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Gamma Ray Bursts from the Evolved Galactic Nuclei

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ABSTRACT

A new cosmological scenario for the origin of gamma ray bursts (GRBs) is proposed. In our scenario, a highly evolved central core in the dense galactic nucleus is formed containing a subsystem of compact stellar remnants (CSRs), such as neutron stars and black holes. Those subsystems result from the dynamical evolution of dense central stellar clusters in the galactic nuclei through merging of stars, thereby forming (as has been realized by many authors) the short-living massive stars and then CSRs. We estimate the rate of random CSR collisions in the evolved galactic nuclei by taking into account, similar to Quinlan & Shapiro (1987), the dissipative encounters of CSRs, mainly due to radiative losses of gravitational waves, which results in the formation of intermediate short-living binaries, with further coalescence of the companions to produce GRBs. We also consider how the possible presence of a central supermassive black hole, formed in a highly evolved galactic nucleus, influences the CSR binary formation. This scenario does not postulate ad hoc a required number of tight binary neutron stars in the galaxies. Instead, it gives, for the most realistic parameters of the evolved nuclei, the expected rate of GRBs consistent with the observed one, thereby explaining the GRB appearance in a natural way of the dynamical evolution of galactic nuclei. In addition, this scenario provides an opportunity for a cosmological GRB recurrence, previously considered to be a distinctive feature of GRBs of a local origin only. We also discuss some other observational tests of the proposed scenario.

Subject headings: gamma-rays: bursts — galactic nuclei — black hole physics
1. Introduction

In spite of significant progress in the accumulation of data on GRBs they are still mysterious — chiefly because of uncertainty whether they represent a local or a cosmological phenomenon or a mixture of both (for reviews, see e.g. Meegan et al. 1992, Lamb 1995, Paczyński 1995) and due to the enigmatic nature of the central engine.

If GRBs are cosmological in origin (Usov and Chibisov 1975; Mao and Paczyński 1992), they have to have a huge intrinsic luminosity — on the level of, or higher than, the luminosity of a supernova explosion. In the framework of a cosmological scenario, different possible sources of GRBs have been proposed, such as the collapse of supermassive magnetic stars (Usov and Chibisov 1975; Ozernoy and Usov 1973), the merging of neutron stars (NSs) or neutron stars and black holes (BHs) in close binaries of distant galaxies (Cavallo and Rees 1978; Paczyński 1986; Goodman 1986), the superconducting cosmic strings (Plaga 1994), etc.

If at least a part of GRBs occurs in the Milky Way halo, they are generated in the magnetosphere or on the surface of NSs (Higdon and Lingenfelter 1990; Harding 1991). Isotropy of GRB distribution puts severe constraints on both the distribution of the relevant NSs between the Galactic disk and halo and the associated physical parameters of NS (Paczyński 1991; Li & Dermer 1992; Gurevich et al. 1993; Hakkila et al. 1995; Hartmann & Narayan 1996; Briggs et al. 1996).

Owing to statistical uncertainties and inhomogeneities of current GRB samples, available data on possible scalings of bright and dim GRB durations, fluxes, and spectra fail to provide an unambiguous distinction between the cosmological and local (the Galactic) origin of GRBs. Some statistical investigations of different GRB distributions give support to cosmological location of GRBs (Norris et al. 1994; Wijers & Paczyński 1994; Kolatt & Piran 1996), whereas others favor the local one (Gurevich et al. 1993; Hakkila et al. 1995;
In the framework of a cosmological scenario, the fitting of the integral GRB luminosity function [i.e. source number $N(F)$ with photon fluxes $> F$] for different GRB samples and model assumptions about the source spectra and evolution makes it possible to estimate the GRB peak luminosity and the production rate of GRBs per comoving unit volume to be, correspondingly (Mao & Paczyński 1992; Cohen & Piran 1995; Mészáros & Mészáros 1995; Rutledge et al. 1995)

$$L_\gamma \sim 10^{51} - 10^{52} \text{ erg s}^{-1},$$

$$\dot{n}_0 \sim 10^{-8} - 10^{-7} \text{ events yr}^{-1} \text{ Mpc}^{-3}. \tag{1}$$

Eq. (2) implies that the rate of NS merging in galaxies necessary to explain the GRB phenomenon must be of the order of

$$\dot{N}_g \sim 10^{-6} - 10^{-5} \text{ events yr}^{-1} \text{ galaxy}^{-1}. \tag{3}$$

This value of $\dot{N}_g$ is consistent with the calculations of the NS merging rate for the Galactic binaries (Clark et al. 1979; Narayan et al. 1991): $\dot{N}_g \sim 10^{-6} - 10^{-4} \text{ events yr}^{-1} \text{ per galaxy}$ (see however Sec. 4).

