Collapse of rotating stars in the Universe and the cosmic gamma ray bursts

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Abstract
We analyze here late evolutionary stages of massive ($M_0 \gtrsim 8 M_\odot$) close binary stars. Our purposes are to study possible mechanisms of gamma ray bursts (GRBs) origin. We suppose in this paper that GRB phenomenon require formation of massive ($\sim 1 M_\odot$) compact ($R \lesssim 10$ km) accretion disks around Kerr black holes and neutron stars. Such Kerr black holes are products of collapse of Wolf-Rayet stars in extremely close binaries and merging of neutron stars with black holes and neutron stars in close binary systems. Required accretion disks also can be formed around neutron stars which were formed during collapse of accreting oxygen-neon white dwarfs. We have estimated frequencies of events which lead to a rotational collapse concerned with formation of rapidly rotating relativistic objects in the Galaxy. We made our calculations using the "Scenario Machine".

1 Introduction
Investigation of the gamma ray bursts (GRBs) physics is one of the most actual astrophysical problems during last decades and it’s popularity permanently grow. Some years ago frequency of appearance of the articles on GRB physics had exceeded the frequency of the recorded GRBs which equals to approximately one flash per day for the detectors with threshold level $\sim 10^{-7}$ erg cm$^{-2}$ sec$^{-1}$ in the range $30$ KeV – $100$ MeV \cite{64,72}. About thirty year have elapsed since pioneering works about observed GRBs \cite{37,96,59}, but reliable observational limits on the main parameters of the events have appeared only during recent years and two conceptions which probably present two main types of GRBs were accepted. These types are short (SGRBs) which duration is lower than 2 seconds and long (LGRBs) which duration is $\sim 2 – 200$ seconds \cite{38,34}.

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GRBs were supposed to have cosmological nature by Usov and Chibisov [96]. Now numerous GRBs positions were identified with positions of galaxies and some supernovae type I b,c since 1997 [18]. So, cosmological nature of the most of the GRBs had become evident [96, 65, 66, 51, 72, 15, 34]. It can be illustrated by the isotropy of the GRBs distribution in the sky and by the deficiency of faint flashes in comparison with isotropic distribution in the Euclidean space [51, 82, 83, 15]. These facts enable researchers to realize cosmological distances to the most GRBs and to reconstruct some cosmological parameters, also they put problem of reconstruction of the star formation history in the Universe [89, 15]. Direct identification of red shifts of some GRBs (until $z \sim 6$) [23] supports this possibility. Identification of the host galaxies enables to estimate distances to some GRBs and their total energy in the assumption of spherically symmetric radiation $\sim 0.1 M_\odot c^2$ [72], and frequency of the GRBs in a galaxy with mass like the mass of the Milky Way $\sim 10^{-6} - 10^{-7}$ yr$^{-1}$ [58, 67]. Assumption about colli- mation of the gamma radiation in the narrow space angle ($\sim 0.1$ steradian) [67, 57] allows to get the last estimations up to the energy $\sim 10^{51} - 10^{52}$ erg and frequency $\sim 10^{-4} - 10^{-5}$ yr$^{-1}$. Note that these numbers are still uncertain by a factor of $\sim 10$. Also it is important to note that GRBs frequency is less than frequency of the known supernovae at least several tens times. This circumstance directed investigators to the most relic, but powerful events in stellar life. It is important to say that energetics of SGRBs in X-ray and gamma ray ranges is almost one hundred times less than energetic of LGRBs [17]. This is direct indication that frequency of SGRBs per galaxy can be higher than frequency of LGRBs. Additional indication of relatively higher frequency of SGRBs is relatively small distance to typical identified SGRB ($z \approx 0.2$) with comparison to the distance to typical GRB ($z=2$) [42].

