Supernovae – Optical Precursors of Short Gamma-Ray Bursts

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The probability of observing “supernova – gamma-ray burst” (GRB) pair events and recurrent GRBs from one galaxy in a time interval of several years has been estimated. Supernova explosions in binary systems accompanied by the formation of a short-lived pair of compact objects can be the sources of such events. If a short GRB is generated during the collision of a pair, then approximately each of $\sim 300$ short GRBs with redshift $z$ must have an optical precursor – a supernova in the observer’s time interval $< 2 \cdot (1+z)$ yr. If the supernova explosion has the pattern of a hypernova, then a successive observation of long and short GRBs is possible. The scenario for the generation of multiple GRBs in collapsing galactic nuclei is also discussed.

INTRODUCTION

Progress in investigating gamma-ray bursts (GRBs) in the last decade is associated primarily with the observation of their radio, optical, and X-ray afterglows. Concurrently, the theoretical models of stellar evolution and supernova explosions, in particular, the models for the collimation of high-energy jets probably responsible for the generation of GRBs, are improved. According to the most popular scenarios, long GRBs (with a duration of more than 2 s) emerge during supernova explosions called hypernovae (Paczynski 1998; MacFadyen and Woosley 1999), while short bursts are produced during the coalescence of two neutron stars (NSs) or a NS and a black hole (BH) in binary systems (Blinnikov et al. 1984). However, the models in which long GRBs can be generated at the final stage of the collision between compact and ordinary stars in a binary system have also been proposed (Barkov and Komissarov 2009).

GRBs that have a complex structure with a long time interval between gamma-ray peaks and a delay between gamma-ray, optical, and X-ray maxima deserve special attention. A significant duration of the light curves for some GRBs (up to $2 \cdot 10^4$ s) and the presence of precursor peaks suggest that the central engine can operate much longer than the gamma-ray generation stage (Lipunov and Gorbovskoy 2007). Apart from bursts with a complex structure, several GRBs that can be considered as recurrent ones or as clusters of bursts may have been observed. One of the most unusual events of this kind was recorded in October 1996, when four separate GRBs came from a small region of the sky during two days (Meegan et al. 1996; Graziani et al. 1998). The probability of a chance projection of the sources of independent GRBs onto the same line of sight is only $3.1 \cdot 10^{-5} \div 3.3 \cdot 10^{-4}$. Since in an individual galaxy the NS-NS or NS-BH coalescences in binary systems occur, on average, once in $10^5 – 10^6$ yr, the generation of four GRBs in one galaxy during two days seems highly unlikely in this model. At the same time, the spectra of these GRBs rule out their interpretation as the emission of a soft gamma
repeater. However, this event can be attributed to the class of superlong (with a duration > 500 s) GRBs; several such bursts were detected in the BATSE catalog (Tikhomirova and Stern 2005). If the events recorded in October 1996 belong to different episodes of superlong bursts, then the probability that these events are recurrent GRBs is very low (Graziani et al. 1998; Tikhomirova and Stern 2005). GRB clusters were also searched for previously by the methods of statistical analysis (Kuznetsov 2001).

Several multistage supernova core collapse models and explanations of GRBs with a complex structure have been proposed. The model for the fragmentation of a rotating supernova core with the formation of several low-mass NSs or BHs that subsequently coalesce under the influence of losses through gravitational radiation was discussed by Imshennik and Nadyozhin (1992) and Imshennik (1995). In particular, the possibly observed double neutrino burst from SN 1987A (Stella and Treves 1987; Berezinsky et al. 1988; Imshennik and Nadyozhin 1988; Imshennik and Ryazhskaya 2004) can be explained in such models. Davies et al. (2002) investigated the scenario in which the fragments coalesce several hours or days after the supernova explosion and a GRB is generated during their collision. The intense peaks in the GRB profile (e.g., in GRB 050502b) long after its onset can be explained in a similar model (King et al. 2005). Variants with two collapse stages with the formation of initially a NS and subsequently a BH have been proposed (Rujula 1987; Hillebrandt et al. 1987). Successive high-energy events in a short time interval are also possible in this model. GRBs with a precursor in a time interval of ~100 s can be explained in the spinar model (Lipunov and Gorbovskoy 2007; Lipunova et al. 2009). Superlong GRBs (with a duration up to several thousand seconds) and precursor peaks in the GRB time profile can emerge at the long collapse stage of the coalesced stars in a binary system (Barkov and Komissarov 2009). The observation of multiple GRBs can also be the result of gravitational lensing (Babichev and Dokuchaev 2000).

