1} seem to follow a power law distribution in energy, $dN \propto E^{-\gamma}dE$ where $\gamma \sim 1.4-1.8$ (Cheng et al. 1996; Göğüş et al. 2000) similar to that found in earthquakes and solar flares. Intermediate bursts with energies and luminosities between the short bursts and giant flares are also seen, and it is possible therefore that this distribution continues to higher energies and includes the giant flares themselves, particularly since Göğüş et al. (2000) found no evidence for a high energy cutoff in their work. However, Cheng et al. (1996) did find evidence of a cutoff around 5×10^{41} erg, and furthermore the intermediate bursts are generally seen following giant flares and may be some form of aftershock rather than representing part of a continuous spectrum of flare activity. Theory suggests that the common bursts are produced by the release of magnetic energy gated by a small scale fracturing of the crust sufficient only to relieve crustal stresses, whereas the giant flares are the result of large scale cracking sufficient to allow external field reconfiguration to a new equilibrium state (Thompson & Duncan 1993, 1995). Assuming the latter is a physically distinct process discontinuous (in terms of energy release) from the short bursts, then it must have some minimum energy release, and a maximum defined by the total destruction of the external field via the Flowers-Ruderman instability (Flowers & Ruderman 1977) where entire hemispheres of the magnetar flip with respect to each other (Eichler 2002). Having only the 3 observed events to go on, a lognormal LF is once again plausible for giant flare luminosities. The possibility of a continuous luminosity distribution between the short, intermediate and giant flares is not ruled out however, and we therefore also consider a single power law LF as well.

To summarise, we consider the possibility that short GRBs may be produced via two different progenitor routes, both NS-NS mergers and SGR giant flares, each population with intrinsically different luminosities. The forms chosen for the luminosity functions examined are as follows:

1. Lognormal distribution

$$\frac{dN}{d\log L} \propto \exp\left(\frac{-(\log L - \log L_0)^2}{2\sigma^2}\right) \qquad (5)$$

2. Schechter function

$$\frac{dN}{dL} \propto \left(\frac{L}{L_0}\right)^{\alpha} \exp\left(-L/L_0\right)\ ,\ L \geqslant L_{min} \qquad (6)$$

3. Power Law

$$\frac{dN}{dL} \propto \left(\frac{L}{L_0}\right)^{\alpha}\ ,\ L_{min} \leqslant L \leqslant L_0 \qquad (7)$$

where $L_{min} = 10^{44}$ erg s^{-1} for normalisation and convergence; L_0, and α or σ are the free parameters to be estimated.

2.3 Constraining the models

The C_{max}/C_{min} table from the current BATSE catalogue (Paciesas et al. 1999) provides peak count rate for bursts in units of the threshold count rate. Not all bursts are included and in addition the BATSE threshold was varied historically. Therefore in order to analyse a consistent set of bursts we restricted the table to only those sGRBs recorded when the 64ms timescale threshold was set to 5.5σ above background in at least 2 detectors in the $50-300$ keV range. The all sky equivalent period (including correction for BATSE's sky coverage) this represents is estimated as ~ 1.8 years.

We then examined the differential distributions of predicted overall counts from both single and (various) combined populations of burst progenitor. By varying the parameters of the chosen luminosity functions, we compared the predicted overall counts $N(>p)$ to the C_{max}/C_{min} distribution. For each set of LF parameters, the redshift distribution of predicted sGRBs was calculated, and the nearby distributions compared with the observed correlated distributions from Tanvir et al. (2005) (extended here to 155 Mpc). χ^2 minimization (assuming all deviations from the model predictions to be Poisson based) was then used to optimise the LF parameters by simultaneously considering the fits to both overall count rate and the local distribution.