Millisecond variability of observed flux of GRBs is evidence of a small volume of the main energy-release region, it’s size does not exceed $\sim 10^{8}$ cm. Three sorts of astrophysical objects with such dimensions are known: degenerated dwarfs (DD, or white dwarfs, WD), neutron stars (NS) and black holes (BH). High energy release $\sim 10^{51} - 10^{52}$ erg is typical for NSs and BHs. It provides for conditions upon ideas how to explain GRB mechanism. Concept of merge of two NSs under influence of gravitational waves was advanced to depict SGRBs. Roche lobe overflow by one of the compact stars leads to it’s decay in dynamical time scale $10^{-4} - 10^{-5}$ sec. [91]. It allows to conclude that energy release during such event is enough to produce a SGRB and to make a relation between a SGRB and a NS+NS merging [6]. NS also can be a component in a close binary including BH. List of the four known close binary systems consisting of neutron stars and radio-pulsars in the Galaxy which are able to merge in timescale shorter than Hubble time was compiled [32]. It includes such systems as B1913+16 with orbital period about eight hours. According to the scenario program such pairs also have to merge with frequency equals to frequency of merging of the close binary systems $1 \cdot 10^{-4} \text{ yr}^{-1}$ [50, 92, 93]. In the present article we consider both variants of SGRB formation to estimate their frequencies. It is necessary to note that in spite of formal high ”delay” of merging after the moment of the formation of the system (NS+NS, NS+BH) considerable part of merging happen in first 1-2 Gyr. Although short GRBs can be found also in old elliptical galaxies [70, 22], most of them have to be related to galaxies with active current star formation [25]. In fact one short GRB was found in the galaxy with active star formation [74]. Observation of
the short GRB 050709 in optics allows to exactly exclude even a faint SN Ic in the same place [27]. But it is important that in elliptical galaxies there are only SGRBs [19, 26, 45, 74, 7]. It is evidence in favour of the model of NS+NS or NS+BH mergers.

LGRBs are concerned with collapses of rapidly rotating nuclei of massive presupernova which produce Kerr BH [67]. Collapse of a fast rotating star as mechanism of supernova explosion was suggested by [5]. Numerical gas-dynamic model of such event was constructed by [95]. There are two possible causes of fast presupernova nucleus rotation: acceleration of the star nucleus rotation by its grip with angular momentum conservation [87, 56] or companion presence near presupernova helium Wolf-Rayet star (WR) which is one of components in a close binary [30, 103, 67, 73, 89, 90]. The last version seems to be preferable due to very probable significant slowing down of rotation of cores of single massive stars during their evolution [88, 60]. Orbital period of the system consisting of presupernova type I b,c (WR star) and another component has to be shorter than 1-3 days to produce Kerr black hole. At least one binary including WR-star (progenitor of GRB) is known at present time: Cyg X-3 [89]. There are also some known binary systems including post-Kerr BH, for instance, V 518 Per [89]. Observational data allow to make relation between LGRBs and explosions of SN I b,c which mean the end of WR-star evolution [12, 16] in galaxies with active current star formation [22, 81, 9]. A companion of a WR-star (a progenitor of a Kerr BH) can be a main sequence star, a BH or a NS. We investigate here such systems to estimate frequency of formation of Kerr black holes in them. Note that we treat a black hole as Kerr BH in this paper if Kerr parameter

\[ a = \frac{I\Omega}{GM_{BH}^2/c} \geq 1, \tag{1} \]

where \( I \) is the moment of inertia of the black hole, \( \Omega \) is its angular velocity, \( M_{BH} \) is the mass of the black hole.

It is known that even in very close binaries with helium non-degenerated progenitors which mass is about \( 2.5M_{\odot} \) NS formation does not allow to produce NS with period of rotation shorter than \( \sim 0.05 \) sec. according to elementary estimations\(^1\). At the same time the ultimate lower limit of the period of a neutron star is much shorter and equals to \( \sim 0.001 \) sec. It excludes such NSs from list of progenitors of the GRBs. Nevertheless probably there is another channel of formation of a fast rotating single NS due to merging of close binary degenerated dwarfs. And at least one of the components in the case has to be oxygen-neon (ONe) white dwarf. Oxygen burning in it does not produce enough energy to destroy compact dwarf and finally leads to collapse and formation of a neutron star [61, 63]. Initial mass of a star in a close binary system has to be \( \sim 8-10M_{\odot} \) to form oxygen-neon WD [30]. Collapse of such dwarf during merging of the components of the close pair will guarantee NS formation with over critical rotation that leads to formation of a LGRB according to our model. In

\(^1\)For \( M_{He} = 2.5M_{\odot} \) practically filling its Roche lobe with radius \( R_{He} = 0.34\,R_\odot \) major semi-axis \( a \simeq R_\odot \) for another companion of solar mass, \( P_{orb} = 10^4 \frac{a^{3/2}}{M_1^{1/2} + M_2^{1/2}} \) sec. (\( a = a/R_\odot, M = M/M_\odot \)), radius of the neutron star is \( R_{NS} = 10^6 \) cm., radius of the iron core of the helium star is \( R_{Fe} = 3 \cdot 10^8 \) cm [35]. \( P_{NS} = 10^4 \frac{a^{3/2}}{M_1^{1/2} + M_2^{1/2}} \left( \frac{R_{NS}}{R_{Fe}} \right)^2 = 10^4 \frac{1}{\sqrt{3}} \left( \frac{10^6}{3 \cdot 10^8} \right)^2 \approx 0.06 \) sec.
general this model is similar to the model of collapse of a fast rotating WR-star and it is probably possible to use this model to explain "long" flashes of gamma-rays.

