Scenario Machine: fast radio bursts, short gamma-ray burst, dark energy and Laser Interferometer Gravitational-wave Observatory silence

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ABSTRACT

We discuss the recently reported discovery of fast radio bursts (FRBs) in the framework of the neutron star–neutron star (NS+NS) or neutron star–black hole (NS+BH) binary merger model. We concentrate on what we consider to be an issue of greatest importance: what is the NS merger rate given that the FRB rate (1/1000 yr−1 per galaxy) is inconsistent with gamma-ray burst rate as discussed by Thornton and should be significantly higher. We show that there is no discrepancy between NS merger rate and observed FRB rates in the framework of the Scenario Machine population synthesis – for a kick velocity of 100–150 km s−1 an average NS merger rate is 1/500–1/2000 yr−1 per galaxy up to z = 0.5–1. Based on the Scenario Machine NS merger rate estimates, we discuss the lack of positive detections on the ground-based interferometers, considering the Laser Interferometer Gravitational-wave Observatory.

Key words: gravitational waves – gamma-ray burst: general.

1 INTRODUCTION

The discovery of four fast radio bursts (FRBs; Thornton et al. 2013) combined with the previously discussed Lorimer burst (Lorimer et al. 2007) sparked interest in the generation mechanisms of extremely non-stationary and powerful radiation by neutron stars (NSs). There are different scenarios for FRBs (see Totani 2013 for a review) but here we discuss only NS+NS mergers, which we consider to be the most plausible explanation.

The possibility of the FRBs being generated by coalescing NSs was predicted by Lipunov & Panchenko (1996). A sufficiently close neutron binary transforms, by emitting gravitational waves, into a supercompact system with a lifetime of several milliseconds (several orbital revolutions). In the process, strong electric fields are generated and conditions arise for acceleration of relativistic particles, which, in turn, generate non-thermal radio emission (see also Hansen & Lyutikov 2001; Lyutikov 2013). Furthermore, Lipunova (1997) pointed out that a merger of NSs produces a highly magnetized and rapidly rotating object (a spinar), which can lose up to 10 per cent of its total energy in the form of electromagnetic radiation in the process of collapse (cf. Lipunova & Lipunov 1998; Lipunov & Gorbovskoy 2007a; Pshirkov & Postnov 2010). However, the radiation of a rapidly and, possibly, differentially rotating spinar has to be highly concentrated along the axis of the object and, most likely, should be properly identified with the gamma-ray burst (GRB; Lipunov & Gorbovskoy 2007b).

It is tempting to associate FRB with coalescing NSs, which, in turn, are viewed as the most likely source of short GRBs (Blinnikov et al. 1984; Paczynski 1986), the latter, in addition, being the best source of events for gravitational-wave experiments like Laser Interferometer Gravitational-wave Observatory (LIGO), Virgo, etc. (Grishchuk et al. 2001). However, in the case of this interpretation we have to answer the fundamental question of the occurrence frequency of such bursts in the Universe. A statistical analysis of FRBs shows that its rate should be equal to 10−3 yr−1 per a Milky Way type galaxy (Thornton et al. 2013). At the same time, the studies based on the population synthesis of binary stars usually yield substantially lower star merger frequencies: 10−6–10−4 yr−1 per galaxy (Clark, van den Heuvel & Sutantyo 1979; Hils, Bender & Webbink 1990; Portegies-Zwart & Sperew 1996; Bethe & Brown 1998; Portegies-Zwart & Yungelson 1998; Fryer 2000; Kalogera & Lorimer 2000; Kalogera et al. 2001; Belczynski & Kalogera 2002; Kim, Bhakthi Pranama Perera & McLaughlin 2013). The statistics of GRBs yields even lower occurrence frequencies. However, the latter estimate depends on the beaming angle of GRBs, which is very poorly defined (Sari, Piran & Halpern 1999; Coward et al. 2012). At the same time, Totani (2013) points out that theoretically estimated NS coalescence rates reported, in particular, by Thornton et al. (2013), characterize the average or present-day occurrence frequencies, whereas the actual NS merger rate varied dramatically over the age of the Universe.

This study is based on the results of the Scenario Machine (see a monography; Lipunov, Postnov & Prokhorov 1996a), which is the first and most mature population synthesis program aimed at simulating the evolution of a large number of single and binary stars. We focus on estimates of FRB rate in the framework of the
NS+NS binary merger model. In Section 2, we give a brief review of the Scenario Machine population synthesis. In Section 3, we calculate the NS merger rate for more plausible star formation rate (SFR) and compare with observed frequency of FRB events. In Section 4, we discuss NS mergers as a result of the long binary evolution process and put some constraints on the natal kick velocities of NSs. In Section 5, we compare our estimates of NS+NS and BH+BH merger rate with the upper limits for these rates set by the lack of gravitational-wave event detection in LIGO experiment. In Section 6, we summarize our results.