In order to check the plausibility and consistency of the best fit models, we further compare the derived redshift distribution with that of sGRBs observed by *Swift*. We caution that this *Swift* sample is neither uniformly selected nor complete. For example, redshifts have so far only been found from host galaxies, the identification of which is not always unambiguous. Furthermore, even the classification of some bursts as either short or long is controversial since their durations change substantially depending on whether or not emission from the long-soft tails (seen in a number of bursts) is included. However, ~ 10 probable short-hard bursts have reasonably secure redshifts, with which we compare our predicted distributions. Specifically we include GRBs 050509B, 050724, 051221a, 060801, 061006, 061201, 061210, 061217 (see Berger (2007) and references therein), 070714B (Graham et al. 2007) and

Merger LF	Parameters ($l_0 \equiv \log L_0$)	Flare LF	Parameters ($l_0 \equiv \log L_0$)	χ^2 (dof)
Lognorm	$l_0 = 48.2$	Lognorm	$l_0 = 45.1$	36.2
(SMD)	$\sigma = 1.1$	(SMD)	$\sigma = 0.7$	(24)
Schechter	$l_0 = 51.75$	Lognorm	$l_0 = 44.5$	37.2
	$\alpha = 1.3$		$\sigma = 0.8$	(24)
Lognorm	$l_0 = 47.1$	Lognorm	$l_0 = 44.3$	46.6
	$\sigma = 1.2$		$\sigma = 0.9$	(24)
Schechter	$l_0 = 51.75$	Power law	$l_0 = 47.5$	55.2
	$\alpha = 1.3$		$\alpha = 1.55$	(24)
Lognorm	$l_0 = 47.5$	Power law	$l_0 = 47.4$	61.4
	$\sigma = 1.05$		$\alpha = 1.55$	(24)
Lognorm	$l_0 = 46.4$	-	-	275.4
	$\sigma = 1.4$			(22)
Schechter	$l_0 = 51.75$	-	-	276.3
	$\alpha = 1.4$			(22)

Table 1. Results of single and various combination dual population LFs, ordered by decreasing goodness of fit (i.e. increasing χ^2/dof). l_0 is in units of log(erg s^{-1}), σ in dex and α is dimensionless.

071227 (D'Avanzo et al. 2007). In order to produce the predicted *Swift* redshift distribution, the Swift BAT threshold for sGRBs was assumed to be twice that of BATSE (Band 2006).

3 RESULTS

Table 1 lists the best fit parameters found from fitting LFs to the data as described above. The table is ordered in decreasing goodness of fit (i.e. increasing χ^2/dof), and it can readily be seen that neither of the single population progenitor models is a good fit to the data when tested against both overall number counts and the local population (indeed, a local population is not reproduced at all). If we remove the local population constraint from the χ^2 fitting procedure and constrain the single LFs against overall number counts alone, then broad single merger progenitor populations fit the BATSE data well, but do not reproduce the local population or a redshift distribution which is consistent with the *Swift* distribution. Figure 1 shows an example of the distributions obtained from a single Schechter function LF merger population.

The best-fit two progenitor model as defined by minimum χ^2 is the dual log-normal LF, with merger rates following the SMD model of Equation 4. Figure 2 (upper panel) shows the comparison of this model to the local sGRB redshift distribution determined by our BATSE cross-correlation analysis. Since these data were used to constrain the fit, a good agreement is to be expected, but it is still interesting to note that the merger population contributes only a small fraction to these local bursts. The lower panel of Figure 2 shows the comparison of the model prediction to the *Swift* redshift distribution. These data were not used in the fit, and the agreement is surprisingly good. All dual populations reproduce the local population well, and all dual populations including a log-normal merger LF are reasonable matches with the *Swift* redshift distribution. However, when the merger LF is described by a Schechter function the models consistently

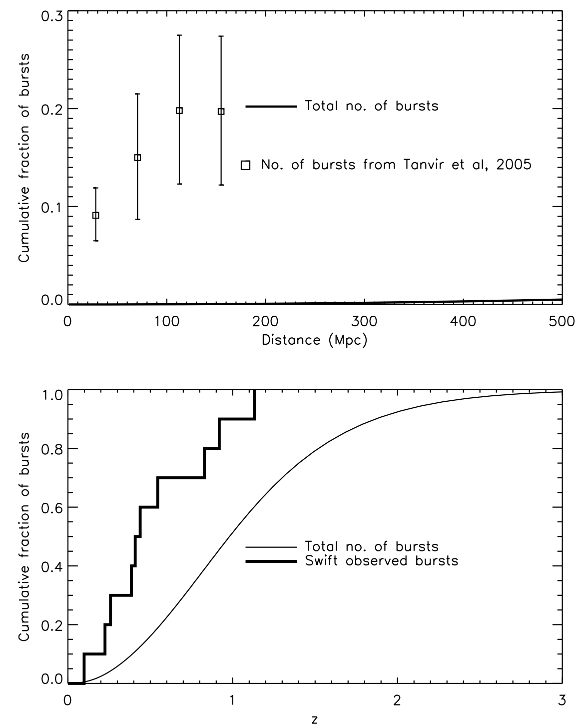

Figure 1. Burst distributions from the best fit binary merger single population Schechter function LF (upper panel shows local distribution, lower panel cumulative fraction out to $z = 3$). Though this produces a good fit to the overall number counts ($\chi^2/dof = 30.1/22$), it can produce neither any local sGRBs nor is it consistent with the *Swift* redshift distribution.

overpredict the high end of the *Swift* redshift distribution in a similar, though less pronounced, way to the single populations.

