SHORT GAMMA-RAY BURSTS AND MERGERS OF COMPACT OBJECTS: OBSERVATIONAL CONSTRAINTS

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ABSTRACT

Gamma-ray burst (GRB) data accumulated over the years have shown that the distribution of their time duration is bimodal. While there is some evidence that long bursts are associated with star-forming regions, nothing is known regarding the class of short bursts. Their very short timescales are hard to explain with the collapse of a massive star but would be naturally produced by the merger of two compact objects, such as two neutron stars (NS-NS), or a neutron star and a black hole (NS-BH). As for the case of long bursts, afterglow observations for short bursts should help reveal their origin. By using updated population synthesis code calculations, we simulate a cosmological population of merging NS-NS and NS-BH and compute the distribution of their galactic offsets, the density distribution of their environment, and, if indeed associated with GRBs, their expected afterglow characteristics.

Subject heading: gamma rays: bursts

1. INTRODUCTION

Since data on gamma-ray bursts (GRBs) started to accumulate over the past two decades, it was recognized that their time distribution appears to be bimodal, with about 25% of bursts having a short duration, of mean $\sim0.2$ s, and the rest having a much longer duration, of mean $\sim20$ s (Mazets et al. 1981; Hurley et al. 1992; Kouveliotou et al. 1993; Norris, Scargle, & Bonnell 2000). The separation between the two classes appears to be around 2 s. While the two classes of bursts seem to have similar (isotropic) spatial distributions, they differ in several other respects. Short bursts tend to have harder spectra than long bursts (Kouveliotou et al. 1993; Dezalay et al. 1996) and about 20 times more pulses per burst, pulse width, and intervals between pulses, clearly showed that the two classes of long and short bursts are disjoint.

The existence of two distinct populations of GRBs might very well be an indication of the presence of two distinct types of progenitors. The currently favored GRB models can be divided into two classes: models involving mergers of two compact objects (Goodman 1986; Eichler et al. 1989; Paczynski 1990; Narayan, Paczynski, & Piran 1992; Meszaros & Rees 1992; Katz & Canal 1996) and models involving the collapse of a massive star (Woosley 1993; Paczynski 1998; MacFadyen & Woosley 1999; Vietri & Stella 1998). According to the internal shock model (see, e.g., Piran 2000 for a review), for the production of the observed $\gamma$-ray emission, the duration of the event, whatever it is, is very likely to be a direct measure of the time interval during which the powering engine is active. Simulations of mergers of two compact objects have shown that the duration of the neutrino-driven wind possibly producing the GRB (Ruffert & Janka 1999) is less than a second. On the other hand, the relativistic outflow generated by the collapse of a massive star (MacFadyen & Woosley 1999) can last several tens of seconds. Therefore, if one were to associate the two classes of GRBs with two classes of models, it would be natural to associate long GRBs with the collapse of massive stars and short ones with mergers of two compact objects.

Traditionally, it has been considered that an important way to test the above assumption and possibly distinguish between the two classes of models is by determining the location in which the bursts occur. Massive stars have short lifetimes and, therefore, are expected to die close to where they are born, that is, in dense and dusty environments. On the other hand, compact objects receive kicks when they are born and are therefore expected to travel far from their birthplaces.

Along these lines, several methods have been proposed to constrain the GRB location and the characteristics of their environment. The long-lived remnants resulting from the interaction between GRBs and their afterglows with the surrounding medium can be identified in nearby galaxies based on their spectral signatures (Wang 1999; Perna, Raymond, & Loeb 2000; Perna & Raymond 2000) or their dynamical interaction with the medium (Efremov, Elmegreen, & Hodge 1998; Loeb & Perna 1998; Ayal & Piran 2001), thus allowing a close study of the GRB sites. On the much shorter timescale during which the afterglow propagates in the medium, several independent analyses can be made. When multifrequency data are available, a determination of the various break frequencies and the peak flux in the afterglow spectrum (Sari, Piran, & Narayan 1998) allows constraining of the burst parameters; this has been done in several cases by a number of authors (e.g., Wijers & Galama...
1999; Panaitescu & Kumar 2001a). Time variability of absorption lines owing to the gradual photoionization of the medium by the X-ray UV radiation is also sensitive to the type of environment (Perna & Loeb 1998; Böttcher et al. 1998; Lazzati, Perna, & Ghisellini 2001), as it is the time delay between the γ-ray emission and the onset of the afterglow (Vietri 2000).

So far, afterglow observations have only been possible for long GRBs.8 For this class of bursts, there has been mounting evidence that they are associated with the collapse of massive stars. Bloom, Kulkarni, & Djorgovski (2000) compared the observed offset distribution of 20 GRBs with the theoretical predictions of two models, one that is representative of collapsars and promptly bursting binaries (such as binaries in which the black hole merges with the helium core of an evolved star during a common envelope [CE] phase) and another representative of delayed merging remnants. They found that the latter population can be ruled out to a high confidence level. Their conclusions are strengthened by the observed correlation of GRB locations with the UV light of their hosts, which is strongly suggestive of the occurrence of GRBs in star-forming regions (see also Sahu et al. 1997; Kulkarni et al. 1998, 1999; Fruchter et al. 1999).

An analysis of the evolution of the X-ray prompt emission of GRB 980329 and GRB 780506 by Lazzati & Perna (2002) has led to similar conclusions. An intriguing hint toward the connection of GRBs with the collapse of massive stars has been provided by the presence of a bump, interpreted as an underlying supernova (SN) component, in the light curve of GRB 900326 (Bloom, Sigurdsson, & Pols 1999) and GRB 970228 (Reichart 1999; Galama et al. 2000). The evidence for extinction by dust of some burst afterglows has provided further support to the GRB–collapsar connection. Finally, the recent detection of an iron line in the afterglow spectrum of five GRBs (Piro et al. 1999, 2000; Yoshida et al. 1999; Antonelli et al. 2000; Amati et al. 2000) provides evidence for the presence of dense matter in the vicinity of the burst sites (Vietri et al. 2001; Weth et al. 2000; Lazzati, Covino, & Ghisellini 2000a). The association between GRBs and collapsars, once well established, would have very important implications for our understanding of the star formation history in the universe (Blain & Natarajan 2000).