In this paper, we investigate the limiting case of the standard picture (Hills 1983; Grishchuk et al. 2001) of supernova explosions in binary systems where a fully-fledged (unfragmented) NS or BH is produced by the explosion that acquires a kick velocity, passes to a new orbit, and then, under gravitational radiation, comes closer to and coalesces with the second compact object of the pair. A change in parameters is possible during the explosion when the coalescence occurs only a few years after the supernova explosion. Thus, the generation of a recurrent high-energy event from one source in a short time interval is also possible within the standard picture of a supernova explosion. The main goal of this paper is to estimate the probability of such events and to discuss the prospects for their recording.

As an alternative scenario for the generation of multiple GRBs, we briefly discuss the scenario of collisions between NSs and BHs in collapsing galactic nuclei. These collisions can serve as GRB sources. The dynamical evolution of a NS cluster can lead to its gravitational collapse in the process of avalanche-like contraction (Zel’dovich and Podurets 1965; Shapiro and Teukolsky 1986). Multiple GRBs can be generated during this stage in a time interval of several days. The GRB detected in October 1996 (Meegan et al. 1996; Graziani et al. 1998) can be naturally explained in this model.
COLLISIONS IN BINARY SYSTEMS

In this section, we will follow the notation from Grishchuk et al. (2001), which presents the main results of the kinematics of binary star systems and their evolution as a result of supernova explosions and gravitational wave emission. Additionally, we will take into account the gravitational capture effect.

Consider a binary system in a circular orbit that consists of a star with mass $M_1$ and a compact object (NS or BH) with mass $M_2$. In reality, the orbits of binary systems with compact objects are highly eccentric and the supernova explosion can occur at any point of their elliptical orbits. It can be assumed that the explosion is most likely at apastron and periastron, where the star undergoes gravitational kicks from tidal forces. Gravitational kicks can serve as triggers of the explosion of an unstable star on the verge of collapse, but this effect has not yet been investigated. Here, we consider a circular orbit to obtain an analytical estimate. Although this approach is not quite accurate, it simplifies considerably the calculations and, in a sense, serves as an averaging of the actual elliptical orbit. A more accurate calculation could be performed by population synthesis methods.

The star $M_1$ explodes as a supernova, leaving a compact remnant with mass $M_c$ behind. We will mark the quantities immediately before and after the explosion by the subscripts “i” and “f”, respectively. Denote $M_i = M_1 + M_2$, $M_f = M_c + M_2$, and $\mu_f = M_c M_2 / (M_c + M_2)$. The initial separation between the pair components is $a_i$ and the initial relative velocity is $v_i = (GM_i / a_i)^{1/2}$. We will direct the x axis from $M_2$ to $M_1$ and the y axis along $\vec{v}_i$. After the explosion, $M_c$ acquires a kick velocity $\vec{w}$ in the rest frame of $M_1$ in such a way that $\vec{v}_f = (w_x, v_i + w_y, w_z)$. The orbital parameters after the explosion can be found from the energy and angular momentum conservation laws. We will write the energy conservation law as

$$\frac{\mu_f v_f^2}{2} - \frac{GM_c M_2}{a_i} - \Delta E_{gw} = -\frac{GM_c M_2}{2 a_f},$$

where, in contrast to Grishchuk et al. (2001), we added the energy losses through gravitational radiation during the first approach $\Delta E_{gw}$.