Figure 3 shows the best fit LFs and associated contours of χ^2 with respect to L_0 for the dual population from Figure 2. Despite the uncertainties in the underlying Galactic rates of the models, the best fit parameters obtained for this and the other dual LFs are plausible given the known properties of SGR giant flares and classic sGRB luminosities. It is also interesting to note that the slopes of the SGR flare power law LFs obtained (1.55 in both cases) are entirely consistent with the slopes found for ordinary SGR burst fluence distributions (1.4 - 1.8) (Cheng et al. 1996; Göğüş et al. 2000).

4 DISCUSSION

Figure 2 raises two issues worth remarking on. Firstly, it suggests that a combined (local) flare and (cosmological) merger population is sufficient to reproduce adequately the *Swift* z-distribution without the need for further cosmological populations as suggested, for example, in Salvaterra et al. (2007). Secondly, the lower panel implies Swift should have triggered on about one SGR flare to date (this would rise by a factor of ~ 2 if the redshift completeness for such flares were greater than for sGRBs as a whole, as is likely given that low-redshift

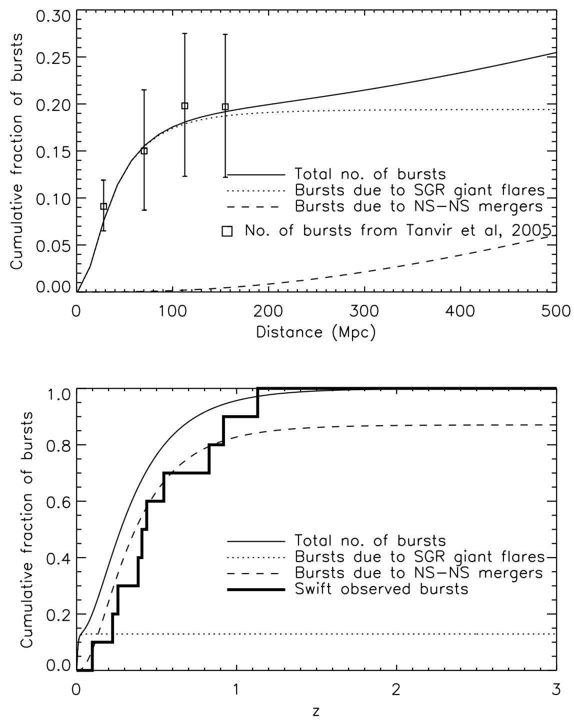

Figure 2. Burst distributions from the overall best fit dual population Luminosity Functions. Top panel shows predicted sGRB distribution within 500 Mpc compared to the local burst fraction measured in Tanvir et al. (2005). The bottom panel shows the predicted burst distribution out to $z = 3$ normalised and compared to the *Swift* distribution discussed in the text.