It can be found from Eq. (1) that in each act of NS merging the energy $Q_\gamma \sim 10^{51} - 10^{52} \text{ erg}$ is emitted (assuming isotropic radiation) in the form of gamma rays. Therefore the transformation efficiency of the total energy $Q$ of two merging NSs into gamma rays must be of the order of $\eta = Q_\gamma / Q \sim 10^{-3} - 10^{-2}$. This value being rather large is challenging for the models of a GRB generation by NS merging. In the concept of relativistic fireball as radially expanding, optically thick electron-positron plasma (Cavallo and Rees 1978; Paczyński 1986; Goodman 1986; Shemi and Piran 1990), the value of $\eta$ can be made smaller by taking into account the possible relativistic boosting of the observed GRB intensity if the fireball expansion occurs with the bulk Lorentz-factor $\Gamma \sim 10^2 - 10^3$
(Yi 1993; Yi & Mao 1994). However, the necessary rate of GRB generation in the unit comoving volume would also be increased by a factor of \((2\Gamma)^2\) thereby destroying the above consistency between the inferred and estimated \(\dot{N}_g\).

This problem is abandoned in a different cosmological scenario proposed here: a GRB generation is considered to occur by involving coalescence of binary NSs and/or BHs formed by radiative capture in the central compact stellar clusters of the evolved galactic nuclei. This new scenario of GRB origin is complementary to the standard cosmological scenario, in which coalescence of neutron stars in very distant galaxies is assumed, without specifying the origin of parent binaries. In Sec. 2, dynamical evolution of galactic nuclei leading to the formation of the central dense stellar clusters is briefly outlined. Sec. 3 deals with the rate of collisions and coalescence of compact stars which result in GRB production. Discussion of our scenario is given in Sec. 4. A brief account of this work was published elsewhere (Ozernoy, Dokuchaev & Eroshenko 1996).

2. Central Compact Clusters in the Galactic Nuclei

According to well known models of the dynamical evolution of stellar systems, those galactic nuclei which are dense enough, inevitably proceed through the stellar collision and coalescence stage (Spitzer and Saslaw, 1966; Colgate 1967; Sanders 1970; Spitzer 1971; Dokuchaev 1991). This process is enhanced by the hardening of hard binaries formed in several ways (Ozernoy & Dokuchaev 1982, Dokuchaev & Ozernoy 1982). The enhanced evolution of the galactic nucleus results in a copious formation of short-living massive stars and subsequent supernova explosions implying the ‘build up’ of a subcluster of compact stellar remnants (CSRs) with an appreciable fraction of NSs and BHs (Begelman & Rees 1978, Quinlan & Shapiro 1990 and refs. therein). Since so formed binaries are much heavier than the field stars, they settle on a relaxation time scale (which is much shorter than the
cluster’s age) to the center of the nucleus, thus making the subcluster of CSRs contain an enhanced fraction of tight binaries (Dokuchaev & Ozernoy 1982, Quinlan & Shapiro 1990).

Let us consider a central stellar cluster in the galactic nucleus of mass $M$ and radius $R$, consisting of $N \gg 1$ CSRs, the relics of massive stars. The CSR velocity dispersion in the cluster is given by the virial theorem to be $v \simeq (GM/2R)^{1/2}$. If the space density of galaxies with the evolved galactic nuclei contributes a fraction $\Omega_g$ of the critical density $\rho_c = 3H_0^2/8\pi G$, where $H_0 = 75 h$ km s$^{-1}$ Mpc$^{-1}$ is the Hubble constant, then the mean number density of the evolved galactic nuclei in the Universe is

$$n_g = \rho_c \Omega_g/M_g = 1.6 \cdot 10^{-2} h^2 \left(\frac{\Omega_g}{10^{-2}}\right) \left(\frac{M_g}{10^{11} M_\odot}\right)^{-1} \text{Mpc}^{-3},$$

(4)

assuming the evolved galactic nuclei to be the typical inhabitants of the bulk of galaxies, $M_g$ being the luminous mass of the typical host galaxy. Below, we find the allowed range of parameters $M$ and $R$, for which encounters/collisions of CSRs in the host galactic nuclei can provide the observed GRB rate. We also take into account the possible presence of a central supermassive black hole formed in a highly evolved galactic nucleus and we consider how its presence influences the CSR binary formation.

3. Collisions and Coalescence of Compact Stellar Remnants

3.1. Radiative Capture of CSRs vs. Direct Collision

The cross section for coalescence of two identical CSRs of mass $m$ moving with a relative velocity $v_\infty = \sqrt{2} v$ can be presented, similarly to the cross section for the capture of nonrelativistic test particles by a massive object, in the form:

$$\sigma_{\text{coll}} = \pi r_p^2 \left(1 + \frac{r_g c^2}{r_p v^2}\right)^2 \approx \pi r_p^2 \left(\frac{c}{v}\right)^2,$$

(5)
where \( r_g = 2Gm/c^2 \) is the gravitational radius of a CSR, and \( r_p \) is the maximum collision periastron separation allowing for CSR coalescence. For the direct coalescence of two CSRs, \( r_p = 2r_g \) (Shapiro & Teukolsky 1985).