In most situations, the gravitational radiation is very weak and the term $\Delta E_{gw}$ in (1) may be neglected. Let us first consider this case. Given the angular momentum conservation law, well known results for the new orbital parameters are then obtained (Grishchuk et al. 2001). The binary system remains bound under the condition $v_f < v_i (2/\chi)^{1/2}$, where $\chi = M_i / M_f$. Subsequently, slow secular contraction of the binary through the emission of gravitational waves takes place. We are interested in the case where a short-lived binary whose orbit has a high ellipticity $1 - e_f \ll 1$ is formed after the explosion. From Eqs. (A.22)-(A.24) in Grishchuk et al. (2001), we derive an asymptotic (when $1 - e_f \ll 1$) expression for the lifetime of the pair:

$$t_f = \frac{3 c^5 a_i^4 (1 - e_f^2)^7/2}{85 G^3 M_f^2 \mu_f}.$$
Figure 1: The two upper curves indicate the formation probability $P_1(< \tau)$ of a pair of compact objects with a lifetime $< \tau$ (3). The lower curves indicate the probability $P_2(< \tau)$ in the case of a gravitational capture (9). The solid curves correspond to an isotropic kick velocity distribution $\sigma_x = \sigma_y = \sigma_z = 250$ km s$^{-1}$ and the dashed curves correspond to $\sigma_x = \sigma_z = 50$ km s$^{-1}$ and $\sigma_y = 250$ km s$^{-1}$.

Let us require that the lifetime be less than some fixed value: $t_f < \tau$. Below, we will assume that the distribution in velocity $\vec{w}$ is Gaussian (Grishchuk et al. 2001) in each component with the root-means-square values of $\sigma_x$, $\sigma_y$, and $\sigma_z$. Note that other (non-Gaussian) distributions fitting the pulsar velocity data were also proposed (for a discussion, see, e.g., Grishchuk et al. 2001). The condition $t_f < \tau$ separates out the region corresponding to the event we consider in velocity space. Integrating the Gaussian distribution over the velocity components $w_x$, $w_y$, and $w_z$ under the condition $t_f < \tau$, we obtain the probability of the necessary change in orbit:

$$P_1(t_f < \tau) \simeq \frac{\nu_i^3 A^{2/7}}{2\sqrt{2\pi} \sigma_x \sigma_y \sigma_z} e^{-\nu_i^2/2\sigma_i^2} \int_0^{p_{\text{max}}} dp \frac{(2 - \chi p^2)^{1/7} e^{-p^2/2\nu_i^2}}{\nu_i^2 \tau},$$  \label{eq:3}

where

$$A = \frac{85 M_f^2 \mu_f \nu_i^8}{3c^5 G M_i^4 \chi^{7/2} \tau},$$  \label{eq:4}

and $p_{\text{max}}$ corresponds to the condition that the period of the new orbit does not exceed $\tau$:

$$p_{\text{max}}^2 = \frac{2}{\chi} - \left(\frac{2\pi G M_f}{\nu_i^3 \tau}\right)^{2/3}.$$  \label{eq:5}

At low $\tau$, the probability $P_1(t_f < \tau)$ may turn out to be zero, because not only the time of contraction through gravitational radiation but also even the orbital period $T_f$ of the
new orbit will be greater than \( \tau \). From the condition \( p_{\text{max}} = 0 \), we obtain the minimum possible time \( \tau \):

\[
\tau_{\text{min}} = \frac{2\pi GM_f}{v_i^3} \left( \frac{\chi}{2} \right)^{3/2}.
\]

In (3), we disregarded the low probability of a direct hit at exact compensation \( w_y = -v_i, w_z = 0 \). However, this case was included in the probability of a direct capture calculated in the next section.

As an example, let us perform calculations for the following typical set of parameters: \( M_1 = 15M_\odot, M_2 = 10M_\odot, M_c = 1.4M_\odot, T_i = 1 \text{ day}, \sigma_x = \sigma_y = \sigma_z = 250 \text{ km s}^{-1} \); then, \( \tau_{\text{min}} = 0.44 \text{ day} \). The derived probability (3) is very low (see the figure). We are interested in the ratio of quantity (3) to another small quantity \( P_{\text{tot}} \) — the probability that a binary with a lifetime less than the age of galaxies will be produced by the explosion. To accurately calculate \( P_{\text{tot}} \), we need detailed population synthesis calculations; it is also necessary to take into account the distribution of binary systems in their component masses and in \( a_i \) as well as the gas-dynamic interaction between the stars. However, no such detailed calculation is required for the purposes of this paper. The result (3) becomes inaccurate at large \( \tau \), because it was obtained in the limit \( e_f \to 1 \), but as an acceptable estimate we can assume that \( P_1(t_f < \tau) \propto \tau^{2/7} \). The fraction of the cases where the collision occurs a time \( \tau \) after the supernova explosion can then be found as follows:

\[
P_{\text{rel}} = P_1/P_{\text{tot}} \sim (\tau/t_G)^{2/7} \simeq 3 \cdot 10^{-3} \left( \frac{\tau}{2 \text{ yr}} \right)^{2/7},
\]

where \( t_G \simeq 12 \cdot 10^9 \text{ yr} \) is the characteristic age of the galaxies formed at \( z_G \simeq 4 \). The relative probability (7) is the main result of this paper. A slightly lower value, \( P_1(t_f < 2 \text{ yr})/P_1(t_f < t_G) \sim 1.6 \cdot 10^{-3} \), is obtained in a direct calculation based on Eq. (3) for the above set of parameters.

Thus, if the collisions of compact objects in pairs produce short GRBs, then approximately one GRB preceded by a supernova explosion in the observer’s time interval \( < 2 \cdot (1 + z) \text{ yr} \), where \( z \) is the redshift of the GRB source, will be found among every \( \simeq 300 \) such GRBs. In addition to the optical afterglow, such GRBs have an optical precursor. Since several thousand GRBs have been detected to date, the events considered here can be among them.

Long GRBs can also be generated during supernova explosions if the explosion has the pattern of a hypernova (Paczynski 1998; MacFadyen and Woosley 1999). If a hypernova exploded in a binary system and if a collision involving a NS subsequently occurred after time \( \tau \), then we have two successive GRBs, long and short ones. However, since only a small fraction of collapsing massive stars produce an observable long GRB (the GRB is seen only if the collimated jet is directed toward the observer), the probability of observing recurrent GRBs is very low and, to all appearances, is outside the observational capabilities.

From the viewpoint of observations, it is also necessary to estimate the probability of a chance projection of an independent supernova into the error box of the observed GRB. The question about the properties of such GRBs is also of considerable interest, because
the collision of compact objects occurs in the medium that left after a recent supernova explosion and that affects the expanding fireball.

To ascertain how reasonable the values given by Eq. (3) are at large \( \tau \), let us make the following simple estimate. The rate of supernova explosions in one galaxy is \( \sim 2 \cdot 10^{-2} \) yr\(^{-1} \). About 50\% of the stars are members of binary systems. Let us assume that the pair survival probability during the first explosion is \( \sim 0.5 \). It follows from Eq. (3) for our set of typical parameters that \( P_1(t_f < t_G) \sim 4 \cdot 10^{-2} \). Multiplying these numbers yields an estimate of the collision rate per galaxy \( \sim 2 \cdot 10^{-4} \) yr\(^{-1} \), which is consistent, in order of magnitude, with the population synthesis calculations. A modification of the scenario considered in this section could be a consideration of the change in the orbits of compact objects during supernova explosions in triple hierarchical systems, but the probability of the corresponding events is much lower.

The kick velocity acquired by a compact supernova remnant has a significant effect on the collision rate of binary NSs and BHs (see Grishchuk et al. 2001; Postnov and Kuranov 2008; Kuranov et al. 2009; and references therein). Both the origin of the kick velocity and its distribution in directions remain unclear so far. The observed correlation between the velocity direction and the spin axis in young single radio pulsars may be the key to understanding the mechanism for the appearance of the kick velocity. However, this correlation is not absolute and about half of the pulsars have a large angle between these directions. Variants with a non-central kick, when the NS acquired an additional angular momentum during the explosion, are also possible.

A rotating presupernova has the preferential directions along the spin axis in which the kick velocity may be directed, while the choice between these two directions is determined by the inclination of the spin axis to the direction of the orbital angular momentum if the kick velocity is affected by the interaction between the pair components (mass transfer, tidal forces, or magnetic field structure). Another preferential direction is the line connecting the two stars, because it is along this line that the star is deformed by the tidal gravitational forces and the explosion nonsphericity may correspond to this direction. This deformation can lead to an asymmetric, in the x direction, explosion and, accordingly, to the appearance of a kick velocity along the x axis. The combined effect of various factors in such a way that the kick velocity has different directions in binary systems with different parameters is not ruled out either.