At the same time compact accretion disk can be formed near young NS and supercritical accretion onto this NS can leads to a formation of a transient source of high energy photons \[90\]. A close companion of ONe WD has to be helium, carbon-oxygen or ONe dwarf. And although observational evidences of such merge stay not totally clear we have included these events in our analysis of frequencies. There are some known observable analogues of close binary degenerated dwarfs which are necessary to realize such scenario. They were found in the last years during search for progenitors of supernova stars type Ia. Most of known close binary degenerated dwarfs have common mass lower Chandrasekhar limit, but three of them have masses higher than this limit and only one of them can merge during period of time \(~ 10^{10}\) years \[62\]. This circumstance and scenario estimations give us basis to hope that it is possible to produce binary systems consisting of ONe WD and degenerated companion with common mass higher than Chandrasekhar limit which also are able to merge under gravitational waves influence during Hubble time. This is third possible scenario explaining observation of "long" flashes of gamma rays.

It is necessary to note that although the fact of possible formation of NS during ONe WD collapse was mentioned \[77\] more than once, but the picture of the explosion of accreting matter ONe white dwarf with NS formation is not known in details yet. Observational manifestations of degenerated ONe dwarfs with comparable masses have not been detailed analyzed in spite of relatively high possible frequency of such events. According to scenario model it is \(~ 0.01\) per year in the Galaxy \[93\]. But the most part of them are helium WDs. Duration of the phase of the destruction of a dwarf is only some seconds. After NS and massive disk formation the disk will evolve in dissipative time scale depending on the disk thickness and this time will be \(10^2 – 10^4\) times longer than Keplerian time of the disk \[79, 90\]. That is, process of destruction of degenerated companion can manifest as powerful X-ray flash with duration of some hours or days. Non-recurrent events of such type are actually recorded \[78\]. It is evidently that observed X-ray bursts present a heterogeneous group \[80\] and it is a problem for the distant future to pick out among them events of dynamical disruption of degenerated components in binary stars. It is important for investigations of GRB models to discuss how we can explain production of short flashes with magnitude comparable with SN explosions in close binary systems. Current classification of GRBs based on their duration is probably not exhaustive. Investigations of spectra of GRBs allow, for example, to outline indications of third subgroup of the phenomenon; it has duration 2-10 seconds and relatively soft gamma-spectra. It is obtained that optical afterglows during first \(~ 100\) days have bimodal behaviour \[46\]. This result is based on investigation of about forty light curves of optical "echoes" of bright GRBs \[46\]. Subgroup of short GRBs is also heterogeneous \[84\]. It is possible that following detailed study of these phenomena will allow to determine new sorts of GRBs which will differ in models of progenitors, in parameters of the models or jet axis orientation relative to observer.

Formation of young neutron star due to ONe dwarf collapse with mass higher than Chandrasekhar limit seems to be interesting not only as potential mechanism of GRB formation, but also as possible way of magnetars – X-ray pulsars formation \[49\]. Only one of them – XTE J1810-197 was revealed as transient radio-pulsar. Magnetars are
neutron stars with magnetic fields $\sim 10^{15}$ Gs and rotational periods 5-12 sec. and current estimation of their birth frequency $\sim 10^{-3}$ per year [85, 39, 86, 75]. It is well known that magnetic fields of some degenerated dwarfs reach to $\sim 10^8$-$10^9$ Gs [99]. During collapse of such dwarf with radius $\sim 10^9$ cm into NS with radius $10^6$ cm trapped magnetic field will be intensified by a factor of million, i.e. will reach to $\sim 10^{14}$-$10^{15}$ Gs (observed value, see [102] for details). Slow rotation of magnetars is probably consequence of their very strong field which rapidly increases their rotational periods from initial, which are probably very short, up to observed value [4]. To accelerate ONe dwarf rotation to the quantity enough to form Keplerian disk around young neutron star after dwarf collapse, i.e. GRB, it is enough according to simple estimation to accrete a part of matter of the Keplerian disk with mass $\Delta M/M_\odot \sim (R_{NS}/R_{ONe})^2 \sim 0.03 M_\odot$, where $R_{NS}$ and $R_{ONe}$ – radii of NS and degenerated ONe dwarf correspondingly.