2 SCENARIO MACHINE AND NEUTRON STAR MERGER RATE

The idea of population synthesis is to use our (not always complete) understanding of the evolution of binary stars, including relativistic stages, to generate millions of computer-simulated artificial binaries in order to construct an artificial Universe and estimate the occurrence rates of various types of binaries and the associated cataclysmic events: supernova (SN) explosions, mergers, disruptions, etc. (Kornilov & Lipunov 1983). It allows one to study the evolution of a large ensemble of binaries, to estimate the number of binaries at different evolutionary stages, and to explain the observational data.

The very first population synthesis computations performed using the Scenario Machine showed that the current NS merger rate in a galaxy like ours is equal to several events in 4000 years (see Fig. 1, case e – 1 yr\(^{-1}\), \(\leq 20\) Mpc in Lipunov et al. 1987). Subsequent computations demonstrated a strong evolution of merger rate with the age of the Universe (Lipunov et al. 1995) and kick velocity (Lipunov, Postnov & Prokhorov 1997b).

Currently, about a dozen teams are implementing a Monte Carlo version of the population synthesis (Abadie et al. 2010). We use the Scenario Machine population synthesis program (see a monography; Lipunov et al. 1996a). The Scenario Machine, first, incorporates not only the evolution of binary stars, but also the rotational evolution of compact stellar objects: NSs and white dwarfs (WDs). Furthermore, because of a certain number of obscure issues in our understanding of the evolution of binary stars: poor understanding of common-envelope stages, possible collapse anisotropy, poor knowledge of the initial component mass ratio distribution in binaries – our approach uses the idea of optimization of all model parameters concerning NS evolution. For example, before computing the NS coalescence rate we optimize the parameters of evolution by comparing our artificial Galaxy with observations (Lipunov, Postnov & Prokhorov 1996b). We make sure that (1) the number of simulated binaries of various types agrees (approximately) with the corresponding number of actually observed binaries: binary radio pulsars, X-ray pulsars, black holes (BHs) with massive and low-mass companions, (2) the distribution of space velocities of radio pulsars agrees with the corresponding distribution for actually observed radio pulsars, and (3) that the same is true for the number and parameters of radio pulsars with optical components, etc.

If the number of observed reference quantities (the number of objects genetically related to NS+NS mergers) is sufficiently large, it is no longer important to what extent we might misestimate the hidden parameters such as the common-envelope parameter or the initial distribution of component mass ratios in binary stars. In other words, given a satisfactory explanation of the statistics of observed binary types we can be sure enough of the predicted statistics of unobserved events, such as NS mergers.

![Figure 1. Estimated merger rates for NS at the present epoch normalized per year per galaxy with a constant SFR of 1 M\(_{\odot}\) per year (like the Milky Way). The squares show the coalescence rate estimates obtained using the method of population synthesis (they are sometimes referred to as theoretical estimates). The asterisks show the ‘observed’ estimates based on the statistics of binary radio pulsars. The grey region outlines the Scenario Machine predictions. Clark et al. – Clark et al. (1979); SM87 – Lipunov et al. (1987); Hils et al. – Hils et al. (1990); Phinney – Phinney (1991); Narayan et al. – Narayan, Paczynski & Piran (1992); Tutukov, Yungelson – Tutukov & Yungelson (1993); Ibni et al. – Ibni, Tutukov & Yungelson (1995); SM95 – Lipunov et al. (1995); Curran, Lorimer – Curran & Lorimer (1995); SM97 – Lipunov et al. (1997b); Portegies-Zwart, Sperew – Portegies-Zwart & Sperew (1996); Van den Heuvel, Lorimer – Van den Heuvel & Lorimer (1996); Bailes – Bailes (1996); Portegies-Zwart, Yungelson – Portegies-Zwart & Yungelson (1998); Bethe, Brown – Bethe & Brown (1998); Stairs et al. – Stairs et al. (1998); Arzoumanian et al. – Arzoumanian, Cordes & Wasserman (1999); Fryer – Fryer & Kalogera (1997); Fryer – Fryer (2000); Burgay et al. – Burgay et al. (2003); Kim et al. – Kim et al. (2013).](https://academic.oup.com/mnras/article-abstract/440/2/1193/1024002)
considered BHs with mass close to the Oppenheimer–Volkoff limit ($\sim 2–2.5 \, M_\odot$). Such low-mass BHs are formed due to hyperaccretion during common-envelope stage (Chevalier 1993). In case of Fig. 1 low-mass BH+NS mergers are equivalent to NS+NS mergers because the horizon distance for these two types of binaries is approximately the same. Consequently, $10^{-4} \, \text{yr}^{-1}$ per galaxy is a real estimate for NS+NS mergers.