We performed calculations for several relations between \( \sigma_x \), \( \sigma_y \), and \( \sigma_z \). In the case of \( \sigma_x = \sigma_z = 50 \) km s\(^{-1} \) and \( \sigma_y = 250 \) km s\(^{-1} \), the probability \( P_1 \) is higher than that for the isotropic case of \( \sigma_x = \sigma_y = \sigma_z = 250 \) km s\(^{-1} \), because a lower kick velocity along the x and z axes facilitates the compensation of the orbital velocity along the y axis. However, the case with the greatest \( \sigma_y \) probably cannot be realized, because the y direction is not preferential in the above sense. On the contrary, in the cases of \( \sigma_x = 250 \) km s\(^{-1} \), \( \sigma_y = \sigma_z = 50 \) km s\(^{-1} \), and \( \sigma_x = \sigma_y = 50 \) km s\(^{-1} \), \( \sigma_z = 250 \) km s\(^{-1} \), the derived probability is considerably lower (it is not shown in the figure), because the compensation of the velocity \( v_i \) is suppressed exponentially.
Thus, the kick velocity is fundamentally important in determining the total probability. However, it should be noted that our calculations of the relative fraction of short-lived pairs are largely independent of the pattern of the kick velocity, because it affects both $P_1$ and $P_{\text{tot}}$ in a similar way, while their ratio and the universal dependence $P_{\text{rel}} \propto \tau^{2/7}$ remain almost unchanged.

**GRAVITATIONAL CAPTURE IN A BINARY SYSTEM**

Let us now take into account the gravitational capture effect, when the binary components pass fairly close to each other after the supernova explosion and an energy comparable to the total kinetic energy of the binary components is emitted through gravitational waves already during the first approach. Using the results from Quinlan and Shapiro (1987), we will obtain the energy emitted in the time $T_f/2$ (half of the orbital period),

$$\Delta E_{gw} \simeq \frac{85\pi G^{7/2}M_2^2M_2^2M_f^{1/2}}{3 \cdot 2^{7/2}c^5r_p^{7/2}},$$

where $r_p = a_f(1 - e_f)$ is the minimum distance of the closest approach during the first flyby. An exact solution of the problem including strong gravitational wave emission presents great difficulties. However, the following simple estimate can be made. During the gravitational capture, an energy comparable to the kinetic energy is emitted through gravitational waves. In this case, the first and third terms on the left-hand side of Eq. (1) and the term on the right-hand side are all of the same order of magnitude. Hence, integrating, as in Eq. (3), over the distribution of velocities $\vec{w}$, we obtain

$$P_2(t_f < \tau) \simeq \frac{v_i^2 B^{2/7}}{2\sqrt{2\pi} \sigma_x \sigma_y \sigma_z} e^{-v_i^2/2\sigma_y^2} \int_{p_{\min}(\tau)}^\infty dp \, p^{-4/7} e^{-p^2/2\sigma_z^2},$$

where

$$B = \frac{85\pi M_e M_2 v_i^5}{3c^5 M_1^2 \chi^5},$$

$$p_{\min}(\tau) = \max \left\{ \frac{GM_i}{v_i^3 \tau}; \left( \frac{\sqrt{2\pi} GM_f}{v_i^3 \tau} \right)^{1/3} \right\}.$$  

Here, the first term in parentheses corresponds to the condition that $M_e$ will reach $M_2$ in time $\tau$, while the second term was obtained from the relation $t_f = \tau$, where $t_f$ is expressed by (2). If all masses are of the same order of magnitude, then $B/A \sim T_i/\tau$, i.e., the gravitational capture effect dominates only for very low $\tau$, less than the initial orbital period. The results of our calculations in the case of gravitational captures are shown in the figure. At $\tau \geq 0.5$ day, the gravitational capture effect may be neglected.

Note that the binary system can remain gravitationally bound even if $v_f > v_i(2/\chi)^{1/2}$ due to the gravitational capture. Thus, including the gravitational capture removes the constraint on $v_f$, although the capture probability is very low.
In this section, we will discuss an alternative GRB recurrence scenario that associates recurrent and multiple (> 2 events) bursts with the final evolutionary stage of the central star clusters in galactic nuclei and the formation of supermassive BHs. Bursts are generated during random collisions between NSs and BHs in clusters. Some elements of this model were discussed previously (Dokuchaev et al. 1997, 1998).