2 Population synthesis

We use the "Scenario Machine" to estimate frequencies of the described above events which can lead to GRB formation. For every set of the initial parameters we have conducted population synthesis of $10^6$ binary systems.

Since the "Scenario machine" working principles were described more than once, in present work we will limit ourself only with mentioning of the most important parameters which influence on the results of numerical modelling binaries under investigation. Detailed description of the "Scenario machine" may be found in the book written by [53].

2.1 Initial mass ratio distribution

Population synthesis was conducted for two types of the initial distribution of the mass ratio of the components in a binary system $f(q) = q^{\alpha_q}$: flat $\alpha_q = 0$ (the most probable value, see [40] for details) and quadratic $\alpha_q = 2$ (see [52] for details). As the coefficient of the mass ratio in a binary system $q = m_2/m_1$ we assume the ratio of the mass of the secondary companion $m_2$ to the mass of the primary companion $m_1$ of the system ($m_1 > m_2$). Note that for low mass systems ($m_1 \leq 10 M_\odot$) we take $\alpha_q = 0$ in all scenarios.

2.2 'Kick' during supernova explosion

It was supposed in our calculations that neutron star or black hole during supernova explosion is able to get additional "kick" $v$, it’s velocity distributed by Maxwell function:

$$ f(v) \sim \frac{v^2}{v_0^2} e^{-v^2/v_0^2}, $$

it’s direction is equiprobable. But the quantity of dispersion $v_0$ of the remnant is one of the crucial parameters for estimations of the frequencies. We should to say that the results of population synthesis are highly dependent on the quantity of the parameter
Increasing \( v_0 \) higher than orbital velocity in close binary systems \( \sim 100 \text{ km s}^{-1} \) leads to sharp reduction of number of systems including relativistic companion.

Let us suppose that absolute value of kick velocity during BH formation depends on the part of the mass loss by an exploding star during supernova explosion. In our calculations we assumed that during supernova explosion a star lose a half of its mass (see [8] for details). If we assumed characteristic velocity of the neutron star kick \( v_0 \), the quantity of the parameter \( v_0 \) for the case of formation of the black holes is defined as \( v_{0}^{bh} = 0.5v_0 \) in present work.

### 2.3 Stellar wind

Mass loss by an optical star during its evolution is still poorly known at present time. Although it is possible to significantly reduce uncertainties (see, for instance, [8]), there are no ample reason to choose single scenario of mass outflow by stellar wind as a standard, so population synthesis was done using two different scenarios of mass loss rate by a non-degenerated star. Let us call them A and C.

Stellar wind significantly influences on evolution of the massive stars which core’s collapse can lead to a GRB formation. In our conception the phenomenon of GRB can happen only in a close binary system. It’s components either merge with Kerr black hole formation or rotational collapse of WR-star (into Kerr black hole) or white dwarfs (into neutron star) is enabled due to orbital motion. Optical star mass loss greatly influences on the major semi-axis of binary system and is able to significantly change number of close binary systems which can produce GRB.

In this work we use quasi-conservative mass transfer (see [53, 98] for details). In this case we calculate the major semi-axis of the system using formula

\[
a_f/a_i = \left( \frac{q_f}{q_i} \right)^3 \left( \frac{1 + q_i}{1 + q_f} \right) \left( \frac{1 + \beta}{1 + \beta/q_f} \right)
\]

where \( a_f \) is the final major semi-axis, \( a_i \) is the initial major semi-axis. In this equation \( q_f \) and \( q_i \) are final and initial values of \( q = M_{\text{acrer}}/M_{\text{donor}} \), here \( M_{\text{acrer}} \) is the mass of the accreting star and \( M_{\text{donor}} \) is the mass of the donor star. Parameter \( \beta \equiv -(M_{\text{acrer}}^f - M_{\text{donor}}^f)/(M_{\text{acrer}}^i - M_{\text{donor}}^i) \) we calculate in this case as minimal value between \( \beta = 1 \) and the ratio \( \beta = T_{KH}(\text{donor})/T_{KH}(\text{acrer}) \), where \( T_{KH}(\text{donor}) \) is the Kelvin-Helmholtz time for the donor, \( T_{KH}(\text{acrer}) \) is the same for the accretor.