The LIGO experiment will detect nearby ($<100 \, \text{Mpc}$) coalescence events and therefore we are primarily interested in the estimate of the current coalescence rate. To estimate the total number of events to be recorded in LIGO and other ground-based experiments, we must sum up the SFR within the volume of the gravitational-wave horizon and add a small contribution provided by elliptical galaxies.

Note that population synthesis depends on an important hidden parameter, the so-called kick velocity. Here, we mean the natal kick velocity, in other words a velocity that NS receives due to anisotropy of SN explosions. However, this parameter can be constrained substantially by comparing the results of population synthesis with the statistics of NS+NS and NS+WD binaries. This is understandable. If the collapse of an SN is highly anisotropic then the probability for the binary to be preserved after the explosion is very low. The collapse anisotropy is especially critical for the number of NS binaries (i.e. Taylor type radio pulsars), because such systems form as a result of two SN explosions in the same binary. A special analysis performed in 1997 showed that the collapse anisotropy cannot be very high: 100–150 km s$^{-1}$ (Fig. 4; Lipunov et al. 1996b, see also fig. 1 in Lipunov et al. 1997b). With such a kick velocity the current coalescence rate should be equal to $1/3000–1/5000 \, \text{yr}^{-1}$ per $10^{11} \, M_\odot$ in a Milky Way type galaxy. However, this is the coalescence rate at the present epoch. As Totani (2013) pointed out, the coalescence rate could have been significantly higher in the past, and we appear to be dealing with redshifts about 0.5–0.1 if FRBs are cosmological events. It was first shown by the computations performed using the Scenario Machine that the coalescence rate evolves dramatically even if normalized to the rest frame (Lipunov et al. 1995).

Based on these computations and the modern data on SFR we derived the dependence of the NS coalescence rate in the Universe. We used the compilation of $U, F, R$, radio and $H\alpha$ SFR data from Hopkins & Beacom (2006) that were fitted with parametric form of Cole et al. (2001): $\rho_\ast = (a + b \, z) h/[1 + (z/c)^\alpha]$, where $h = 0.7$ is Hubble constant. SFR was determined up to $z \sim 6$. However, we extended it up to $z = 10$, because the SFR measurements at redshifts $6 < z < 10$ (Bouwens et al. 2004, 2005; Bouwens & Illingworth 2006) showed that the decline in SFR seen near $z = 6$ continues to higher redshifts. We used two sets of parameters for two possible extreme initial mass function (IMF): the modified Salpeter IMF with the high-power-law slope of $-1.35$ (Salpeter 1955) and the IMF of Baldry & Glazebrook (2003) with the high-power-law slope of $-1.15$, because other IMF approximations lie between these two (Hopkins & Beacom 2006). We then computed the NS coalescence rate, $n$, per comoving Mpc$^3$ at time $t$ for this type of SFR and the cumulative NS merger rate, $N$, for different kick velocities obtained from the Scenario Machine simulations (see Figs 2 and 3) and find that

$$n(t) = \int_0^t \text{SFR}(\tau) G(t - \tau) \, d\tau; \quad t \to z.$$  

Here, $G(t)$ is the NS merger rate in a sample galaxy after an instantaneous star formation at the moment $t = 0$. The number of events per unit time within the sphere of redshift $z$ is

$$N(z) = 4\pi \int_0^z \frac{n(t(z)) D(z)^2 \, dD}{1 + z^2},$$  

where $D(z)$ is a comoving distance.