This huge wealth of information on the class of long GRBs has been gathered as a result of the afterglow observations. No similar types of studies have been possible for the short bursts so far. At this point, optical and radio searches have been performed only for the four bursts that were well pinpointed by the Interplanetary Network (Hurley et al. 2002), but the search did not lead to detections. The situation is going to change, however, with HETE II and then Swift, which will provide quick arcminute localizations; longer wavelength follow-ups will then be possible as well for this class of short events, thus allowing one to perform the same type of science for them as well.

As already mentioned, a strong candidate for the class of short bursts is provided by the coalescence of two compact objects, whose timescales and energetics are compatible with those inferred for the class of short GRBs. Therefore, an analysis of the afterglow properties that such a population would have is needed. That is the goal of this work. More specifically, in this paper we use updated population synthesis code calculations to study the afterglows that a cosmological population of GRBs owing to mergers of compact objects should have. We consider two classes of progenitors: double neutron stars (NS-NS) and neutron star–black hole (NS-BH). The former population includes the new class of short-lived neutron stars identified by Belczynski & Kalogera (2001), Belczynski, Bulik & Kalogera (2002a), and Belczynski, Kalogera, & Bulik (2002c). As will be discussed in § 2.2, this population has a very short lifetime and it dominates the merger rates. The environment of this population would therefore be more similar to that of collapsars and helium star–black hole mergers. On the other hand, the population of NS-BH binaries has a much longer lifetime; therefore, it has time to travel farther away from its birth site. More generally, we want to point out that whereas the motivation of this paper has been a detailed study of merger events in relation to the class of short bursts, our results regarding the new class of tight NS-NS binaries can also be potentially relevant for the class of long GRBs. In fact, as discussed above, some of the evidence on the connection of long GRBs with massive stars is based on the association of long GRBs with star-forming regions, but this would also be the case for the new population of tight NS-NS binaries.

To generate our simulated set of data, we incorporate the results of the population synthesis code StarTrack by Belczynski et al. (2002c) within the context of a cosmological model, which, with the help of a Monte Carlo–type approach, accounts for (1) the redshift distribution of the merger events, (2) the mass distribution of the galaxies where the events occur (which is a function of redshift) using a Press-Schechter type formalism (Press & Schechter 1974), and (3) the redshift dependence of the probability that a certain merger occurs at a given position within a galaxy of a given mass. This last effect is particularly important for the population of NS-BH binaries, whose lifetime can be comparable with the Hubble time and has not been considered thus far. A by-product of our computation is the distribution of the offsets that merging binaries have from the centers of their host galaxies. For each merger event, the density of the surrounding medium is also determined within the simulation itself. The other parameters that are needed to compute the afterglow intensity for each event are randomly drawn from distributions which have the typical values found in the afterglow modeling of long GRBs.

The paper is organized as follows: in § 2 we describe the various elements of the computation, which include the population synthesis code, the new population of NS-NS, the galaxy potential and its density profile, and the afterglow modeling. The results of the simulation of the data are presented in § 3, while § 4 is devoted to a discussion with conclusions.

2. MODEL

In this section we describe the various ingredients of the calculation.

2.1. Population Synthesis Model

We use the StarTrack population synthesis code developed by Belczynski et al. (2002c). In the following we
summarize the basic assumptions and ideas of the code. However, for more detailed description of StarTrack, we refer the reader to Belczynski et al. (2002c).

The evolution of single stars is based on the analytic formulae derived by Hurley, Pols, & Tout (2000). With these formulae we are able to calculate the evolution of stars for zero-age main-sequence (ZAMS) masses 0.5–100 $M_\odot$ and for metallicities: $Z = 0.0001–0.03$.

Stellar evolution is followed from ZAMS through different evolutionary phases depending on the initial (ZAMS) stellar mass: main sequence, Hertzsprung gap, red giant branch, core helium burning, asymptotic giant branch, and for stars stripped of their hydrogen-rich layers, helium main sequence and helium giant branch. We end the evolutionary calculations at the formation of a stellar remnant: a white dwarf, a neutron star, or a black hole.

There are two modifications to the original Hurley et al. (2000) formulae concerning the treatment of (1) final remnant masses (see Belczynski et al. 2002c) and (2) helium-star evolution (see Belczynski & Kalogera 2001).

The StarTrack code employs Monte Carlo techniques to model the evolutionary history and coalescence rates of binary compact objects, e.g., NS-NS and NS-BH. A binary system is described by four initial parameters: the mass $M_1$ of the primary (the component that is initially more massive), the mass ratio $q$ between the secondary and the primary, the semimajor axis of the orbit $A$, and the orbital eccentricity $e$. Each of these initial parameters is drawn from a distribution. More specifically, the mass of the primary is drawn from the Scalo initial mass function (Scalo 1986),

$$\Psi(M_1) \propto M_1^{-2.7},$$

and within the mass range $M_1 = 5–100 \, M_\odot$. The distribution of the mass ratios is taken to be

$$\Phi(q) = 1, \quad 0 \leq q \leq 1,$$

following Bethe & Brown (1998). The initial binary separations, $A$, are assumed as in Abt (1993)

$$\Gamma(A) \propto \frac{1}{A},$$

and finally, the initial distribution of the binary eccentricity is taken following Duquennoy & Mayor (1991).

$$\eta(e) = 2e, \quad 0 \leq e \leq 1.$$

Furthermore, the initial distribution of binaries is assumed to follow the mass distribution in the young disk (Paczynski 1990); i.e.,

$$P_{\text{bin}}(R, z) dR dz = \frac{P(R) dR p(z) dz}{2\pi R^2} e^{-z/2z_0} dR dz.$$

For a galaxy like the Milky Way, $R_0 = 4.5$ kpc up to $R_{\text{max}} = 20$ kpc, and $z_0 = 75$ pc. These parameters are assumed to scale with the galaxy mass as discussed in the following section.

As we are interested only in NS-NS and NS-BH systems, we evolve only massive binaries with primaries more massive than $5 \, M_\odot$. We generate a large number ($N = 1.6 \times 10^7$) of primordial binaries and evolve them until formation of the remnant system. During the evolution of every system we take into account the effects of wind mass loss, asymmetric SN explosions, binary interactions (conservative/nonconservative mass transfers [MTs] and CE phases) on the binary orbit, and the binary components. We also include effects of accretion onto compact objects in CE phases (Brown 1995; Bethe & Brown 1998) and rejuvenation of binary components during MT episodes. Once a binary consists of two compact remnants (NS or BH), we calculate its merger lifetime, the time until the components merge owing to gravitational radiation and associated orbital decay.

