THE REDSHIFT DISTRIBUTION OF SHORT GAMMA-RAY BURSTS FROM DYNAMICALLY FORMED NEUTRON STAR BINARIES

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ABSTRACT

Short-hard γ-ray bursts (SHBs) may arise from gravitational-wave (GW) driven mergers of double neutron star (DNS) systems. DNSs may be “primordial” or can form dynamically by binary exchange interactions in globular clusters during core collapse. For primordial binaries, the time delay between formation and merger is expected to be short, \( t \sim 0.1 \) Gyr, implying that the redshift distribution of merger events should follow that of star formation. We point out here that for dynamically formed DNSs, the time delay between star formation and merger is dominated by the cluster core-collapse time, rather than by the GW inspiraling time, yielding delays comparable to the Hubble time. We derive the redshift distribution of merger events of dynamically formed DNSs and find it to differ significantly from that typically expected for primordial binaries. The observed redshift distribution of SHBs favors dynamical formation, although a primordial origin cannot be ruled out, because of possible detection biases. Future redshift observations of SHBs may allow us to determine whether they are dominated by primordial or dynamically formed DNSs.

Subject headings: binaries: general — gamma rays: bursts — gravitational waves — stars: neutron

Online material: color figures

1. INTRODUCTION

Observations of γ-ray bursts (GRBs) indicate that they divide into two classes (Kouveliotou et al. 1993). GRBs of one class are of relatively long duration (\( \approx 2–200 \) s) and have softer spectra. Long-soft GRBs occur in star-forming galaxies with high redshift z (van Paradijs et al. 1997), and their association in several cases with Type Ic supernovae (Galama et al. 1998; Stanek et al. 2003; Hjorth et al. 2003; Malesani et al. 2004; Campana et al. 2006) suggests that they are the result of core-collapse supernova explosions of massive stars (Woosley 1993; Paczyński 1998, MacFadyen & Woosley 1999). The second class of GRBs have short duration \( \sim 2 \) s and harder spectra. Afterglows of short-hard GRBs (SHBs) have only recently been observed (e.g., Gehrels et al. 2005; Berger et al. 2005; Fox et al. 2005; Bloom et al. 2006), and this has led to the first identifications of SHB host galaxies. In contrast to long GRBs, SHBs were found to occur, in at least some cases, in elliptical galaxies with very low star formation rates (SFRs), on the order of \( \approx 0.1 M_\odot \) yr\(^{-1}\). It is therefore unlikely that the progenitors of SHBs are also massive stars, since these have very short lifetimes (about a few million years).

The gravitational-wave (GW) driven merger of a double neutron star (DNS) may lead to an SHB (Goodman 1986; Paczyński 1986; Eichler et al. 1989; Narayan et al. 1992). If the time lag \( t \) between DNS formation and the merger is large (comparable to a Hubble time), it forms a natural explanation for the light distribution of such dynamically formed systems (GPZM06). The delay time for dynamically formed DNSs is expected to be very high. The delay time for primordial DNSs is considerably smaller, or less certain, due to the uncertainty in the mass of the remnants and the remnant mass function.

2. DISTRIBUTION OF MERGER TIMES

The delay time \( t \) is a sum of the time \( t_{\text{cc}} \) until the dynamical formation of a DNS during core collapse and the time \( t_{\text{GW}} \) until the DNS merges. Here we determine the resulting delay function \( dp/dt_{\text{GW}} \), of dynamically formed DNSs. GPZM06 performed scattering experiments with scatter3 and sigma3 in the Starlab environment (Portegies Zwart et al. 2001) to determine the cross section for the formation of NS binaries when an NS interacts with an NS-MS binary. We
use the orbital parameters of the resulting binaries to determine the resulting DF of GW merger times \( dp_{GW}/dt_{GW} \), which was found to be well fitted by \( dp_{GW}/dt_{GW} \sim t_{GW}^{-1} \). Typical merger times \( t_{GW} \) are very short compared with the Hubble time.