We also take into account the formation of compact star binaries through dissipative two-body encounters via gravitational radiation. The maximum periastron separation for the radiative capture of compact stars which results in the formation of a hard binary (i.e. a binary of a binding energy \( \epsilon_b \gtrsim mv^2/3 \)) is estimated to be \( r_p \approx (3/2)r_g(c/v)^{4/7} \) (see Giersz 1985; Quinlan & Shapiro 1987 for details). Therefore, the cross section for the radiative capture into a binary is given by

\[
\sigma_{\text{cap}} \approx \frac{3}{2} \pi r_g^2 \left( \frac{c}{v} \right)^{18/7}.
\]

We define the BH collision as such a close encounter of two BHs, which leads to the intersection of their event horizons so as to inevitably terminate in their coalescence. The total energy radiated during the head-on collision of two identical Schwarzschild BHs on a parabolic orbit is \( \Delta \epsilon_{\text{gr}} \approx 2.5 \cdot 10^{-3}mc^2 \) (Smarr 1979). Therefore, the radiative capture of two CSRs into a binary can take place in the cluster with velocity dispersion

\[
v \lesssim v_{\text{cap}} = (\Delta \epsilon_{\text{gr}}/m)^{1/2} \approx 1.5 \cdot 10^4 \text{ km s}^{-1}.
\]

In clusters with \( v \gtrsim v_{\text{cap}} \), gravitational radiation losses during two-body CSR encounters are insufficient for the formation of binaries. Meanwhile in a nonrelativistic cluster with \( v \lesssim v_{\text{cap}} \), as can be seen from Eqs. (5)–(7), the capture cross section \( \sigma_{\text{cap}} \) of radiative binary formation exceeds the direct collision cross section \( \sigma_{\text{coll}} \) by a large factor \( r_p^{\text{cap}}/r_p^{\text{coal}} \approx (3/4)(c/v)^{4/7} \).

Components of a circular binary of radius \( r \) coalesce, due to successive gravitational radiation losses, in a time

\[
t_{\text{gr}} = \frac{5}{64} \frac{r_g}{c} \left( \frac{r}{r_g} \right)^4.
\]
The bulk of the newly formed tight binaries are highly eccentric, $1 - e \ll 1$. In this case, the exact solution for time evolution of eccentric binary orbital parameters due to the quadrupole gravitational radiation (Pierro & Pinto 1996) indicates that the binary lifetime is of the same order as $t_{gr}$ given by Eq. (8) with $r = r_p$, where $r_p \approx (3/2)r_g(c/v)^{4/7}$ is the periastron separation during the first encounter. This has a simple physical meaning: circularization of a highly eccentric orbit is fast compared to the subsequent slow evolution of a nearly circular orbit until two CSR components coalesce. The value of $t_{gr}$ is less than the cosmological time [say, the age of the flat Universe $t_H = (2/3)H_0^{-1}$] in the galactic nuclei with velocity dispersion

$$v \gtrsim v_H = c \left( \frac{5 \cdot 3^5}{2^{11}} \frac{H_0}{c} r_g \right)^{7/16}.$$  

The numerical value of the r.h.s. is astonishingly low: $v_H \simeq 3.0(m/M_\odot)^{7/16}$ cm s$^{-1}$, far less of any real velocity dispersion in the central stellar cluster. This implies that actually there is no lower limit to velocity dispersion of CSRs able to form binaries by radiative capture: all such formed binaries are short-living compared to the age of the Universe, i.e. they have more than enough time to coalesce. Below, only those central clusters in the galactic nuclei are considered for which the upper limit to $v$ given by Eq. (7) is satisfied.

### 3.2. The Rate of CSR Radiative Capture

In this subsection, we mainly follow to Quinlan & Shapiro (1987, 1989) to calculate the CSR collision rate in an evolved stellar cluster. The rate of CSR radiative capture into a binary, followed by a successive coalescence of the components and then a GRB event, is given by $\dot{N}_c \simeq (1/2)Nn\sigma_{cap}v_{\infty}$ per one galactic nucleus, where $n$ is the CSR mean number density and $N = M/m \simeq (4\pi/3)R^3n$ is the total number of CSRs in the central cluster. As
a result, the rate of CSR collisions is given by

$$\dot{N}_c \simeq 9\sqrt{2} \left(\frac{v}{c}\right)^{17/7} \frac{c}{R} \simeq 5.8 \cdot 10^{-6} \left(\frac{M}{10^7 M_\odot}\right)^{17/14} \left(\frac{R}{0.1 \text{ pc}}\right)^{-31/14} \text{ events yr}^{-1} \text{ galaxy}^{-1}, \quad (10)$$

where fiducial parameters for the central nuclear cluster $M = 10^7 M_\odot$ and $R = 0.1 \text{ pc}$ are used (see discussion in Sec. 4). Therefore, the rate of GRBs per unit of comoving volume is expected to be