The StarTrack code was used in its standard mode, described by the set of parameters that are thought to best represent our understanding of stellar single and binary evolution.

1. Kick velocities.—Compact objects receive natal kicks during SN explosions, when they are formed. NS kicks are drawn from a weighted sum of two Maxwellian distributions with $\sigma = 175$ km s$^{-1}$ (80%) and $\sigma = 700$ km s$^{-1}$ (20%; Cordes & Chernoff 1997). For black holes formed via partial fallback we use smaller kicks but drawn from the same distribution as for neutron stars. The kick scales with the amount of material ejected in SN explosion or inversely with the amount of falling back material (the bigger the fallback, the smaller the kick). And for black holes formed in direct collapse of massive stars we do not apply any kicks, as in those cases no SN explosion accompanies the formation of such objects.

2. Maximum NS mass.—We adopt a conservative value of $M_{\text{max}} = 3 \, M_\odot$ (e.g., Kalogera & Baym 1996). It affects the relative fractions of neutron stars and black holes and the outcome of NS hypercritical accretion in CE phases.

3. Common envelope efficiency.—We assume $\alpha_{\text{CE}} \propto \lambda = 1.0$, where $\alpha_{\text{CE}}$ is the efficiency with which orbital energy is used to unbind the stellar envelope, and $\lambda$ is a measure of the central concentration of the giant.

4. Nonconservative mass transfer.—In cases of dynamically stable MT between nondegenerate stars, we allow for mass and angular momentum loss from the binary (see Podsiadlowski, Joss, & Hsu 1992), assuming that the fraction $f_a$ of the mass lost from the donor is accreted to the companion, and the rest $\left(1 - f_a\right)$ is lost from the system with specific angular momentum equal to $2n f_a A^2 / P$, where $A$ is the orbital separation and $P$ the period. We adopt $f_a = 0.5$ and $j_1 = 1$.

5. Star formation history.—We assume that star formation has been continuous in the disk of a given galaxy. We start the evolution of a single or a binary system $t_{\text{birth}}$ ago and follow it to the $t(z)$, where $t(z)$ is the present time at a given redshift $z$ of the galaxy. The birth time $t_{\text{birth}}$ is drawn randomly within the range $0–t(z)$, which corresponds to continuous star formation rate (SFR).

6. Initial binary.—We assume a binary fraction of $f_{\text{bin}} = 0.5$, which means that for any 150 stars we evolve, we have 50 binary systems and 50 single stars.

7. Metallicity.—We assume solar metallicity $Z = 0.02$.

8. Stellar winds.—The single-star models we use (Hurley et al. 2000) include the effects of mass loss owing to stellar winds. Mass loss rates are adopted from the literature for different evolutionary phases, that is, for hydrogen-rich stars on the main sequence (Nieuwenhuijzen & de Jager 1990), for red giant branch stars (Kudritzki & Reimers 1978) using the $Z$ dependence of Kudritzki et al. (1989), for asymptotic giant branch stars (Vassiliadis & Wood 1993),
and finally for luminous blue variables (Hurley et al. 2000). For helium-rich stars Wolf-Rayet mass loss is included using rates derived by Hamann, Koesterke, & Wessolowski (1995) and modified by Hurley et al. (2000).

The population synthesis code allows us to compute the probability distribution, \( P_{\text{merg}}(t) \), of a merger of a given type as a function of the time \( t \) since the formation of the system. It also yields the probability distribution, \( P_{\text{loc}}(R, \eta; t, M_{\text{gal}}) \), that a merger in a galaxy of mass \( M_{\text{gal}} \) after a time \( t \) of formation of the system occurs at the position \( (R, \eta) \) from the galaxy center.

We have considered a grid of galaxy masses with 15 equal logarithmically spaced intervals in the range \( 10^{8} \)–\( 10^{11} \) \( M_{\odot} \). For each value of the mass, 10 values of the cosmological time corresponding to redshifts linearly spaced in the interval \( \{0, 10\} \) were considered. For each of the values of \( M_{\text{gal}} \) and \( z \) on the grid, the population synthesis code was run to obtain probability distributions for the positions \( R(M_{\text{gal}}, z), \eta(M_{\text{gal}}, z) \) of the mergers taking place in the galaxy of mass \( M_{\text{gal}} \) at the redshift \( z \). Probability distributions for values of \( M_{\text{gal}} \) and \( z \) not on the grid were obtained by interpolation.

### 2.2. Double Neutron Star Binaries

Belczynski & Kalogera (2001) and Belczynski et al. (2002a, 2002c) identified new subpopulations of NS-NS binaries. The new subpopulations dominate the group of coalescing NS-NS systems, and due to their unique characteristics, they predominantly merge inside the host galaxies. Given the importance of these populations to our conclusions, in what follows we briefly summarize the results of Belczynski & Kalogera (2001) and Belczynski et al. (2002a, 2002c).

Double neutron stars are formed in various ways, including more than 14 different evolutionary channels, as discussed by Belczynski et al. (2002c). However, the whole population of coalescing NS-NS systems can be divided into three subgroups.

Group I consists of nonrecycled NS-NS systems, which terminate their evolution in a double CE of two helium giants. Two bare carbon-oxygen (CO) cores emerge after envelope ejection, and they form neutron stars in two consecutive SN Ic explosions. Provided that the system is not disrupted by SN kicks and mass loss, the two neutron stars form a tight binary, with the unique characteristic that no neutron star had a chance to be recycled. (For more details see Belczynski & Kalogera 2001.) Group II includes all the systems that finished their evolution through single CE phase, with a helium giant donor and an NS companion. During the CE phase, the neutron star accretes material from the giant envelope, becoming most probably a recycled pulsar. The CO core of the helium giant, soon after CE phase is finished, forms another neutron star. The system has a good chance to survive even a high kick that the newly born neutron star may receive, because after the CE episode it is very tight and well bound. (For more details see Belczynski et al. 2002a.) Group III consists of all the other NS-NS systems formed, through more or less classical channels (Bhattacharya & van den Heuvel 1991).