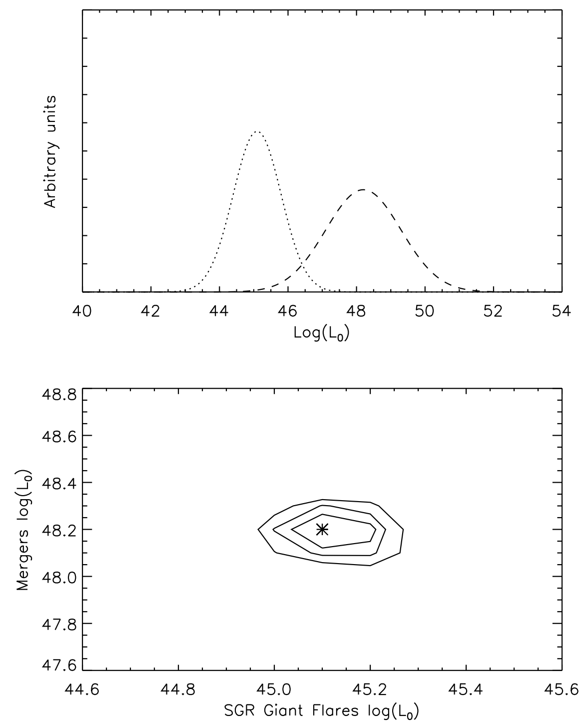

Figure 3. Overall best fit dual population LFs from Figure 2. The LFs (top panel: dotted line SGR giant flares, dashed line mergers) are lognormal with intrinsic merger rate components following the SMD model of Equation 4. The bottom panel shows contours of χ^2 in $\log(L_0)$ space. Contours shown represent 0.6, 0.9 and 0.99 confidence limits with the minimum χ^2 value plotted as an asterisk.

host galaxies are easily identified). We note that a possible candidate is GRB 050906, which may have originated in a galaxy at ≈ 130 Mpc (Levan et al. 2007b).

There are two recent sGRB events which are candidate extragalactic SGR flares: GRB 051103 whose IPN error box includes the outskirts of M81 at 3.5 Mpc (Golenetskii et al. 2005), and GRB 070201 whose error box similarly overlaps a spiral arm of M31 at only $\sim$ 0.77 Mpc (Perley 2007; Pal'Shin 2007; Mazets et al. 2007). Both have characteristics of SGR giant flares (Frederiks et al. 2007; Mazets et al. 2007; Ofek et al. 2007b), and furthermore the non-detection of gravitational waves by LIGO from GRB 070201 (LIGO Scientific Collaboration 2007) excludes a merger progenitor within M31 with $> 99\%$ confidence. If both these events were due to extragalactic SGRs then this brings to three the number of giant flares with peak luminosity $> 10^{47}$erg s^{-1} seen in just a few years.

Levan et al. (2007b) estimated that a Galactic SGR giant flare rate of $\sim 0.5 \times 10^{-4}$ yr^{-1} would be sufficient to produce ~ 10 extragalactic flares within a sphere of radius 100 Mpc. Using a power law LF (constrained by a search for positional coincidences between galaxies within 20 Mpc and the IPN error boxes of a sample of 47 sGRBs), Ofek (2007) estimated the rate of extragalactic flares with energy $> 3.7 \times 10^{46}$erg (the energy of the 2004 SGR1806-20 event (Hurley et al. 2005)) to be $\sim 0.5 \times 10^{-4}$ yr^{-1} per SGR, and the 95% confidence lower limit of the Galactic rate to be 2×10^{-4} yr^{-1}. Our analysis estimates the rate of flares with peak luminosity $> 10^{47}$ erg s^{-1} to be between these two values at $\sim 1 \times 10^{-4}$ yr^{-1}. We estimate the SFR of galaxies within 5 Mpc listed by Ofek (2007) (with revised distance estimates (Karachentsev et al. 2004)) to be about $22\times$ that of the Milky Way. Adopting our predicted flare rate, the probability of observing two (one) such flares within this volume during the 17 years of IPN3 observation is 0.6% (10%). This indicates we have been witness to a rather rare coincidence, and is perhaps suggestive that not both GRB 051103 and GRB 070201 are SGR flares.

5 SUMMARY AND CONCLUSIONS

We have examined a selection of plausible Luminosity Functions, singly and in combination, for both neutron star mergers and SGR giant flares as progenitors of short Gamma-ray Bursts. Assuming observed and theoretical Galactic intrinsic rates, merger delay time distributions, Star Formation Rate and Stellar Mass Density parameterisations, we exclude both lognormal and Schechter type LFs for a single NS merger population of progenitor. Indeed, given that even a Schechter function (dominated by low luminosity events) cannot reproduce the likely local population, it is hard to conceive of any unimodal LF which could and still be consistent with the higher redshift distribution. We suggest that at least a bimodal LF, and therefore likely a dual population model, is necessary. Given the uncertainties in the intrinsic rates assumed, we cannot sensibly choose between the LF combinations, but we point out that the best fit LF parameters in all dual populations considered are in reasonable agreement with the known properties of SGR giant flares and classic sGRBs. Furthermore, all dual populations (except those where the merger population is described by a Schechter function) produce a redshift distribution in reasonable agreement with that of sGRBs in the *Swift* era.

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