Scenario A has a weak stellar wind. The mass loss rate \( \dot{M} \) during the main sequence (MS) stage [33] is

\[
\dot{M} \sim \frac{L}{V_\infty},
\]

where \( L \) is the luminosity of the star and \( V_\infty \) is the wind velocity at infinity.

For giants we take a maximum between [4] and the result obtained by [44]:

\[
\dot{M} \sim L^{1.42} R^{0.61}/M^{0.99},
\]

where \( R \) is the stellar radius, \( M \) is its mass.
For red supergiants we take a maximum between $41^3$ and Reimers’s formula $41^3$:

$$\dot{M} \sim LR/M, \quad (6)$$

The mass change $\Delta M$ in wind type A during one stage (except WR-stars) is no more than $0.1(M - M_{\text{core}})$, where $M$ is the mass of the star at the beginning of a stage and $M_{\text{core}}$ is its core mass. Mass loss during the Wolf-Rayet (WR) star stage is parametrized as $0.3 \cdot M_{WR}$, where $M_{WR}$ is the maximum star mass during this stage. For calculations of stellar wind type A we used the core masses obtained by $10^9$ and $30^9$.31.

In scenario C the stellar evolution model is based on the results of $97^3$, which reproduce most accurately the observed galactic WR star distributions and stellar wind mass loss in massive stars. Calculations of mass loss by a star were conducted if we used the formula

$$\Delta M = (M - M_{\text{core}}), \quad (7)$$

where $M_{\text{core}}$ is the stellar core mass $8^3 - 8^3$. If the maximum mass of a star (usually it is initial mass of a star, but mass transfer in binary system is able to increase its mass over the initial value) $M_{\text{max}} > 15M_\odot$ the mass of the core in the main sequence stage is determined using $8^3$, and in giant and in supergiant stages using $8^3$. In the Wolf-Rayet star stage, if $M_{WR} < 2.5M_\odot$ and $M_{\text{max}} \leq 20M_\odot$ it is described using $8^3$, if $M_{WR} \geq 2.5M_\odot$ and $M_{\text{max}} \leq 20M_\odot$ as $8^3$, if $M_{\text{max}} > 20M_\odot$ using $8^3$.

$$M_{\text{core}} = \begin{cases} 1.62M_\odot^{0.83}, \\ 0.83M_{WR}^{0.36}, \\ 3.03M_{\text{max}}^{0.342}, \end{cases} \quad \begin{aligned} \text{(a)} & \quad \text{if } M_{\text{max}} > 15M_\odot, \\ \text{(b)} & \quad \text{if } M_{WR} < 2.5M_\odot, \\ \text{(c)} & \quad \text{if } M_{\text{max}} > 20M_\odot. \end{aligned} \quad (8)$$

Scenario C has high mass loss during the WR stage, it may reach 50% of a star mass or more here. Mass loss in other stages (MS, giant, supergiant) for stars with masses higher than $15M_\odot$ (for less massive stars this scenario is equivalent to a type A wind) may reach $\approx 30\%$ of the mass of a star. Total mass loss $\Delta M$ during all stages always is larger than in scenario A.

### 2.4 Common envelope stage efficiency

An effective spiral-in of the binary components occurs during the common envelope (CE) stage. The effectiveness of the CE-stage is described by the parameter $\alpha_{CE} = \Delta E_b/\Delta E_{\text{orb}}$, where $\Delta E_b = E_{\text{grav}} - E_{\text{thermal}}$ is the binding energy of the ejected envelope matter and $\Delta E_{\text{orb}}$ is the drop in the orbital energy of the system during spiral-in $98^3$.

$$\alpha_{CE} \left( \frac{GM_aM_c}{2a_f} - \frac{GM_aM_d}{2a_i} \right) = \frac{GM_d(M_d - M_c)}{R_d}, \quad (9)$$
where $M_c$ is the mass of the core of the mass-losing star of initial mass $M_d$ and radius $R_d$ (which is simply a function of the initial separation $a_i$ and the initial mass ratio $M_a/M_d$, where $M_a$ is the mass of the accreting star).

### 2.5 Restrictions on key parameters of binary evolution

Previous estimations of possible value area of parameters of binary stars evolution were made in papers \[54, 55\]. But during these years some new results have appeared and we made some additional calculations.