Group II strongly dominates the population of coalescing NS-NS systems (81%) over groups III (11%) and I (8%). This is due to the fact that we allow for helium star radial evolution, and usually just prior to the formation of tight (coalescing) NS-NS system we encounter one extra CE episode, as compared to classical channels. This has major consequences for the merger time distribution of the NS-NS population and, in turn, for the distribution of NS-NS merger sites around their host galaxies. Merger times of classical systems are comparable with Hubble time, and that gives them ample time to escape from their host galaxies. As has been shown in previous studies (e.g., Bulik, Belczynski, & Zbijewski 1999; Bloom et al. 1999), which did not include helium star detailed radial evolution, a significant fraction of the NS-NS population tended to merge outside host galaxies, exactly like our group of classical systems. In contrast, the binaries of groups I and II owing to the extra CE episode, are tighter, and their merger times are much shorter, on the order of \( \approx 1 \) Myr. Thus, even if they acquire high systematic velocities, owing to the asymmetric SN explosions, they will merge within the host galaxies near the places they were born. Since groups I and II dominate the population, the overall NS-NS distribution of merger sites will follow the distribution of primordial binaries or star formation regions in the host galaxy.

Note that NS-NS binary systems with rather short lifetimes had also been proposed by Tutukov & Yungelson (1993, 1994) and discussed in the context of GRBs as well. They find merger times that are generally shorter than those found in other studies (e.g., Portegies Zwart & Yungelson 1998; Fryer, Woosley, & Hartmann 1999) but not as short as those found by Belczynski et al. (2002a, 2002c). In the Tutukov & Yungelson scenario the short timescales are mainly the result of assumption that the secondary star, once it becomes a low-mass helium-rich star, can initiate an extra MT phase. In the Belczynski et al. scenario, the short timescales are the result of allowing both the primary and the secondary star to initiate an extra MT or CE phase. Moreover, in contrast to Tutukov & Yungelson, the Belczynski et al. scenario incorporates the assumption that neutron stars do receive natal kicks. Owing to the natal kicks, the widest binaries are disrupted, and the surviving ones gain high eccentricities, which further reduces their merger times (i.e., lifetimes). We want to stress that the Belczynski et al. (2002a, 2002c) results rely on the assumption that low-mass helium stars can actually survive the CE phase, and this assumption needs yet to be tested through detailed hydrodynamic calculations.

The distribution of merger times of BH-NS systems is similar to that of the classical NS-NS subpopulation (long merger times, \( \gtrsim 0.1–1 \) Gyr). However, these systems have obtained smaller systematic velocities as, on average, black holes receive smaller kicks than neutron stars. As a result, a certain fraction of BH-NS binaries escape and merge outside of the host galaxies; however, the fraction of escaping BH-NS systems is smaller than that of classical NS-NS binaries (this is a result seen in previous studies, in which only classical NS-NS were considered). More detailed study of all proposed binary GRB progenitors can be found in Belczynski, Bulik, & Rudak (2002b).

### 2.3. Cosmic Event Rate

The merger rate of a given type of progenitors is obtained by combining the results of the population synthesis code with the star formation history. Let \( \dot{R}_{\text{SFR}}(t) \) be the cosmic SFR at time \( t \); here we adopt the SFR of Rowan-Robinson (1999). Let \( f_{i} \) be the mass fraction (of all stars, single and
binary, in mass range 0.08–100 $M_\odot$) leading to formation of the GRB progenitor of type “i.” The cosmic event rate for that type of mergers at redshift $z$ is then given by

$$R_{\text{merg}}(z) = \int_{t(z)}^t R_{\text{dt}}(t') f(t') P_{\text{merg}}[t(z) - t'] dt' ,$$

where $P_{\text{merg}}(t)$ is defined in the previous section, and $dt = h^{-1}dz(1+z)^{-1}(1 + \Omega_M z) [(1+z)^z - z(z+2)\Omega_M]^{-1/2}$. The rate of events up to redshift $z$ for the GRB progenitor of type $i$ is correspondingly given by

$$R_i(z < z) = 4\pi \int_0^z dz' \frac{dR_{\text{merg}}(z')}{dz'} ,$$

with $r_z = cH_0^{-1} \int_0^z [\Omega_m (1+z)^3 + \Omega_\Lambda]^{-1/2} dz'$. Throughout the paper we adopt a flat cosmology with $h = 0.65$, density parameter $\Omega_m = 0.3$, and cosmological constant $\Omega_\Lambda = 0.7$.

### 2.4. Galaxy Model

The potential of a spiral galaxy can be described as the sum of three components: a bulge, a disk, and a dark matter halo. A good approximation to the potential of the disk and the bulge has been proposed by Miyamoto & Nagai (1975):

$$\Phi_{b,d}(R, \eta) = \frac{GM_{d,b}}{\sqrt{R^2 + (a_{b,d} + \sqrt{z^2 + c_{b,d}^2})^2}} ,$$

where $a_{b,d}$ and $c_{b,d}$ are parameters (which depend on whether one considers the bulge or the disk). $M_{d,b}$ is the mass either of the bulge or the disk, $R = (x^2 + y^2)^{1/2}$ is the coordinate in the plane of the disk, and $\eta$ is the coordinate in the plane perpendicular to the disk.

The mass density distribution associated with the potential $\Phi_{b,d}(R, \eta)$ is

$$\rho_{b,d}(R, \eta) = \frac{\left(c_{b,d}^2 M_{d,b} / 4\pi\right)}{R^2 + \left(a_{b,d} + \sqrt{\eta^2 + c_{b,d}^2}\right)^2} \times \left[ R^2 + \left(a_{b,d} + \sqrt{\eta^2 + c_{b,d}^2}\right)^2 \right]^{3/2} \left(\eta^2 + c_{b,d}^2\right)^{1/2} .$$