Dense star clusters are present in the nuclei of most large structured galaxies. For spiral galaxies, the masses of these clusters correlate with the total stellar masses of the galaxies (Erwin and Gadotti 2010). A compact cluster of NSs and BHs must be formed at the center of an initial cluster of ordinary stars through mass segregation (the settling of more massive stars to the cluster center) and supernova explosions (Colgate 1967; Sanders 1970). Below, it is this inner subsystem of compact objects that we call a cluster. Stellar-mass BHs are formed during pair collisions of NSs that subsequently continue to build up their mass through recurrent mutual coalescences. Concurrently, the central region of the cluster contracts through the processes of pair relaxation, which can result in the loss of stability by it and gravitational collapse into a supermassive BH. Although most supermassive BHs in galactic nuclei have probably been formed according to a different scenario, through the collapses of gaseous clouds in protogalaxies (for a review, see Dokuchaev et al. 2007), the model of a collapsing cluster is, in a sense, an inevitable evolutionary stage of galactic nuclei. The possibility of a gravitational collapse is limited only by the time needed for pair relaxation of stars in the cluster (Dokuchaev 1991). In this section, we will assume that the gravitational collapses of central clusters consisting of stellar-mass BHs with an admixture of non-coalesced NSs actually took place in a significant fraction of galaxies, \( f_c \sim 1 \). We consider the fraction of NSs in the cluster \( f_{NS} \) at the stage immediately before its collapse to be a free parameter that depends on the cluster’s evolutionary track.

Single GRBs can be generated in clusters that are still far from the collapse stage (Dokuchaev et al. 1998). However, here we are interested in the cases of fast GRB recurrence. Such GRBs can be generated directly in the process of cluster core collapse accompanied by rapid avalanche-like contraction at the cluster center (Zel’dovich and Podurets 1965; Shapiro and Teukolsky 1986). We will show that the avalanche can last \( \sim 2 \) days when some plausible cluster parameters are chosen and about four NS coalescences will occur in this time, which corresponds to the multiple burst detected on October 27, 1996 (Meegan et al. 1996; Graziani et al. 1998).

The BH masses in the central part of a collapsing cluster grow significantly by the time of its collapse through coalescences (Quinlan and Shapiro 1987). Suppose that their masses immediately before the collapse are \( m_{BH} \sim 10m \), where \( m \simeq 1.4M_\odot \) is the NS mass. Suppose also that the cluster has mass \( M \) (predominantly in the form of BHs) and that NSs account for a small fraction \( f_{NS} \ll 1 \) of this mass. The effective radius of the cluster is \( R = MG/2v^2 \), where \( v \) is the velocity dispersion. When the cluster reaches the collapse stage, a dense core with mass \( M_c \), radius \( R \simeq 3R_{g,c} \), where \( R_{g,c} = 2GM/c^2 \), and velocity
dispersion $u \simeq 0.3c$ (at the marginally stable orbit) emerges at its center. All stars with an angular momentum $J < 2mcR_{g,c}$ will fall along a spiral to the core without returning to the cluster. The presence of quasi-elliptical orbits that connect different layers of stars between themselves are of crucial importance for the growth of the avalanche of falling stars (Zel’dovich and Podurets 1965). According to the numerical calculations by Shapiro and Teukolsky (1986), several percent of the total cluster mass will fall onto the forming BH in a dynamical time $t_{\text{dyn}} = R/v$.

At $f_{\text{NS}} \ll 1$, the NS-BH coalescences are more efficient than the NS-NS ones. At the above mass ratio $m_{\text{BH}} \sim 10m$, the NS does not vanish under the BH horizon as a whole but is disrupted by tidal forces to produce a relativistic fireball and to generate a GRB. The rate of NS-BH coalescences in the core can be calculated from the formula $\dot{N}_c = \sigma_{\text{cap}}uN_{\text{NS}}n_{\text{BH}}$, where the gravitational capture cross section $\sigma_{\text{cap}}$ is given in Mouri and Taniguchi (2002), $N_{\text{NS}} = f_{\text{NS}}M_c/m$ is the number of NSs in the core, and $n_{\text{BH}}$ is the BH number density in the core. If we choose $M = 10^7M_\odot$ and $v = 0.066c$, then the cluster’s dynamical time (core collapse duration) will be $t_{\text{dyn}} = GM/v^3 = 2$ days. The number of NS-BH collisions in the core in this time is

$$\dot{N}_c t_{\text{dyn}} \simeq 4 \left( \frac{f_{\text{NS}}}{10^{-4}} \right) \left( \frac{M_c}{5 \cdot 10^8 M_\odot} \right)^{-1}.$$  