Newest observational estimations of neutron star kick during supernova explosion is \[28\]. The authors concluded that characteristic kick velocity $v_0 = 265$ km s$^{-1}$. \[11\] suggested to make more correct estimations for common envelope stage efficiency. They argued to make correction of gravitational energy taking into account the fact that matter of the stars concentrates to their center $GM_d(M_d - M_c)R_d\lambda$. But in their calculations they supposed common envelope stage efficiency $\mu_{CE}$ to be equal to 1. In general, we don’t know this parameter exactly. Our coefficient $\alpha_{CE}$ is the production of the common envelope efficiency $\mu_{CE}$ and the parameter $\lambda$. So we use estimations of $\alpha_{CE}$ suggested by \[54\].

We would like to note one important circumstance. Poorly known evolution parameters, such as $v_0$, $\alpha_q$, stellar wind, etc. are intrinsic parameters of population synthesis. In future they can be defined more exactly or their physical context can be changed: distribution of kick velocity might not be Maxwell, complicated hydrodynamics of common envelope probably can not be described in terms of $a_{ce}$ and $\lambda$, distribution $f(q)$ might not be power law. So, we have only one way to move ahead in investigations, what is to compare predictions of our models with observational data.

We suggest here two tests for our model: comparisons between calculated number of systems of Cyg X-3 type and ratio $\frac{N_{NS+P_{sr}}}{N_{P_{sr}}}$ (number of radio pulsars in binary systems with a neutron star divided by total number of radio pulsars, binary and single). To avoid differences between young and recycled radio pulsar we take only young pulsars. Note that current observational estimation of value of this ratio is $\sim 0.001$ (more exactly, catalogue duplicity rate, \[3\]): there are two known young binary radio pulsars with a neutron star companion ($J2305+4707$ and $J0737-3039$) and $>1500$ known radio pulsars. As Cyg X-3 type system we take here a black hole with WR-star, mass of WR-star is $>7M_\odot$ and orbital period of the pair is less than 10 hours.

In the Figure 1 we show how ratio $\frac{N_{NS+P_{sr}}}{N_{P_{sr}}}$ (here $N_{NS+P_{sr}}$ is the calculated number of binary neutron stars with radio pulsars and $N_{P_{sr}}$ is the calculated number of all radio pulsars) depends on two parameters: kick velocity $v_0$ and common envelope stage efficiency $\alpha_{CE}$. ”Width” of the filled area depicts models with $\alpha_{CE}$ in the range between 0.2 and 1.0. We used stellar wind type A, $\alpha_q = 0$ for these calculations.

In the Figure 2 we show OCCO criterion \[53\] for ratio $\frac{N_{NS+P_{sr}}}{N_{P_{sr}}}$, $O + C$, where $O$ is the observed number of the quantity and $C$ is the calculated number of the quantity. If $O = C$ this value is equal to 2. As one can see from the Figure 2 high kick velocity $v_0 > 200$ km s$^{-1}$ leads to lack of binary radio pulsars with neutron stars.

In the Figure 3 we present estimated with our model number of Cyg X-3 systems. As we can see from this figure, they are practically exclude values of $\alpha_{CE} < 0.3$. 
Figure 1: This figure shows how ratio \( \frac{N_{NS+P_{sr}}}{N_{P_{sr}}} \) (here \( N_{NS+P_{sr}} \) is the calculated number of binary neutron stars with radio pulsars and \( N_{P_{sr}} \) is the calculated number of all radio pulsars) depends on two parameters: kick velocity \( v_0 \) and common envelope stage efficiency \( \alpha_{CE} \). "Width" of the filled area depicts various values of \( \alpha_{CE} \) in the range between 0.2 and 1.0.

Figure 2: This figure shows OCCO criterion [53] for ratio \( \frac{N_{NS+P_{sr}}}{N_{P_{sr}}} \). \( v_0 \) is NS’s characteristic kick velocity. "Width" of the filled area depicts various values of \( \alpha_{CE} \) in the range between 0.2 and 1.0. Note that observation value of this ratio is \( \sim 0.001 \).
3 Results and discussions

Frequencies of events which can produce a GRB calculated using "scenario machine" are presented in tables 1, 2, and 3. All shown frequencies are normalized to a galaxy with mass and star formation rate equal to the mass and the current star formation rate in the Milky Way. This suggestion is valid, because even in case of mergers most of the events (merging and collapsing) must happen during first billion years [92, 51] from formation of the appropriate systems. It is important to note that the minimal mass of the star which evolution remnant is the black hole assumed in the present work to be equal to 25 masses of the Sun [52].