The dark matter halo is spherically symmetric and described by the potential

$$\Phi(r) = -\frac{G M_h}{r_0} \left[ \frac{1}{2} \ln \left( 1 + \frac{r^2}{r_0^2} \right) + \frac{r}{r_0} \arctan \left( \frac{r}{r_0} \right) \right] ,$$

where $r = (R^2 + \eta^2)^{1/2}$, and $r_0$ is a parameter. The corresponding mass density distribution is

$$\rho_h(r) = \frac{\rho_0}{1 + (r/r_0)^2} ,$$

where $\rho_0 = M_h/(4\pi r_0^3)$. The fraction of mass in gas is assumed to be $f_{\text{gas}} = 0.5$ for the bulge and the disk, and $f_{\text{gas}} = 0.04$ (Bahcall et al. 1999) for the halo. For the Milky Way, $a_b = 0$ kpc, $c_b = 0.277$ kpc, $a_d = 4.2$ kpc, $c_d = 0.198$ kpc, $M_b = 1.12 \times 10^{10} M_\odot$, $M_d = 8.78 \times 10^{10} M_\odot$, $r_0 = 6.0$ kpc, and $M_h = 5.0 \times 10^{10} M_\odot$. N-body simulations by Bullock et al (2001) have shown that the redshift evolution of the core radius of a halo, $r_0$, is roughly constant, and this is what we assume here. Finally, we assume that the ratio of the parameters describing the various components of the galaxy is constant, independent of the galaxy mass, and that they scale with the galaxy mass as $M^{1/2}$ (constant surface brightness; see, e.g., Binney & Tremaine 1994).

At redshift $z$, the probability distribution $P_{\text{gal}}(M, z)$ of having a merger in a galaxy of mass $M$ can be approximated by the Press-Schechter function (yielding the probability of finding a halo with mass $M$ at redshift $z$) convolved with the number of galaxies, $N_{\text{gal}}$, per halo of mass $M$. For the latter, we use the analytical approximation derived by Scoccimarro et al. (2001), $\langle N_{\text{gal}} \rangle = (N_B + N_R)$, where $N_B$ and $N_R$ represent the number of blue and red galaxies, respectively, per halo of mass $M$, and their mean is given by $\langle N_B \rangle = 0.7(M/M_B)^{\alpha_B}$ and $\langle N_R \rangle = 0.7(M/M_R)^{\alpha_R}$, respectively. The fit parameters are $\alpha_B = 0$ for $10^{11} M_\odot h^{-1} \leq M_\odot \leq 10^{12} M_\odot$, and $\alpha_R = 0.9$, and $M_R = 2.5 \times 10^{12} M_\odot h^{-1}$.

The merger rate of compact objects as a function of galaxy mass is not a well-constrained quantity. The simplest assumption is that it simply scales with the mass of the galaxy. We adopt this model as our “standard” model, but we will also explore how the results change if more weight (than the simple rescaling with mass) is given to galaxies with smaller mass, given the observation (Babul & Ferguson 1996) that small mass galaxies might have an increased SFR. We parameterize the weight of the rate on the galaxy mass through the quantity $M^3$ so that the probability of finding a galaxy of mass $M$ at redshift $z$ is given by

$$P_{\text{merg}}(M, z) dM = A P_{\text{gal}}(M, z) M^3 dM ,$$

where $A$ is a normalization factor so that $\int dM P_{\text{merg}}(M, z) = 1$. We consider the values $\beta = 1$ and $\beta = 0.5$.

Figures 1a, 1b, and 1c show the probability distribution of projected distances $P_{\text{proj}}(R, \eta; z, M_{\text{gal}})$ for a face-on galaxy (i.e., $d_{\text{proj}} = R$) at the redshifts $z = 0, 3, 6$ and for a wide range in galaxy masses: $M = 10^{10} M_\odot$ in Figure 1a, $M = 6 \times 10^{9} M_\odot$ in Figure 1b, and $M = 10^{11} M_\odot$ in Figure 1c. While the distribution of NS-NS mergers does not evolve much with redshift (owing to its very short lifetime), the population of NS-BH mergers does evolve significantly, especially in small-mass galaxies. Therefore, it is important that for a merger occurring at redshift $z$, the location within the host is determined according to the probability distribution at that particular redshift.

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9 We neglect the scatter in the ratio between the disk size and the virial radius of the halo and assume a typical value for it, calibrated on that of the Milky Way. Introducing this scatter here would significantly increase our computation time (requiring a much larger number of runs of the population synthesis code) but would not affect our main results.

10 This relation tries to capture two important physical effects, that is, the fact that at large masses the gas cooling time becomes larger than the Hubble time, hence suppressing galaxy formation in large mass halos; in small-mass halos, on the other hand, phenomena such as SN winds can blow away the gas from halos, also suppressing galaxy formation, and this leads to a cutoff at small halo masses.

11 For the class of long GRBs, their association with blue starburst galaxies (in the great majority of the cases where a host could be identified) suggest that their masses lie in the range $10^9$–$10^{10} M_\odot$ (see Bloom et al. 2001).
2.5. GRBs and Afterglow Parameters

Even though the ultimate energy source that powers short bursts could be different from that associated with long GRBs, there is no reason to expect that the physical mechanisms that produce the gamma radiation and the afterglow should also be different. In the standard fireball scenario (see, e.g., Piran 2000 for a review), GRBs are generated by internal shocks in the expanding fireball, while the afterglow is produced by shocks created by the interaction between the relativistically expanding matter of the fireball itself and the surrounding medium (the so-called external shocks). Moreover, no correlation is expected between the duration of the burst and the decay rate of its afterglow. Therefore, to predict the afterglow properties of the population of short bursts, we use the theory developed and used to study long bursts (e.g., Sari 1998; Waxman 1997; Sari et al. 1998). In the standard model, GRB afterglows are thought to be the result of synchrotron emission by Fermi-accelerated electrons behind the expanding shock. The electrons have a power-law distribution of Lorentz factors above a minimum value $\gamma_m$. As noted by Sari et al. (whose formalism we adopt here), there is also a threshold Lorentz factor, $\gamma_c$, above which electrons rapidly lose their energy to radiation, and
cool down to a Lorentz factor $\sim \gamma_c$. Under this condition, the "fast-cooling regime," the flux at the observation frequency $\nu$ is

$$F_{\nu} = F_{\nu,\text{max}} \left\{ \begin{array}{ll} \left( \nu / \nu_c \right)^{1/3}, & \nu < \nu_c \\ \left( \nu / \nu_c \right)^{-1/2}, & \nu_c \leq \nu < \nu_m \\ \left( \nu / \nu_m \right)^{-(p-1)/2}, & \nu_m \leq \nu < \nu_e \\ \left( \nu / \nu_e \right)^{-p}, & \nu \geq \nu_e \end{array} \right., \quad \text{(13)}$$

having defined $\nu_c \equiv \nu(\gamma_c)$ and $\nu_m \equiv \nu(\gamma_m)$.