The DNS formation rate per GC can be estimated as \( \Gamma \approx (4 \text{ Gyr}^{-1}) n_{v} v \), where \( n = 10^{7} n_{v} \) is the number density of NS stars, \( v = 10 \text{ km s}^{-1} \) is the velocity dispersion, and \( N_{v} \) is the number of progenitor binaries containing one NS (GPZM06). Since \( \Gamma \approx n \), DNSs form when the GC is very dense, that is, during the CC phase. The delay between the formation of the GC and the SHB is the sum of the delay time \( t_{GW} \) and the time \( t_{cc} \) between formation of the GC and CC.

For the DF of CC times, we make the following assumptions: the CC times of the GCs in our Galaxy are representative for the whole universe; the relation between \( t_{cc} \) and the half-mass relaxation time is a function only of concentration and is well approximated by the relation given by Quinlan (1996); and the formation rate of GCs is proportional to the total SFR. We (conservatively) neglect repeated phases of CC (“gravothermal oscillations”; Sugimoto & Bettwieser 1983; Makino 1996), which would lead to even lower redshifts.

We use the half-mass relaxation times given by Harris (1996) to find the cumulative DF, \( P_{cc}(t_{cc}) \), for GCs with CC times smaller than \( t_{cc} \). The time \( t_{cc} \) for a GC between formation and CC is somewhat uncertain. Results in the literature for single-mass systems without binaries are in approximate agreement (e.g., Quinlan 1996; Joshi et al. 2001; Baumgardt 2001). A spectrum of masses can significantly decrease the CC times by the GC luminosity. Since the GW inspiral time DF diverges toward small times, \( (dp/d\tau)_{GW} \) is mostly determined by the DF of CC times. It is also shown in Figure 2 that the delay time DF \( (dp/d\tau)_{dyn} \) is not modified significantly by choosing a \( t_{cc} \) smaller than that of Figure 1 by a factor of 10. This demonstrates the robustness of the conclusion that for dynamical DNSs, the delay times are comparable to the Hubble time.

In contrast to the delay function for primordial DNSs, we find that the delay function of dynamically formed DNSs grows with the delay time. For delay times shorter than 10 Gyr, the average delay time is \( \bar{\tau} \approx 6 \text{ Gyr} \).

3. REDSHIFT DISTRIBUTION

We derive the predicted \( z \)-DF of SHBs, which depends on the event rate of SHBs as a function of \( z \), the luminosity DF of SHBs, the delay function, and the detection threshold.

3.1. The Intrinsic Redshift Distribution

For DNS mergers, the intrinsic (as opposed to observed) SHB rate is given by the convolution of the star formation rate SFR(z) with the distribution \( dp/(d\tau) \) of time delays,

\[
N_{\text{obs}}(z) \propto \int_{z}^{\infty} dz' \frac{dt}{dz'} \frac{dp}{d\tau} [\tau(z) - \tau(z')] \tag{2}
\]

(e.g., Guetta & Piran 2005 [hereafter GP05], 2006; Nakar et al. 2005); \( \tau(z) \) is the age of the universe as function of \( z \). We employ the SF2 model of Porciani & Madau (2001).

\[
\text{SFR}_{\text{RM}}(z) \propto \frac{23 e^{14z}[\Omega_M(1+z)^3 + \Omega_\Lambda(1+z)^2 + \Omega_\Lambda]^{1/2}}{(e^{14z} + 22)(1+z)^{3/2}}, \tag{3}
\]

and the Rowan-Robinson (1999) SFR,

\[
\text{SFR}_{\text{RR}}(z) \propto \begin{cases} 10^{0.75z}, & \text{if } z < 1, \\ 10^{0.35}, & \text{if } z \geq 1. \end{cases} \tag{4}
\]
In Figure 3, we show the intrinsic SHB $z$-DF $N(z)$ for $(dp/dt)_{\text{prim}} \propto 1/\tau$ (as possibly appropriate for primordial DNSs; Bloom et al. 1999; Belczynski et al. 2006) and for $(dp/dt)_\text{dyn} = (dp/dt)_{\text{prim}}$ (eq. [1]).