$$\dot{n}_0 = \dot{N}_c n_g \simeq \frac{27}{8\pi \sqrt{2}} \Omega_g \left(\frac{H_0}{c}\right)^2 \left(\frac{v}{c}\right)^{3/7} M \frac{c}{M_g R^2} \simeq 9.1 \cdot 10^{-8} \left(\frac{\Omega_g H_0^2}{10^{-2}}\right) \left(\frac{M_g}{10^{11} M_\odot}\right)^{-1} \left(\frac{M}{10^7 M_\odot}\right)^{17/14} \left(\frac{R}{0.1 \text{ pc}}\right)^{-31/14} \text{ events yr Mpc}^{-3}. \quad (11)$$

Eqs. (10) and (11) are fairly consistent with the rate of NS merging in galaxies required to explain the GRB phenomenon as mentioned in the Introduction [see Eqs. (3) and (2)]. Yet, while confronting the value of $\dot{n}_0$ given by Eq. (11) with Eq. (2), one should emphasize that such a comparison would not solely depend on CSR merging. In fact, it would incorporate two more factors: (i) evolutionary effects associated with how the CSR merging rate evolves in time as a result of evolution of galactic nuclei, and (ii) effects depending on the choice of a cosmological model (parameters $q_0$, $H_0$, etc.). Each specific model for galactic nucleus evolution would come up with a corresponding relationship $M = M(R)$. This issue is out of the scope of the present paper.

### 3.3. An Allowed Range of Masses and Radii of the Evolved Galactic Nuclei as GRB Sources

Here, we constrain ourselves by evaluating the range of parameters of a central dense cluster in which coalescence of NSs or BHs could provide the rate of GRBs $\dot{n}_0$ consistent with the observed one. By incorporating the numerical estimation for the inferred value of $\dot{n}_0$ given by Eq. (2) [or, correspondingly, $\dot{N}_g$ given by Eq. (3)], we find from Eq. (11) the
relationship of interest between $M$ and $R$:

$$M = M_{GRB} \simeq 1.6 \cdot 10^6 \left( \frac{\Omega_g}{10^{-2} \dot{n}_{-8} M_{g11}} \right)^{14/17} \left( \frac{R}{0.1 \text{ pc}} \right)^{31/17} M_\odot, \quad (12)$$

where $\dot{n}_{-8} = \dot{n}_0/10^{-8}$ events yr$^{-1}$ Mpc$^{-3}$ and $M_{g11} = M_g/10^{11} M_\odot$.

It is instructive to discuss available constraints on the range of the allowed $M$ and $R$. One of the general physical constraints is the requirement that the cluster radius be greater than several gravitational radii, say, $R \gtrsim 5R_g = 10 GM/c^2$ (Zel’dovich & Podurets 1965). Obviously, this is a very stringent condition and it would be more realistic for the time of dynamical evaporation of the central cluster, $t_{ev} \simeq 40 t_r$, where $t_r$ is the two-body relaxation time (Spitzer & Hart 1971), to marginally exceed the age of the universe:

$$t_{ev} \simeq \frac{10}{\pi} \frac{v^3}{G^2 m^2 n \ln(0.4N)} \gtrsim \frac{2}{3} H_0^{-1} \quad (13)$$

(otherwise, i.e. in the case of $t_{ev} \ll H_0^{-1}$, there would be an inappropriately high recurrence of GRBs due to an overabundant CSR merging in a too dense central core). Another constraint to this model is a firm (though a trivial one) upper limit to the mass of the nucleus compared to that of the host galaxy: $M \lesssim M_g$. Although a more sophisticated relationship between $M$ and $M_g$ depends on (yet unknown) conditions of galaxy formation, a more realistic upper limit to $M$ consistent with the available data would be $M \lesssim 10^{-3} M_g$ or something of that nature.

Eqs. (12), (13), and the condition $M \lesssim M_g$ yield an allowed range of values for radius $R$ and mass $M$ of the central compact cluster [we put $\ln(0.4N) = 10$ throughout the numerical estimations]:

$$0.41 \dot{h}^{-3/41} \left( \frac{\Omega_g}{10^{-2} \dot{n}_{-8}} \right)^{7/41} \left( \frac{m}{M_\odot} \right)^{17/41} M_{g11}^{-7/41} \lesssim \frac{R}{1 \text{ pc}} \lesssim 45 \left( \frac{\Omega_g h^2}{10^{-2} \dot{n}_{-8}} \right)^{14/31} M_{g11}^{3/31}; \quad (14)$$

$$2.1 \cdot 10^7 \dot{h}^{-73/41} \left( \frac{\Omega_g}{10^{-2} \dot{n}_{-8}} \right)^{-21/41} \left( \frac{m}{M_\odot} \right)^{31/41} M_{g11}^{21/41} \lesssim \frac{M}{M_\odot} \lesssim 10^{11} M_{g11}. \quad (15)$$
Hence, Eqs. (14) and (15) define, in the framework of our cosmological scenario, a range of radius $R$ and mass $M$ [connected by relationship (12)] for those dense CSR clusters, which could provide, by the CSR coalescence, the necessary GRB rate and fluence consistent with observations. The most appropriate values of $R$ and $M$ for the evolved galactic nuclei scenario would correspond to the left-hand-sides of Eqs. (14) and (15) where $t_{\text{ev}} = t_H$, i.e. $R \approx 0.4$ pc and $M \approx 10^7 \, M_\odot$, respectively.