On the other hand, if the condition $\gamma_c > \gamma_m$ is satisfied, only electrons with $\gamma_e > \gamma_c$ can cool efficiently. In this case, the "slow-cooling regime," the observed flux varies according to the relation

$$F_{\nu} = F_{\nu,\text{max}} \left\{ \begin{array}{ll} \left( \nu / \nu_m \right)^{1/3}, & \nu < \nu_m \\ \left( \nu / \nu_m \right)^{-(p-1)/2}, & \nu_m \leq \nu < \nu_e \\ \left( \nu / \nu_e \right)^{-(p-1)/2}, & \nu \geq \nu_e \end{array} \right., \quad \text{(14)}$$

In equations (13) and (14), the parameter $p$ is the power-law index of the electron energy distribution, while the quantity $F_{\nu,\text{max}}$ represents the maximum value of the flux in the afterglow spectrum. This is achieved when the observing frequency is $\nu = \nu_e$ in the fast-cooling regime and when $\nu = \nu_m$ in the slow-cooling regime. Under the assumption that the magnetic field energy density in the shell rest frame is a fraction $\xi_B$ of the equipartition value and that the power-law electrons carry a fraction $\xi_e$ of the dissipated energy, this maximum intensity of the afterglow flux is given by

$$F_{\nu,\text{max}} = 110 n^{1/2} \xi_B^{1/2} E_{52} d_{28}^{-2} (1 + z) \text{ mJy}, \quad \text{(15)}$$

where $d_{28}$ is the luminosity distance in units of $10^{28} \text{ cm}$, $n$ is the mean density of the surrounding medium in units of $\text{cm}^{-3}$, and $t_d$ is the time in days, as measured in the observer frame since the beginning of the burst. Here and in the following a fully adiabatic shock is assumed. Then the cooling frequency $\nu_c$ and the synchrotron frequency $\nu_m$ are given, respectively, by (Sari et al. 1998)

$$\nu_c(t) = 2.7 \times 10^{12} n^{-1/3} \xi_B^{2/3} E_{52}^{1/2} t_d^{-2/3} (1 + z)^{-1/2} \text{ Hz}, \quad \text{(16)}$$

and

$$\nu_m(t) = 5.7 \times 10^{14} \xi_c^{1/2} \xi_B^{1/2} E_{52}^{1/2} t_d^{3/2} (1 + z)^{3/2} \text{ Hz}. \quad \text{(17)}$$

The transition between the fast- and slow-cooling regimes occurs at the time defined by $\nu_c(t_0) = \nu_m(t_0) \equiv t_0$,

$$t_0 = 210 e^{2} \xi_c^{2} E_{52} n_1 \text{ days}, \quad \text{(18)}$$

and the corresponding frequency is

$$\nu_0 = 1.8 \times 10^{11} \xi_B^{5/2} \xi_c E_{52}^{-1} n_1^{-3/2} \text{ Hz}, \quad \text{(19)}$$

always under the assumption of adiabatic shock. When $\nu_{\text{obs}} > \nu_0$, the flux reaches its peak value at $t < t_0$, i.e., in the fast-cooling regime, and thus at the time when $\nu_c(t_c) = \nu_{\text{obs}}$, that is,

$$t_c = 7.3 \times 10^{-6} \xi_B^{3} E_{52}^{-1} n_1^{-2} \nu_{\text{obs}}^{-2} (1 + z)^{-1} \text{ days}. \quad \text{(20)}$$

On the other hand, if $\nu_{\text{obs}} < \nu_0$, the flux peaks during the slow-cooling regime, corresponding to the time at which

$$\nu_m(t_m) = \nu_{\text{obs}}, \quad \text{where} \quad t_m = 0.69 \xi_B^{1/3} E_{52}^{1/3} \nu_{\text{obs}}^{-2/3} (1 + z)^{-1/3} \text{ days}. \quad \text{(21)}$$

The fraction of energy that goes into electrons, $\xi_e$, and the fraction that is shared by the magnetic field, $\xi_B$, are not well constrained either theoretically or observationally, and they are likely to vary significantly from burst to burst (see, e.g., Kumar 1999). Therefore, we draw them from a distribution that we assume uniform in an interval that encompasses for each of them the observationally inferred values in those few cases where they could be derived from fits to the light curve (Wijers & Galama 1999; Panaitescu & Kumar 2001a) and the theoretical expectations (e.g., Waxman 1997). More specifically, for each burst, we draw $\xi_e$ from a uniform distribution in the interval (0.01, 0.2) and $\xi_B$ from a uniform distribution in the interval (0.001, 0.1).

Finally, simulations of mergers between two compact objects have shown that a typical energy release in $\gamma$-rays (deriving from neutrino-antineutrino annihilation) is $E_\gamma \sim \text{a few } 10^{50} \text{ ergs}$ (Ruffert & Janka 1999). This is the isotropic equivalent energy (i.e., after correcting for the typical beaming angles found in the simulations) based on the neutrino annihilation flux. However, other channels (such as the energy of an accretion disk that forms in a merger) are possible. Katz & Canel (1996) report $\sim 10^{51} \text{ ergs}$ as typical energy in $\gamma$-rays. Assuming an efficiency $0.2$ of conversion to $\gamma$-rays (Guetta, Spada, & Waxman 2001), we adopt a typical value of $E = 5 \times 10^{51} \text{ ergs}$ for the total isotropic equivalent energy of the bursts. Small variations around this value would not really affect the computed afterglow distributions, given the spread in the other parameters. However, the dependence of our final results on the assumed value of the energy (see eqs. [13]–[20] should be kept in mind).