In the table 1 we have presented frequencies of events which are able to produce a GRB. In the first place we put merging of oxygen-neon white dwarfs with oxygen-neon, carbon-oxygen and helium white dwarfs and accretion induced collapses (AIC) of oxygen-neon white dwarfs in systems with optical companion. Also we showed in the table 1 frequencies of merging neutron stars with neutron stars and neutron stars with black holes. So, in the table 1 we have showed frequencies calculated using the next scenario parameters: stellar wind A, $\alpha_{ce} = 0.5$, $\alpha_{q} = 0$, characteristic kick velocity $v_0 = 0$ for neutron stars and black holes. In the table 2 frequencies of rotational collapses of Wolf-Rayet stars in close binary systems are presented. Since the critical period of rotation of WR-star is not reliably fixed yet we have made our calculations using two values of critical orbital period $P_{crit}$, where $P_{crit}$ is the maximum orbital period of a close binary system in which GRB is able to be formed. Calculations of rotational collapses of WR-stars we take into account three types of close binary systems: consisting of a black hole and a Wolf-Rayet star (BH+WR), WR-star and main sequence star (WR+MS), WR-star and non-degenerated star in Roche lobe overflow stage (WR+Rlo). It is necessary to note that in case of stellar wind C minimal period

![Figure 3: Model number of Cyg X-3 type systems in the Galaxy as the function of the common envelope stage efficiency.](image)
Table 1: Frequencies of events in the Galaxy which are able to produce a GRB. Stellar wind A, $\alpha_{CE} = 0.5$, $\alpha_q = 0$.

| Event               | Frequency, yr$^{-1}$ |
|---------------------|----------------------|
| **White dwarfs**    |                      |
| ONe+CO              | $1.8 \cdot 10^{-3}$  |
| ONe+He              | $1.7 \cdot 10^{-5}$  |
| ONe+ONe             | $4.9 \cdot 10^{-4}$  |
| ONe AIC             | $8 \cdot 10^{-5}$    |
| **Hyper-nova model**|                      |
| $P_{crit} = 1$ day  |                      |
| BH+WR               | $3.7 \cdot 10^{-6}$  |
| WR+MS               | $3.4 \cdot 10^{-5}$  |
| WR+Rlo              | $1.1 \cdot 10^{-5}$  |
| $P_{crit} = 3$ days |                      |
| BH+WR               | $9 \cdot 10^{-6}$    |
| WR+MS               | $2.6 \cdot 10^{-4}$  |
| WR+Rlo              | $2.9 \cdot 10^{-5}$  |
| **Neutron stars**   |                      |
| and neutron stars   |                      |
| and neutron stars   |                      |
| mergers, kick       |                      |
| velocity $v_0 = 0$  |                      |
| NS+NS               | $2.1 \cdot 10^{-4}$  |
| NS+BH               | $7.4 \cdot 10^{-5}$  |

Comment: $P_{crit}$ is the minimal orbital period of close binary system in which rotational collapse of Wolf-Rayet star is possible to produce GRB.

of a binary star including WR-star just before collapse becomes to about five days; it is much higher than estimation of the maximum period of binary in which GRB is able to be formed.

In the tables 2 and 3 one can find how different scenario parameters influence on the calculated frequencies of events which we are studying in this work.

In the table 2 we have presented frequencies of merging of oxygen-neon white dwarf with oxygen-neon, carbon-oxygen and helium white dwarfs and accretion induced collapses (AIC) of oxygen-neon white dwarfs in systems including optical companion for $\alpha_{CE} = 1.0$. Note that in all cases we calculate low mass ($m_1 \leq 10M_\odot$) systems using stellar wind A and $\alpha_q = 0$. Also in the table 2 we have presented frequencies of rotational collapses of Wolf-Rayet stars in close binary systems which were calculated using different scenario parameters.

In the table 3 one can find frequencies of merging of neutron stars with neutron stars and neutron stars with black holes if we used various scenario parameters described above.