The total emitted energy of two colliding stellar mass BHs (which considerably exceeds that of two NS collision) is radiated primarily in the form of strong gravitational waves. Since each colliding BH supposedly contains an accretion disk/torus (AD), left since the collapse of the massive predecessor, coalescence of two BH+AD systems should evidently be accompanied by a generation of hard radiation, presumably gamma rays, although the transformation efficiency of available energy into gamma rays is uncertain until making rather complicated computations. Yet a high transformation efficiency (on the level of, or higher than, that of NS-NS merging) seems to be reasonable if a fireball is formed in the process of two BH+AD collisions. Some small amount of matter in an AD around one or both colliding BHs can act as a “primer” to ignite a fireball. The AD matter can be gradually piled up from the ambient gas by the moving BH.

Although the parameters of gamma rays from two colliding BH+AD systems could only be found in further work, this does not really influence our basic conclusions since the fraction of massive stellar BHs in the galactic nuclei seems to be smaller (perhaps even much smaller) than that of NSs. Therefore, the bulk of GRB progenitors is expected to be related with NS–NS and NS–BH, rather than BH–BH, collisions.
3.4. Influence of a Central Massive Black Hole

In the above consideration, an evolved core of the galactic nucleus is assumed to be not too far evolved, in the sense that a central massive BH has not yet had time to be formed, or its mass is still negligible. In this subsection, we consider the opposite case, when an already formed central BH has acquired a large enough mass to substantially influence the dynamics of the surrounding stellar core. Specifically, we assume that an evolved galactic nucleus harbors a supermassive black hole (SMBH) of mass \( M_h \gtrsim 10^7 - 10^8 M_\odot \) embedded into a dense cluster of \( N \) compact stellar remnants (CSRs), mostly neutron stars and stellar-mass black holes. For simplicity, we assume the total mass of this cluster \( M = mN \ll M_h \) so that the cluster represents a star ‘atmosphere’ of radius \( R \approx GM_h/v^2 \) around the dominating central SMBH, \( v \ll c \) being the CSR velocity dispersion in the gravitational field of the latter.

The star ‘atmosphere’ around a SMBH is genetically related to its precursor, \( viz. \), a central compact stellar cluster, whose evolutionary time scale \( t_{ev} \) was much less than the Universe’s age \( t_H \). If the SMBH formed as a result of the dynamical evolution of the cluster, this happened on an evaporational time scale, i.e. \( t_{ev} \approx 40 t_r \), where \( t_r \) is the two-body relaxation time. After the formation of the central SMBH in the stellar cluster, its interaction with surrounding stars, such as tidal disruption and consumption of stars by the hole, results in an increase of the evolutionary time scale, until \( t_{ev} \) reaches \( t_H \) and becomes frozen thereafter. Therefore, the most probable stage in which one could find an evolved stellar cluster around a ‘dormant’ SMBH would be a star ‘atmosphere’ around it with \( t_{ev} \approx t_H \), which makes the radius of such ‘atmosphere’ to be

\[
R \approx 5.75 \cdot 10^{-2} h^{-2/3} \left( \frac{m}{M_\odot} \right)^{4/3} \left( \frac{N}{10^6} \right)^{2/3} \left( \frac{M_h}{10^7 M_\odot} \right)^{-1} \text{pc.}
\]

This yields \( R \gtrsim 10^{-2} - 10^{-3} \) pc if \( N \sim 10^6 - 10^7 \) and \( M_h \gtrsim 10^7 - 10^8 M_\odot \).
In the dense star ‘atmosphere’ around the central SMBH, close encounters of two CSRs result in a radiative capture followed by a successive coalescence and a GRB event. The capture rate is given, as before, by \( \dot{N}_c \sim \frac{1}{2} \frac{N n \sigma \cap v_{\infty}}{v c} \), but its value \( \dot{N}_c \sim \frac{9}{2} \sqrt{2} \left( \frac{N m}{M_h} \right)^2 \left( \frac{v}{c} \right)^{17/7} \frac{c}{R} \) differs from that given by eq. (10) by a factor \( (N m / M_h)^2 \) since \( v \) now depends upon the BH mass.