In this work, we are primarily interested in some characteristic quantities of the afterglow that would be the strongest diagnostics of a population of mergers of compact objects in long-lived binaries, thus those quantities dependent on the location and, in turn, on the density of the medium. The peak flux scales with $n^{1/2}$ and therefore provides a good diagnostic of the environment. A much stronger probe of the density is the time $t_e$ at which the cooling frequency $\nu_c$ is equal to the frequency of observation. This time depends on $n^{-2}$ and $E^{-1}$ (see eq. [20]), and therefore it is expected that, given the reasonable assumption that the typical range of values of $E$ and $E_{52}$ afterglow is independent of the progenitor, the distribution of these afterglow characteristic quantities should be significantly different for the two classes of long and short bursts if they are indeed associated with two distinct classes of progenitors, one short-lived and the other long-lived.\footnote{12}
3. CHARACTERISTICS OF A POPULATION OF GRBs OWING TO MERGERS

The computation of the properties of this population involves several steps, all of which are Monte Carlo based. First, a random redshift is generated from the rate in equation (6). At that redshift, the mass of the host galaxy is randomly drawn from the distribution in equation (12), and a random inclination with respect to the plane perpendicular to the line of sight to the observer is assigned to it. The location of the burst in terms of the coordinates \( R, \eta \) is then randomly drawn from the probability distribution obtained with the population synthesis code for the galaxy of that given mass at that given redshift. The density of the medium at the location \( R, \eta \) for the host galaxy of mass \( M_{\text{gal}} \) is hence found from equations (11) and (9), and finally the afterglow properties of that given burst are computed as described in § 2.4.

The results of the simulations for a randomly generated sample of 10,000 merger events (for each of the two progenitor types NS-NS and NS-BH) are displayed in Figures 2–7. All these results have been derived for a model with galaxy masses in the range \( 10^8 \text{ } \sim 10^{11} M_{\odot} \) and with parameter \( \beta = 1 \) (i.e., merger probability in a galaxy of a given mass directly proportional to the galaxy mass). We show both the differential distributions (which give a better visual idea of where most of the events are located) and the cumulative distributions, which better quantify our results. To start with, in Figure 2 we show the distances \( d_{\text{proj}} \) from the galaxy centers projected onto the plane perpendicular to the line of sight to the observer. Given their rather short lifetime, NS-NS events occur rather close to the galactic centers. Figure 3 shows the distribution of physical offsets \( \theta = d_{\text{proj}}/d_A \) (where \( d_A \) is the angular diameter distance) corresponding to the projected distances of Figure 2.

The typical ambient densities in which the events occur are shown in Figure 4. NS-NS mergers probe typical interstellar medium (ISM) densities, while a substantial fraction of NS-BH events occurs in a very low density environment. The values of the densities expected from NS-NS events are consistent with those inferred from the afterglow modeling of some of the long bursts. However, if the typical energies released in mergers of compact objects (Ruffert & Janka 1999) are indeed smaller than those inferred thus far for
long GRBs, then the afterglows from NS-NS mergers would be correspondingly dimmer. Figure 5 shows the expected peak in the afterglow spectrum (see eq. [15]) with the assumed isotropic energy release of $5 \times 10^{51}$ ergs.

The rather larger distances from the galactic centers, at which NS-BH mergers occur, result in significantly smaller typical densities of the surrounding medium, as shown in Figure 4. This distribution does not appear consistent with densities inferred thus far for the class of long GRBs. The corresponding peak afterglow flux for the NS-BH events (displayed in Fig. 5) is correspondingly rather lower ($F_{\text{peak}} \propto n^{0.5}$). Here the same value of the energy of $5 \times 10^{51}$ ergs has been adopted, while, as explained in § 2.4, the other afterglow parameters have been drawn from distributions consistent with values inferred for some of the long bursts.

It should be noted that the distributions of $F_{\text{peak}}$ should be considered mostly representative in the X-ray band. Predictions in the longer wavelength bands are affected by other factors that we have not included here. In the optical, obscuration by dust is considered the likely responsible for the failure to detect counterparts in about half of the X-ray identifications of the long GRBs (Djorgovski et al. 2001; Reichart 2001; Venemans & Blain 2001; but see Lazzati, Covino, & Ghisellini 2000b), and its effect on the number counts have been shown to be quite sensitive to the type of dust model considered (Perna & Aguirre 2000). Moreover, dust destruction by the X-ray UV photons (Waxman & Draine 2000; Reichart 2001; Draine & Hao 2002) can introduce time variability in the extinction curve and, consequently, in the measured value of the flux at various times. If the emission is beamed, a further reduction in the flux is expected at later times (Sari, Piran, & Halpern 1999), but the frequency at which this happens depends on the specific value of the beaming angle. For the particular value of the density $n = 10^{-3}$ cm$^{-3}$, and an energy on the order of $5 \times 10^{51}$ ergs, Panaitescu, Kumar, & Narayan (2001) note that optical and radio afterglows of short bursts are likely to be below current detection limits even without accounting for all the other effects.

Figure 6 shows for both the NS-NS mergers (Fig. 6a) and NS-BH mergers (Fig. 6b) the integrated afterglow flux in the 2–10 keV energy band at the observation times $t_{\text{obs}} = 1, 3,$ and $12$ hr after the burst. Given the detection thresholds of the current X-ray instruments BeppoSAX, Chandra X-Ray Observatory, and the upcoming Swift (in the range of a few $\times 10^{-15}$ to $10^{-14}$ ergs cm$^{-2}$ s$^{-1}$), a sizeable fraction of events should be detectable if observed within the first few hours. These simulations have been made with the choice $p = 2$ for the power-law index of the electron energy distribution, in agreement with the average value inferred from numerical modeling of the afterglow by Panaitescu & Kumar (2001b). However, we want to emphasize the fact that the integrated afterglow flux in the band we considered is rather sensitive to this choice. We also performed our simulations with the value $p = 2.5$ (while the rest remained the same) and found that the fluxes of the bursts were typically reduced by a factor of $\sim 10^2$. In general, it is reasonable to expect a distribution of values of $p$ among bursts but most likely not as wide as that of other parameters.