During analysis of the frequencies showed in the tables 1, 2 and 3 it is necessary to take into account collimation of gamma ray emission in the small space angle $\theta$. It means that only a small part of the GRBs might be observed on the Earth. This fact
Table 2: Frequencies of collapses of Wolf-Rayet stars and ONe white dwarfs in the Galaxy calculated using different scenario parameters. Stellar wind A.

| Event          | Frequency, yr$^{-1}$ |
|----------------|----------------------|
| **White dwarfs, $\alpha_{CE} = 1$** |                     |
| ONe+CO         | $1.1 \cdot 10^{-5}$  |
| ONe+He         | $7.2 \cdot 10^{-5}$  |
| ONe+ONe        | $4.5 \cdot 10^{-4}$  |
| ONe AIC        | $2.7 \cdot 10^{-5}$  |
| **Hyper-nova model** |                 |
| $\alpha_q = 2, \alpha_{ce} = 0.5$ |                     |
| $P_{crit}$ = 1 day |                     |
| BH+WR          | $3.2 \cdot 10^{-6}$  |
| WR+MS          | $4.6 \cdot 10^{-6}$  |
| WR+Rlo         | $2.2 \cdot 10^{-6}$  |
| $P_{crit}$ = 3 days |                     |
| BH+WR          | $1.1 \cdot 10^{-5}$  |
| WR+MS          | $8.2 \cdot 10^{-5}$  |
| WR+Rlo         | $1.1 \cdot 10^{-5}$  |
| $\alpha_q = 0, \alpha_{ce} = 1$ |                     |
| $P_{crit}$ = 1 day |                     |
| BH+WR          | $2 \cdot 10^{-3}$    |
| WR+MS          | $4.1 \cdot 10^{-5}$  |
| WR+Rlo         | $8.3 \cdot 10^{-6}$  |
| $P_{crit}$ = 3 days |                     |
| BH+WR          | $3.6 \cdot 10^{-5}$  |
| WR+MS          | $2.9 \cdot 10^{-4}$  |
| WR+Rlo         | $2 \cdot 10^{-5}$    |

Comment: $P_{crit}$ – the same as in Table 1.
Table 3: Frequencies of merging of neutron stars with neutron stars and neutron stars with black holes under different evolutionary scenario parameters.

| Stellar wind A, $\alpha_q = 0$ |  |  |
|---------------------------------|-----------------|---|
| $v_0$, km s$^{-1}$              | $7.3 \cdot 10^{-6}$ | 50 |
|                                 | $2.3 \cdot 10^{-5}$ | 100 |
|                                 | $7.3 \cdot 10^{-6}$ | 200 |
|                                 | $2.6 \cdot 10^{-6}$ | 300 |

| Stellar wind A, $\alpha_q = 2$ |  |  |
|---------------------------------|-----------------|---|
| $v_0$, km s$^{-1}$              | $4 \cdot 10^{-4}$ | 0 |
|                                 | $1.4 \cdot 10^{-4}$ | 50 |
|                                 | $4.7 \cdot 10^{-5}$ | 100 |
|                                 | $1.7 \cdot 10^{-5}$ | 200 |
|                                 | $6 \cdot 10^{-6}$ | 300 |

| Stellar wind C                  |  |  |
|---------------------------------|-----------------|---|
| $\alpha_{CE}$                   | $2 \cdot 10^{-4}$ | 0.5 |

| Stellar wind A                  |  |  |
|---------------------------------|-----------------|---|
| $\alpha_{CE}$                   | $2.4 \cdot 10^{-4}$ | 1.0 |

allows to estimate GRB frequency in the Galaxy: $\sim 10^{-4} - 10^{-5}$ per year [58, 72]. And it is quite possible that collimation depends on the scenario, so table quantities can not be directly related to observed frequencies. Comparison of this quantity with theoretical estimations of events probably forming GRB flashes (see table 2) leads us to a conclusion about potential adequacy of these frequencies for the explanation of observable frequency of GRBs. However note that all these frequencies remain rather uncertain at present time. Analyzing table 2 it is important to notice considerable frequency of ONe degenerated dwarfs merging. For hyper-nova (WR-star collapse) it is necessary flat to use ($\alpha_q = 0$) initial mass ratio distribution and possible maximum orbital period limit $\sim 1$ day. Influence of a model of stellar wind on the frequency of NS+NS or NS+BH merging is inessential, but neutron star’s or black hole’s ”kick” with magnitude higher than $\sim 100$ km sec$^{-1}$ has to be declined if observed GRBs are the products of the phenomena studied in this article [48].

We would like also to note that frequencies of WR-stars collapses have no significant differences in cases of critical orbital periods $P_{crit} = 1$ day and $P_{crit} = 3$ days, but if we assume $P_{crit} \lesssim 0.5$ day all scenarios of GRBs with Wolf-Rayet stars must be declined because of zero frequency of such events in frames of our models.

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