### 3 Neutron Star Mergers and FRB

The most important remaining issue is to explain the observed occurrence frequency of FRB events. Thornton et al. (2013) point out that the occurrence rate of radio bursts is substantially higher than the predicted rate for NS mergers. However, Totani (2013) note that the discrepancy practically disappears if the increase of the NS coalescence rate in the past due to higher SFR in the Universe is taken into account. Actually, NSs should have sufficiently strong magnetic fields for the orbital triggering mechanism (Lipunov & Panchenko 1996) to operate. Unfortunately, the magnetic field dissipation time-scale for an NS is poorly known. Radio pulsar studies appear to imply that magnetic field dissipates during the first 10 Myr.
Figure 3. The number of NS+NS mergers per year inside the sphere of redshift $z$ for SFR based on the adopted Salpeter (1955) (a) and Baldry & Glazebrook (2003) (b) IMF for kick velocities in the 100–150 km s$^{-1}$ interval. The black square shows the estimated FRB rate (Thornton et al. 2013).

after the birth of the NS. However, the decay of radio pulsars may be due to the change of the angle between the magnetic and rotation axes rather than the dissipation of magnetic field. On the other hand, accreting NSs in binaries – X-ray pulsars – show that, judging by the companion, the magnetic field has an age and strength of $10^8$ yr and $10^{12}$ G, respectively (Lipunov 1992). The computations of the coalescence rate evolution as a function of the age after star formation show that 70 per cent of coalescing NSs have ages below 100 Myr (Lipunov et al. 1995).

Let us now compare the resulting NS coalescence rate using the Scenario Machine to the FRB rate. The FRB rate should be $1.0_{-0.5}^{+0.6} \times 10^4$ d$^{-1}$ sky$^{-1}$, where the 1$\sigma$ uncertainty assumes Poissonian statistics (Thronton et al. 2013). If it is interpreted as a burst rate per unit comoving volume out to $z = 1$, then for FRB rate we find $2.4_{-1.5}^{+1.2} \times 10^{-5}$ yr$^{-1}$ per Mpc$^3$. This result is consistent with the Scenario Machine estimate of NS+NS mergers (Fig. 2). The cumulative number of NS+NS mergers per year inside the sphere of redshift $z$ and FRB rate are presented in Fig. 3. The observed FRB rate is in better agreement with the model using SFR based on the adopted Salpeter (1955) IMF, than the Baldry & Glazebrook (2003) IMF-based one.

The concrete mechanism of the burst could be the revival of pulsar mechanism during the last revolutions before the coalescence, when the orbital frequency reaches several kHz (Lipunov & Panchenko 1996). The burst duration agrees well with the observed values. For estimations of burst luminosity it is possible to use the Crab pulsar luminosity and the magnetodipole formula which defines energy flux density (Poynting vector) through the light cylinder. Given that the Crab nebula with its 30 Hz rotation frequency emits a radio flux of 1000 Jy, a similar Crab with a 1 kHz frequency should produce a $10^6$ greater power output. This means that such an object would produce a 1 Jy flux from a distance of 70 Mpc. To explain the observed intensity of FRB, a 1 Jy flux should be observed from a source at 2 Gpc, i.e. 30 times more distant. To this end, we must assume that the FRB magnetic field should be stronger by the same factor of 30. An analysis of the distribution functions of radio and X-ray pulsars shows that up to one half of all NSs may possess such magnetic fields (Lipunov 1992). A factor of 2 is the approximate accuracy of the estimated FRB occurrence rate.

4 NEUTRON STAR MERGERS AND SHORT GRB

Recently, Abadie et al. (2010) published a paper about the predicted observed relativistic binary coalescence rates detectable by gravitational-wave detectors. Most of the paper is dedicated to predicting the detection rates for future (advanced) LIGO versions based on observational data and theoretical predictions. The wide range of the resulting NS merger rates is caused by the large uncertainties of kick velocities assumed in the theoretical models (Kalogera et al. 2004; Belczynski et al. 2008) which are being used by the above authors, although previously it was shown that high kick velocity values contradict to observable fraction of NS+NS binaries among the total number of pulsars on the sky (see fig. 1 in Lipunov et al. 1997b). For example, the used models completely lack the first and most complete, incorporating all the observed stages of the evolution of binaries with relativistic components and of ordinary stars, computations of the NS coalescence rates performed long before the studies used in that paper were published (for example, see a monography; Lipunov et al. 1996a).

We reiterate that NS mergers are a result of the long binary evolution process starting from two optical main-sequence stars, through the two SN explosions, and involving ejector, propeller, accreting evolution of the NSs, and after the pure evolution of the two NSs controlled the angular dissipation of gravitational waves. Before predicting the NS and BH coalescence rate one has to (1) explain the existence and statistical properties (the number and characteristic luminosity) of X-ray pulsars with massive OB-type stars, (2) the statistics of propellers and ejectors in massive systems, (3) the statistics of BHs in massive binaries, (4) the existence of binary radio pulsars with NSs and WDs, and (5) the lack of such systems with BHs. The answer to the question of the NS coalescence rate actually depends on what happens in low-mass stars. The point is that one of the most obscure issues in the evolution of binary stars – the common-envelope stage – shows up most conspicuously during the formation of low-mass cataclysmic variables, which is often controlled by gravitational waves.