The inference of the physical parameters (such as $E$, $\xi_B$, $\xi_e$, $n$) that characterize a burst and its afterglow from an analysis of the light curve requires the observational determination of the characteristics breaks at $\nu_c$, $\nu_m$, $\nu_\alpha$ (absorption frequency) and a measurement of the peak flux (see, e.g., Wijers & Galama 1999). This in turn requires for each burst a coverage over a wide range of frequencies. On the other hand, some statistical information can be obtained by measuring a smaller subset of these quantities but for a larger sample of bursts. A very good probe of the density of the medium is the time $t_c$ at which the cooling frequency $\nu_c$ is equal to the observation frequency $\nu_{\text{obs}}$. This time, in fact, depends on $n^{-2}$ (see eq. [20]). Even with a rather large spread in the values of $\xi_B$, the sensitivity to the density remains very strong. The distribution of cooling times can be particularly useful in identifying differences in the environment between the populations of long and short bursts. In fact, assuming as reasonable that the physics of the afterglow is the same for the two populations and, therefore, that the distribution of the parameter $\xi_B$ is also the same, then the distributions of cooling times should significantly differ for the populations of long and short bursts if their progenitors occur in different environments. Figure 7 shows the distribution of $t_c$ (assuming an observing frequency corresponding to 1 keV) for the NS-NS merger scenario and for the NS-BH case. Note that times that are too short to allow observation at the frequency considered here are longer at lower frequencies ($t_c \propto \nu_{\text{obs}}^{-2}$). They can therefore be measured at longer wavelengths and then simply rescaled to one given frequency to build up the distribution.

While the above simulations of the events were computed for a model with merger rates proportional to the galaxy mass, we explored how our results changed when a relatively higher weight for the rates was given to galaxies with smaller masses (i.e., the model with $\beta = 0.5$ in eq. [12]). The mass distribution obtained with this model is compared with the other one ($\beta = 1$) in Figure 8 for both populations.

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15 For this class of bursts Frail et al. find a typical energy of $3 \times 10^{51}$ ergs after correcting for beaming effects.
of NS-NS and NS-BH mergers. Because of their shorter lifetimes, NS-NS mergers typically occur at higher redshifts than NS-BH mergers, and therefore they have a higher probability of occurring in small mass galaxies than the NS-BH group. This is the reason for the behavior of the two populations shown in Figure 8.

The results of the simulations with the two different mass distributions of Figure 8 are shown and compared in Figure 9 for the distribution of projected distances. When the typical galaxy mass is reduced, there are two competing effects: first, at the beginning of its evolution, the population is much closer to the galaxy center owing to the smaller size of the disks, and therefore it has to travel for a longer time to reach a given $d_{\text{proj}}$; second, the reduced potential of the smaller mass galaxies makes it easier for the population to move farther away from the center. As Figure 9 shows, the
first effect tends to dominate for the NS-NS population owing to its very short lifetime. If more of these events occur in smaller galaxies, then the offsets from the galaxy centers will also be typically smaller. On the other hand, for the population of NS-BH mergers, which has a longer lifetime, the second effect prevails, and an enhanced merger rate in small-mass galaxies results in generally larger distances from the galactic centers.

4. DISCUSSION AND CONCLUSIONS

We have studied the properties that a population of GRB events owing to mergers of compact objects should have with special emphasis on the related afterglows. By using a Monte Carlo type of approach, our simulations take into account the mass distribution of the host galaxies as a function of redshift, as well as the redshift evolution of the probability distributions for the location of the mergers within galaxies of various mass (see Figs. 1a–1c). This last effect needs to be taken into account especially for binaries whose merger time can be comparable with the Hubble time for a sizeable fraction of them (such as the NS-BH population).

Our population of NS-NS binaries includes the new groups of short-lived binaries identified by Belczynski & Kalogera (2001) and Belczynski et al. (2002a, 2002c), which dominate the merger rates. Therefore, our results regarding this population differ from previous studies on the same subject, and the derived distributions trace rather closely the star-forming regions in the disk. The densities in which they occur are typical ISM densities; hence, their afterglows, although dimmer because of the smaller energy released, should still be observable with current X-ray instruments for a large fraction of them. Afterglows produced as a result of NS-BH mergers are even dimmer, but most of them should still be detectable if observed within the first few hours.

Whereas the NS-NS class of candidate GRB progenitors might not be distinguishable from that of collapsars and of other promptly bursting binaries simply on the basis of their location within the host (and the consequent intensity of their afterglows), there are, however, other signatures, such as the presence of an underlying SN explosion, or of iron lines in the afterglow spectrum (see § 1) that, while naturally associated with a collapsar, would be hard to explain within the NS-NS merger scenario.16

On the other hand, the observational properties of the NS-BH binary population that we have studied here, which depend on the location within the hosts (such as offsets, densities, and density-dependent afterglow quantities), differ significantly from those of the NS-NS population (which, as far as the location is concerned, could well be representative also of collapsars). Even if it is not possible to infer all the parameters $E$, $n$, $\xi$, $\xi_B$ at once (which requires that $\nu_c$, $v_m$, $v_{t_a}$, and $F_{peak}$ all be measured), a comparison of the distributions for the class of long and short bursts would provide strong constraints on whether their progenitors actually belong to two different classes of progenitors, one which is short-lived and the other which is long-lived.

The population synthesis code that we used in all the simulations is the StarTrack code by Belczynski et al. (2002c), operated in its standard mode, where the best values of all the parameters are chosen. A complete parametric study of how the distributions for the location within a galaxy of a given mass change when all the model parameters are varied to their extremes is being performed elsewhere (Belczynski et al. 2002b). The main results are that the merger site distribution has the strongest dependence on the prescriptions for the MT and the CE efficiency, and it is also rather dependent on the maximum allowed NS mass and the kick velocity. It is not very dependent on the assumed cosmology. Regarding the new class of short-lived binaries identified by Belczynski & Kalogera (2001) and Belczynski et al. (2002a, 2002c), it is found that 81% of them contribute to the NS-NS population in our standard model described in § 2.1. The parametric study shows that the highest contribution (98%) from this population is obtained for small kicks while the smallest (28%) for very low CE efficiency. We stress once again that our results on GRBs from NS-NS mergers strongly rely on the presence of this short-lived population, whose presence is based on the assumption that low-mass helium stars can survive the CE phase. This will have to be tested through detailed hydrodynamic simulations. In this work, our main interest has been to incorporate the results of the population synthesis code within a proper cosmological context and study the expected afterglows if GRBs are indeed associated with mergers of two compact objects. This is particularly relevant for the population of short bursts, whose very short timescales are hard to account for with the collapse of a massive star, while

16 It should be noted, however, that “SN bumps” can also be explained as the result of dust echoes (Esin & Blandford 2000) and that models that explain iron lines (e.g., Vietri & Stella 1998) require an SN that took place a few months before the GRB, which is inconsistent with the presence of the SN bumps.
being naturally associated with mergers of two compact objects.

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