3.2. The SHB Luminosity Function

For the observed $z$-DF, the DF of peak luminosities and the minimal observable flux $P_{\text{min}}$ are required. Here we follow the procedure outlined in Guetta et al. (2005). We consider a broken power law peak luminosity function (LF) with lower and upper limits $1/\Delta_1$ and $\Delta_2$, respectively:

$$\Phi_2(L) \, d\log L = C_0 \, d\log L \times \left(\frac{L}{L'}\right)^{-\alpha} \left(\frac{L'}{\Delta_1}\right)^{-\beta} \left(\frac{L'}{\Delta_2}\right)^{\beta},$$

where $C_0$ is a normalization constant. This is the “isotropic equivalent” LF; that is, it does not include a correction factor due to beaming. Following Schmidt (2001), we approximate the effective spectral index in the observed range of 20 to 50 keV to 300 keV as $-1.1$ ($N(E) \propto E^{-1.1}$), and we use $\Delta_1 = 30$ and $\Delta_2 = 10$ (GP05). Both values are chosen such that even if there are bursts less luminous than $L'/\Delta_1$, or more luminous than $\Delta_2 L'$, they will be only very few (less than about 1%) of the observed bursts outside the range ($L'/\Delta_1, \Delta_2 L'$).

$$N_{\text{obs}}(z) = \frac{N_{\text{int}}(z) \, dV(z)}{1 + z} \int_{z_{\text{min}}(P_{\text{lim}})}^{z_{\text{max}}(P_{\text{lim}})} \Phi_2(L) \, d\log L,$$

where $L_{\text{max}} = \Delta_1 L' = 100 L'$ and $L_{\text{min}}$ is the luminosity at $z$ corresponding to the minimum peak flux $P_{\text{lim}}$ required for detection. We estimate that $P_{\text{lim}}$ for Swift is similar to that for BATSE, $P_{\text{lim}} \sim 1$ photons cm$^{-2}$ s$^{-1}$, based on the observations that the detection rate of GRBs by Swift ($\sim 100$ yr$^{-1}$) is similar to that of BATSE (taking into account the different fields of view and the fact that BATSE was triggering only one-third of the time) and that the fraction of SHBs is similar for both BATSE and Swift. Figure 4 shows a comparison between the observed and expected integrated $z$-DF of SHBs for the different models listed in Table 1. Our model for dynamical DNS

### Table 1

| Model   | $L^*$ (10$^{51}$ ergs s$^{-1}$) | $P_{\text{lim}}$ (photons cm$^{-2}$ s$^{-1}$) | K-S Test* (with $z = 0.7$) | K-S Test* (no $z = 0.7$) |
|---------|-------------------------------|---------------------------------|--------------------------|--------------------------|
| SF2, 1$\tau$  | 2                             | 1                              | 0.05                      | 0.01                      |
| RR, 1$\tau$   | 1.5                           | 1                              | 0.09                      | 0.03                      |
| SF2, $(dp/dt)_{\text{dyn}}$ | 0.3                           | 1                              | 0.7                       | 0.8                       |
| SF2, 1$\tau$  | 2                             | 2.5                            | 0.15                      | 0.05                      |
| RR, 1$\tau$   | 1.5                           | 2.5                            | 0.25                      | 0.09                      |
| SF2, $(dp/dt)_{\text{dyn}}$ | 0.3                           | 2.5                            | 0.4                       | 0.6                       |

* The redshifts used are $z = 0.225, 0.16, 0.257$, and $0.55$ for SHBs 050509, 050709, 050724, and 051221, respectively. We consider separately the case including GRB 050813, which is tentatively associated with a cluster at $z = 0.7$ (Gladders et al. 2005).
mergers fits the observed SHBs much better than the model for primordial DNSs (see the results of Kolmogorov-Smirnov tests in Table 1).