The first computations of the NS coalescence rate made using the Scenario Machine date back to 1987 (Lipunov et al. 1987) and the results have remained practically unchanged until now. For example, after determining the optimum evolution parameters (Lipunov
et al. 1996b), we performed a detailed analysis of the effect of collapse anisotropy and confirmed our earlier conclusions that the kick velocity cannot exceed 100–150 km s$^{-1}$ for a Maxwellian distribution (Lipunov et al. 1996b, see also fig. 1 in Lipunov et al. 1997b). Otherwise, you cannot explain the observed NS+NS fractions among the total number of pulsars (Fig. 4). It must be emphasized that the characteristic velocity depends on the form of the natal kick distribution. Thus, earlier a number of authors (Lyne & Lorimer 1994; Arzoumanian, Chernoff & Cordes 2002) proposed non-Maxwellian distributions with a higher fraction of higher kick velocities (Fig. 5). This is especially important for explaining the observed distribution of radio pulsar velocities. However, the particular form of the distribution is of little importance for this study, because in all the distributions considered the number of small natal kicks is approximately the same to within a factor of 2.

5 LIGO SILENCE

If we indeed plan to associate FRB with the coalescence of NSs, we must adopt our average estimate of the NS coalescence rate at distances out to 40 Mpc (the horizon distance for LIGO S6; Abadie et al. 2012), i.e. $10^{-2}$ yr$^{-1}$ per Mpc$^3$. Given the small volume of this region, we obtain a rate of two events per year, which is consistent with non-detection of gravitational pulses in the LIGO experiment (see Fig. 6). The upper limit for NS coalescence rate set by the lack of gravitational-wave event detection in LIGO experiment is $1.3 \times 10^{-4}$ yr$^{-1}$ per Mpc$^3$ (35 events per year; Abadie et al. 2012). LIGO silence is therefore consistent with astronomical observational data (Fig. 6). However, since a typical BH is formed with a mass higher than the NS mass and the detection volume is proportional to $M^{3/2}$, where $M$ is a ‘chirp’ mass of the binary system, the expected detection rate of binary BH by LIGO is 10–100 times higher than the binary NS merging rate (Lipunov, Postnov & Prokhorov 1997a). According to this for BH mergers we obtain more than 20 events per year that slightly contradict LIGO limit for such type of events (20 events per year; Abadie et al. 2012).

The optimum horizon distance for NS+NS events in Advanced LIGO is assumed to be equal to 445 Mpc (Abadie et al. 2010). If LIGO reaches such sensitivity, the gravitational waves from merging NS are surely detected. Within such distances the Scenario Machine predicts several thousand events per year. The cumulative rate of events per year in the volume within 500 Mpc can be approximately described by formula: $(4 \pm 2) \times 10^{-5} (R/\text{Mpc})^3 \text{yr}^{-1}$, where $R$ is the horizon distance in Mpc.
6 DISCUSSION

We present for the first time the evolution of NS coalescence rate as a function of redshift in terms of a reasonable star formation function in the Universe. For a kick velocity of 100–150 km s⁻¹ this function yields an average coalescence rate of 1/500–1/2000 yr⁻¹ per galaxy in the comoving volume corresponding to z = 0.5–1, which is consistent with observational estimates (Thornton et al. 2013). Our analysis is based on the results of population synthesis studies performed in 1995–1997 using the Scenario Machine. We accept the criticism from the teams that take into account the following five effects in their computations: mass exchange in binaries, common-envelope stages, angular momentum carry-over by matter, magnetic stellar wind, and gravitational waves, anisotropy of SN explosions (the kick velocity effect), and rotational evolution of magnetized NSs and WDs. In addition, these computations should correctly describe the statistics of 10 types of binaries or their observed properties: (1) binary radio pulsars (with NSs, WDs, and optical companions), (2) X-ray binaries with massive OB-type stars, (3) evolution of the Type Ia SN rate as a function of the age of the Universe, (4) distribution of intermediate polaris, (5) velocities of single radio pulsars, (6) total X-ray luminosity of galaxies, (7) BHs paired with massive companions (Cyg X-1), and (8) statistical properties of millisecond pulsars spun up by accretion. The fact that we did not detect any gravitational waves from NS mergers in LIGO search is consistent with our astronomical predictions but BH mergers could already be registered.

We finally argue that there are no discrepancies between the NS coalescence rate and FRB occurrence rate. Furthermore, we predict a certain (about 20 per cent) anisotropy of FRB (directivity pattern).

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