Assuming that the number density of ‘dormant’ SMBHs is about the same as that of giant galaxies, \( n_g \sim 10^{-2} \text{ Mpc}^{-3} \), the GRB rate per unit volume of the Universe is expected to be

\[
\dot{n}_0 = \dot{N}_c n_g \\
\simeq 2.7 \cdot 10^{-8} \left( \frac{n_g}{10^{-2} \text{ Mpc}^{-3}} \right) \left( \frac{M_h}{10^7 \text{ M}_\odot} \right)^{-1/4} \left( \frac{N m}{10^6 \text{ M}_\odot} \right)^2 \left( \frac{R}{0.01 \text{ pc}} \right)^{-1/11} \text{ events yr Mpc}^{-3}. \tag{18}
\]

One can see that this rate is consistent with the inferred cosmological GRB rate given by equation (2) if the radius of the SMBH star “atmosphere” is as small as

\[
R \simeq 2.2 \cdot 10^{-2} \left( \frac{\dot{n}_{\text{GRB}}}{10^{-8} \text{ yr}^{-1} \text{ Mpc}^{-3}} \right)^{-1/14} \left( \frac{n_g}{10^{-2} \text{ Mpc}^{-3}} \right)^{14/11} \left( \frac{M_h}{10^7 \text{ M}_\odot} \right)^{-11/14} \left( \frac{N m}{10^6 \text{ M}_\odot} \right)^{28/11} \text{ pc}. \tag{19}
\]

This radius is consistent with what is expected according to equation (16) for an evolved stellar core with a central SMBH.

### 3.5. Recurrence of Cosmological GRBs

Some authors consider a would-be-found GRB recurrence as serious evidence for the origin of GRBs in the Galactic halo (see e.g. Bennett & Rhie 1996; Tegmark et al. 1996). However, as we demonstrate below, GRB recurrence could be expected in the cosmological case as well. Eq. (12) represents a relationship only between the average radius \( R \) and mass
$M_{GRB}(R)$ of the evolved galactic nuclei able to provide the observed rate of GRBs. The actual parameters of the evolved nuclei can be widely spread around the average ones, and some nuclei may be very compact. Our model indicates that an extremely compact nucleus would be a source of multiple (recurrent) cosmological GRBs. If the influence of the forming central SMBH is negligible, the radius of the cluster $R$ in which the CSR coalescence rate is $\dot{N}_c$ is given, according to Eq. (10), by

$$R \simeq 3.6 \cdot 10^{-5} \left( \frac{M}{10^7 M_\odot} \right)^{17/31} \left( \frac{\dot{N}_c}{10^2 \text{yr}^{-1}} \right)^{-14/31} \text{pc.} \quad (20)$$

The corresponding velocity dispersion $v$ in the cluster is

$$v \simeq 2.4 \cdot 10^4 \left( \frac{M}{10^7 M_\odot} \right)^{7/31} \left( \frac{\dot{N}_c}{10^2 \text{yr}^{-1}} \right)^{7/31} \text{km s}^{-1}, \quad (21)$$

The characteristic evolutionary time of a cluster as dense as this is determined by the CSR capture time (Quinlan & Shapiro, 1987):

$$t_{\text{cap}} = \frac{N}{\dot{N}_c} \simeq 5.8 \cdot 10^3 \left( \frac{M}{10^7 M_\odot} \right)^{-3/14} \left( \frac{R}{10^{-5} \text{pc}} \right)^{7/31} \text{yrs}, \quad (22)$$

i.e. this evolutionary stage is very brief. Recurrent GRBs might be also associated with a much more advanced stage when the gravitational field is dominated by a central SMBH. The rate of CSR coalescence, accounting for the SMBH influence, is evaluated elsewhere.

After this paper was basically completed and its brief account, with mentioning of the possibility of recurrent GRBs was published (Ozernoy, Dokuchaev & Eroshenko 1996), we become aware of the BATSE observations of 4 GRB events during two days in October 1996 from the same direction in the sky (Meagan et al. 1997). Unless this is just one unusually long event, this might be explainable in the framework of our model as the CSR coalescence in a highly evolved cluster of radius $R \approx 10^{-5} \text{pc}$ and mass $M \approx 10^7 M_\odot$, as Eq. (20) indicates. This stage of cluster evolution, which only lasts $t_{\text{cap}} \approx 10^3 - 10^4 \text{yrs}$, might precede the subsequent formation of a central massive BH, although its mass at this
stage is much smaller than the cluster mass $M$. An alternative possibility to explain such a fast GRB recurrence would be CSR coalescence in the vicinity of a forming (or an already formed) central massive BH. We explore both these possibilities elsewhere in more detail, including possible reasons for the apparent absence of GRBs, both before and after the recurrent events were detected.

4. Discussion

A recent Beppo-Sax finding of distant galaxies as counterparts for two GRBs (e.g. Sahu et al. 1997, Metzger et al. 1997) has confirmed that at least a part of the gamma ray bursts (GRBs) have a cosmological location. Thus, our new scenario for the origin of GRB progenitors proposed in this paper stimulates and challenges its further development and testing.