(12)

The rate of NS-BH collisions in the entire cluster before its collapse can be estimated similarly:

$$\dot{N} \simeq 7 \cdot 10^{-3} \left( \frac{f_{\text{NS}}}{10^{-4}} \right) \left( \frac{M}{10^7 M_\odot} \right)^{-1} \left( \frac{v}{0.066c} \right)^{31/7} \text{yr}^{-1},$$  

(13)

i.e., the cluster before its collapse was not the source of bursts with fast recurrence. As a result, we have four NS-BH collisions and, accordingly, four GRBs from the collapsing core in a time of two days, which is required to explain the temporal characteristics of the multiple burst (Meegan et al. 1996; Graziani et al. 1998). Some influence on the properties of the fireball in this model can be exerted by its scattering by the forming central supermassive BH.

If the BH formation epoch lasts $t_0 \simeq 10$ Gyr, then the total rate of such collapses in the observable Universe is estimated as

$$\dot{N}_h \sim \frac{4\pi}{3} (ct_0)^3 f_{\text{c}} n_g t_0^{-1} \approx 0.1 \left( \frac{f_{\text{c}} n_g}{10^{-2} \text{Mpc}^{-3}} \right) \text{yr}^{-1},$$  

(14)

where $n_g$ is the observed number density of structured galaxies. Since the observations have been carried out for almost 40 years, it seems natural that there can be multiple GRBs predicted by this model among the observed GRBs.

**CONCLUSIONS**

We estimated the probability of supernova-GRB pair events. One of every $\sim 300$ short GRBs in a time interval of $\sim 2$ yr was shown to have an optical precursor – the
supernova during the explosion of which the second compact object was born in the pair. The detection of such supernova-GRB pairs will serve as a weighty argument for the model of the coalescence of binary compact objects as the sources of short GRBs first proposed by Blinnikov et al. (1984). We also considered two mechanisms for the generation of recurrent GRBs from one point of the sky in time intervals of several years and several days. The first mechanism is related to the evolution of stars in close binary systems. In this model, the first GRBs are generated during a supernova explosion, while the second GRB emerges during the collision of compact stars – the supernova remnants. However, the probability of observing such recurrent GRBs is very low, because only a small fraction of exploding massive stars produce a detectable GRB. In the second scenario, recurrent GRBs are generated in evolved star clusters in galactic nuclei immediately before the gravitational collapse of their dense central regions. Since recurrent GRBs are generated in the medium “prepared” by the preceding GRBs, the succeeding GRBs in both scenarios can carry information about their generation conditions in their spectral-temporal characteristics. The evolution of multiple fireballs was considered by Berezinsky and Dokuchaev (2006). Although the events recorded on October 27, 1996, cannot be attributed to short bursts, the evolution of the fireball in the dense gaseous medium of the galactic nucleus perturbed by the preceding fireballs can be different from that in an isolated binary system. Therefore, the question about the properties and duration of the GRBs produced by the collisions of compact objects in central clusters remains an open one. The preceding (on long time scales) supernova explosions or GRBs can also be revealed by the observations of giant gaseous arcs and induced star formation at the boundary of an expanding gaseous bubble (Efremov et al. 1998). Supernova explosions and the collisions of compact objects must be accompanied by the emission of powerful signals in the form of gravitational waves (Ruffert and Janka 1998; Cheng and Wang 1999; Murphy et al. 2000; Grishchuk et al. 2001). Although the searches for the gravitational bursts accompanying GRBs have not yielded any results (Abbott et al. 2009), gravitational wave astronomy can provide decisive data on the GRB mechanisms in the near future (Grishchuk et al. 2001).

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