We note however that ruling out a primordial binary $z$-DF may be premature based on current data. For Swift, only one-third of detected SHBs have secure $z$-determinations. If there is a bias against obtaining a secure redshift for higher $z$ bursts, the observed distribution would be shifted, compared with the expected distribution, to low $z$. Assuming, for example, that obtaining a secure $z$ requires a higher $P_{\text{lim}}$ compared with that required for detection, the lower rate of detection of SHBs with secure $z$ is accounted for by choosing $P_{\text{lim}} = 2.5$ photons cm$^{-2}$ s$^{-1}$ (which reduces the detection rate by a factor of 3 compared with that obtained for $P_{\text{lim}} = 1$ photons cm$^{-2}$ s$^{-1}$). Indeed, inspection of the 15–150 keV peak fluxes of Swift SHBs shows that the average peak flux of Swift SHBs with $z$ is higher than that of SHBs without $z$ ($\langle f_z \rangle = 5.7 \pm 5.7$ photons cm$^{-2}$ s$^{-1}$ for GRBs 050509, 050724, and 051221 compared with $\langle f_{\text{nu}} \rangle = 1.2 \pm 0.5$ photons cm$^{-2}$ s$^{-1}$ for GRBs 050911, 051105, 051114, 051210, and 051227; Barthelmy et al. 2005; Gehrels et al. 2005; Bloom et al. 2006; Berger et al. 2005; Fox et al. 2005; Villasenor et al. 2005).

Choosing $P_{\text{lim}} = 2.5$ photons cm$^{-2}$ s$^{-1}$, the expected $z$-DF of primordial binary mergers is marginally compatible with observations (see Table 1 and Fig. 4). The time-delay distribution ($df/dt|_{\text{obs}}$) for dynamical DNSs yields a $z$-DF compatible with observations for both choices of $P_{\text{lim}}$.

4. SUMMARY AND DISCUSSION

We have shown (Fig. 3) that the $z$-DF of SHBs expected from dynamical formation and subsequent merger of DNSs is markedly different from that expected from primordial DNS mergers [$df/dt|_{\text{prim}} \propto 1/r$]. The large time for core collapse shifts the DF of dynamically formed DNS mergers to low $z$. The observed $z$-DF of SHBs strongly favors that expected for mergers of dynamically formed DNSs, as compared with that expected for primordial DNS mergers (Fig. 4 and Table 1; see also GPZM06 and Nakar et al. 2005).

However, current data do not allow us to rule out a $z$-DF consistent with that expected for primordial DNS mergers, since redshifts were obtained only for a minority of the detected SHBs. This may be due to a bias against obtaining redshift information for high-$z$ (faint) SHBs (Fig. 4, Table 1, and discussion at the end of § 3.3). Future observations should allow us to better constrain the $z$-DF of SHBs and, thus, to differentiate between models. For example, detection of only a few high-redshift ($z > 2$) SHBs would severely constrain the contribution of dynamically formed DNSs.

If the formation rates of primordial and dynamically formed DNSs are comparable (GPZM06), there will be an anticorrelation between $z$ and offset of the SHB from the center of its host galaxy, because DNSs formed in GCs will be closer in $z$ but farther away from their host centers, since GCs reside in the halos of galaxies. The large time delay also implies that more DNS mergers will be observed by LIGO and VIRGO (Nakar et al. 2005).

An alternative method for constraining the progenitors of SHBs is to consider their demographics (Gal-Yam et al. 2006; Zheng & Ramirez-Ruiz 2006). Zheng & Ramirez-Ruiz show that in order to account for the preponderance of SHBs in elliptical galaxies, the delay times should be large, following $df/dt \propto r^2$ with $\delta \approx 1.5$. This method, which does not rely on the observed $z$-DF, also indicates delay times longer than expected for primordial binaries. We note that the specific frequency of GCs (number of GCs per unit luminosity in the V band) is larger for elliptical galaxies than for spirals (see, e.g., Harris 1991) by an order of magnitude.

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