A novel aspect of the evolved galactic nuclei explored above is that those nuclei, which contain in their dense central parts numerous compact stellar remnants (CSRs) such as neutron stars (NSs) and black holes (BHs), might be appropriate sites for the production of GRBs. Collisions between those remnants can achieve, in the most natural way, a high rate of GRBs. A similar model has been proposed for GRB origin in the hypothetical halo dark clusters (Carr & Lacy 1987, Wasserman & Salpeter 1994). While there is no conclusive evidence in favor of those dark clusters, the production of a large number of tight NS and BH binaries in the galactic nuclei is a natural consequence of dynamical evolution of the latter. Compact galactic nuclei as a site for GRBs do not look as speculative as halo dark clusters. Besides, this would enable one to connect the GRB aspect with a previous, and much more solid, work on dynamics of dense galactic nuclei. Moreover, there is a mounting evidence in favor of many dark stellar remnants in the nucleus of the Milky Way Galaxy (Haller et al. 1996, Lipunov, Ozernoy, Popov et al. 1996), although the present number
density of those remnants is apparently not high enough to produce GRB events at the Galactic center.

An encouraging point is that the estimations of the allowed ranges for radii and masses of dense stellar clusters where collisions of CSRs could result in their coalescence and GRB production [Eqs. (14) and (15)], give quite appropriate values consistent with the observed ranges for the galactic nuclei. Yet, it remains to be seen whether the outlined cosmological scenario of GRB origin actually provides both the observed GRB rate and flux. Furthermore, the distribution of galactic nuclei in mass $M$ and radius $R$ has not been taken into account. In reality, the parameters of galactic nuclei change in the process of the dynamical evolution. Accordingly, the rate of compact star remnants collisions changes too and, by the present time, in many galactic nuclei some part of the nucleus could collapse or evaporate. Therefore, in the present approach, the nucleus parameters $M$ and $R$ adopted above must be considered only as fiducial values. Generalization of the present analysis with accounting for possible distribution of nuclei in mass and radius would allow to model the observed $\log N(F) - \log F$ distribution.

One could argue that the advantage of the standard cosmological scenario is that the observed statistics of binary pulsars seems to be consistent with the observed GRB rate (Narayan et al. 1991). Meanwhile there are arguments that the consistency only exists in a hypothetical, multi-parametric scenario for compact binary stars evolution (Tutukov & Yungelson 1993, Lipunov et al. 1995). In contrast, our evolved galactic nuclei scenario produces, as is shown in Sec. 3, an appropriate number of short living binaries fairly consistent with observations of GRBs and arising naturally as a result of the dynamical evolution of galactic nuclei.

A relevant point is whether each appropriate galactic nucleus as a GRB source has evolved so as to produce a central massive black hole (MBH) and to become an active
galactic nucleus (AGN). As we argue in Sec. 3, GRBs could be produced in the evolved nuclei both with and without a MBH. Interestingly, a stage of copious CSR production might even precede the formation of a supermassive BH. Whether or not the central SMBH actually forms, depends on a variety of factors (e.g. the formation and hardening of hard binaries), which are able to either prevent or retard, stop, and reverse the core collapse. Let us suppose that the latter happens and results in reversing the core collapse to core expansion. Since the post-collapse core evolution slows down around the time of maximum expansion, observations will find the core, most probably, to be near that maximum.

Fokker-Planck calculations indicate \( \frac{r_c}{r_h} \sim 10^{-2} \) (\( r_h \) being the half-mass radius) as a typical value around the time of maximum expansion (Murphy et al. 1990). This would justify our choice of \( R \sim 0.1 - 1 \) pc while evaluating \( \dot{N}_c \) with the use of Eq. (10). It is worth noting that the resulting \( \dot{N}_c \) is fairly consistent with the rate of NS merging in galaxies required to explain the GRB phenomenon [Eq. (3)]. The above argument implies that the GRB production might be associated with a specific stage in the dynamical evolution of galactic nuclei. The condition \( \frac{r_c}{r_h} \sim 10^{-2} \) can be used to constrain the expected relationship \( M = M(R) \) for the nuclei responsible for GRB production.

We believe that GRB production could be associated with a far more advanced stage of evolution of galactic nuclei as well, when a central massive black hole is either forming or has already been formed. In this case, a compact CSR cluster continues to exist in the vicinity of the MBH and to serve as a source of GRBs.

Our scenario is, in a sense, inevitable for the evolved galactic nuclei. At the same time, it is complementary (rather than opposing) to the standard cosmological scenario. Moreover, in our scenario very hard (‘superelastic’) binaries are ejected from the galactic nuclei with characteristic velocities \( \gtrsim 1000 \) km/s as a result of interaction with the field stars in the central stellar cluster [for superelastic binaries, the ejection velocity is given by
$v_{ej} \gtrsim \left( \frac{2}{3} \cdot 78.75 \right)^{1/2} v \approx 724 \left( v / 100 \text{ km s}^{-1} \right) \text{ km/s}$ (Ozernoy & Dokuchaev 1982, p.3), where $v$ is velocity dispersion]. Therefore it seems possible, at least in principle, to fill the galactic halo, up to very large distances, with the compact, short living NS binaries ejected from the galactic nucleus. However, the core of the Milky Way does not seem be dense enough as to serve as a source of NS binaries to explain all the observed GRBs.

In the standard cosmological scenario, a NS+NS binary being a product of the evolution of the binary’s normal stellar constituents, is expected to be formed with a high (a few $10^2$ km/s) kick velocity (e.g. Fryer & Kalogera 1997). By the time of merging and producing a GRB ($\sim 10^8 - 10^9$ yrs after its birth), the binary would be found at a $\sim 30$ kpc distance from the birthplace. Therefore, an off-center location of the GRB afterglow found at a cosmological distance (Sahu et al. 1997) seems to be consistent with both new and standard scenarios. It cannot serve solely as a means of differentiating between the origin of the parent binary in the galactic disk (e.g. in a star-forming region) or in the galactic nucleus. The host galaxy also could not make such a differentiation, because the evolved galactic nuclei occur both in spiral and elliptical galaxies.

In a cosmological GRB source, the formation of an optically thick fireball of electron-positron plasma (Cavallo and Rees 1978; Paczyński 1986; Goodman 1986; Shemi and Piran 1990) is inevitable due to reaction $\gamma\gamma \rightarrow e^+e^-$, pair annihilation, and Compton scattering. GRBs resulting from NS–NS and NS–BH merging must be accompanied by bursts of neutrino and gravitational radiation (Eichler et al. 1989; Haensel et al. 1991; Narayan et al. 1992), which could be possible targets for detection by existing installations or those under construction. We note in passing that large neutrino detectors and gravitational interferometers like LIGO/VIRGO would give an opportunity to distinguish between the BH and NS coalescence events because, in the case of BH merging, there will be a relatively stronger gravitational and a less intense neutrino radiation, compared to the merging of two
As it follows from the above considerations, there are potential tests by which our cosmological scenario of GRB production could be observationally distinguished from the standard scenario.

In this respect, detection of gravitational radiation from the vicinity of a GRB would be decisive. The signature of the proposed scenario is the specific pattern of gravitational wave radiation in the galactic nucleus associated with the origin of the given GRB. The coalescence of the CSR binary, which is thought to result in the GRB, is accompanied by the presence of numerous other close CSRs and their binaries in the nucleus. Those objects are the sources of excessive gravitational radiation, which continues to exist for a long time after the gravitational radiation from the GRB disappears. This differs drastically from the standard scenario, according to which there are, along with the binary that has experienced coalescence, just a few (if any) binaries at a similar evolutionary stage and thus no excessive gravitational radiation is expected after the GRB. In order to test our scenario, search for continuing gravitational radiation from the former GRBs could be one of the prime targets for LIGO/VIRGO interferometer.

Another possible signature of the evolved galactic nuclei scenario is a potential recurrency of GRBs. The more evolved the galactic nucleus, the higher the possibility of finding there multiple GRB events.

The evolved galactic nuclei scenario for GRB origin outlined in this paper makes it possible to draw the following conclusions:

(i) The central parts of the galactic nuclei, which in the course of the dynamical evolution produce, through close encounters/collisions, coalescence, and SN explosions of ordinary stars, the abundant compact stellar remnants (NSs and BHs) as well as
binaries consisting of them, could be the sites for the origin of GRB progenitors.

(ii) Actual location of a GRB and its afterglow might be far away from the galactic nucleus (or even the parent galaxy) due to the ejection of ‘superelastic’ binaries as a result of interaction with the field stars in the nucleus.

(iii) In contrast to the standard cosmological scenario of the GRB origin, there is no need in a priori existence of a large number of compact binaries consisting of NS. In compact galactic nuclei, random encounters of CSR, which are accompanying by gravitational wave radiation, result in the radiative binary formation and in further CSR coalescence, and this would naturally explain the GRB phenomenon.

(iv) The signature of the proposed scenario for the GRB origin is the gravitational wave radiation that causes the coalescence of CSR in the course of their close encounters. Spiralling in, which accompanies the process of close binary formation and evolution, results in a specific pattern of gravitational radiation, which is distinguishable from the gravitational radiation of another origin.

(v) In principle, the recurrent GRBs (so far not yet detected with certainty) could be observable from a host galactic nucleus if it is far evolved.

If the proposed scenario for the origin of GRB progenitors in the evolved galactic nuclei is confirmed by further observations, this would imply a major role played by CSR binary formation at the late stages of the dynamical evolution of galactic nuclei. If, on the other hand, it turns out that the major fraction of GRB progenitors is associated, in its origin, with the galactic disks, and not with the nuclei, it would lead to informative constraints on the evolutionary processes in the galactic nuclei.

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