Magnetars, Gamma-ray Bursts, and Very Close Binaries

A. I. Bogomazov,* S. B. Popov†

*Sternberg Astronomical Institute, Moscow State University,
Universitetski pr. 13, Moscow, 119992, Russia
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We consider the possible existence of a common channel of evolution of binary systems, which results in a gamma-ray burst during the formation of a black hole or the birth of a magnetar during the formation of a neutron star. We assume that the rapid rotation of the core of a collapsing star can be explained by tidal synchronization in a very close binary. The calculated rate of formation of rapidly rotating neutron stars is qualitatively consistent with estimates of the formation rate of magnetars. However, our analysis of the binarity of newly-born compact objects with short rotational periods indicates that the fraction of binaries among them substantially exceeds the observational estimates. To bring this fraction into agreement with the statistics for magnetars, the additional velocity acquired by a magnetar during its formation must be primarily perpendicular to the orbital plane before the supernova explosion, and be large.

1 Introduction

The nature of magnetars and gamma-ray bursts (GRBs) is a hotly debated topic in astrophysics. Some standard models for these objects and their origin exist, but alternative models are still discussed, and a number of problems remain in the standard models.

Magnetars [1, 2] are neutron stars whose activity is related to the dissipation of magnetic energy, which distinguishes them from other neutron stars. The observational manifestations of neutron stars may be connected with the release of potential energy of infalling matter (accreting sources), rotational energy (radio pulsars), or thermal energy (cooling neutron stars, such as compact objects in supernovae remnants and the so-called “Magnificent Seven” — nearby, single, radio-quiet cooling neutron stars). Presumed magnetars (soft gamma repeaters, SGRs, and anomalous X-ray pulsars, AXPs) display energy releases that exceed the rate of dissipation of rotational energy or stored heat, and accretion is not a possible source of their activity. Magnetars display large magnetic fields of $\sim 10^{14}$ G. Their periods of rotation are roughly 2-12 s. There exist ordinary radio pulsars with comparable fields and periods; i.e., magnetars are not specified only by their strong magnetic fields. It is important that the energy of the field is being dissipated,
and this source dominates in the object's luminosity. The origin of the fields in strongly magnetized neutron stars of all types remains unclear. In the standard model suggested by Duncan and Thompson [1] and its modifications, this field is generated in a proto-neutron star by the dynamo mechanism, which requires very rapid initial rotation of the neutron star (with periods shorter than several ms).

The standard model for long cosmic GRBs (see, for example, [3]-[7] and the reviews [8]) invokes the collapse of a massive star, with the formation of a black hole and a massive surrounding disk. The formation of a disk with the necessary parameters requires rapid rotation of the collapsing core.

As we can see, in standard models for the formation of both magnetars and GRBs, the core of the progenitor star rotates very rapidly. Some studies (see, for example, [9,10] and references therein, as well as the text below) have considered models in which GRBs (or at least some of them) are directly connected with the formation of a rapidly rotating magnetar. The requirement of rapid initial rotation is a real challenge for descriptions of the evolution preceding the collapse, since the cores of massive stars probably appreciably decelerate their rotation in the course of their evolution (see, for example, [11]-[13]). This contradiction can be resolved if the presupernova was in a close binary system, where its evolution can result in an overspeeding of star rotation due to accretion or tidal synchronization of the components. More exotic mechanisms for untwisting forming neutron stars have also been discussed [14], but they are related to details of the mechanism for the supernova explosion, which remain not fully clarified.

Here, we analyze the hypothesis that there exists a single channel for the formation of GRBs and magnetars. The evolutionary track of a binary system results in the appearance of a pre-supernova with a rapidly rotating core. If the remnant of the evolution is a neutron star, a magnetar is formed. If the pre-supernova was sufficiently massive, its remnant will be a black hole, and a GRB is observed. An indirect argument in support of this scenario (and a motivation for our study) is the fact that, to order of magnitude, the fraction of magnetars among neutron stars (about 10% [15,16]) coincides with the fraction of GRBs among supernova outbursts (about 3%; see, for example, [17]), that are considered to end in the formation of a black hole. In the studies [18,19] (see also references therein to earlier studies carried out by this group), a mechanism for a GRB that is directly connected with the formation of a magnetar is described in detail. The evolutionary channel discussed here can certainly also result in such events.

To analyze the formation of magnetars, we must also take into account the fact that all ≈15 objects of this type known are single. Since no explicit strong selection favoring the detection of single magnetars is known, this restriction must be additionally taken into consideration (it was first discussed in [20]).

2 Population synthesis

Since the principles of the “Scenario Machine” have been described many times before, here, we will only note the parameters of the evolutionary scenario adopted as free parameters in solution of our problem. A detailed description of the code can be found in [21]-[23]. The population-synthesis technique is also described in [24].

For each set of parameters of the evolutionary scenario, we carried out a population
synthesis for $10^6$ binaries. The rates of events and the numbers of objects in the Galaxy are
given assuming that all stars are binaries. As free parameters of the scenario, we adopted
the kick velocity acquired during the formation of neutron stars and the mass-loss rate
for non-degenerate stars.

2.1 The Kick Acquired in a Supernova Explosion

In our calculations we supposed that a neutron star may acquire some additional
velocity $v$ during the supernova explosion in which it is formed (see, for example, [25]
and references therein). Here, we use two versions for the distribution of the speed and
direction associated with this kick velocity.

In the first, the kick velocity is random and distributed according to a Maxwellian function:

$$f(v) \sim \frac{v^2}{v_0^3} e^{-v^2/v_0^2},$$  \hspace{1cm} (1)

where $v_0$ is a free parameter.

In the second case, the distribution of the kick velocity is a $\delta$ function; i.e., all neutron
stars acquire the same kick velocity $v_0$.

The kick velocity was considered to be either uniformly directed, or to be directed
along the rotational axis of the neutron star. The latter case is associated with the fact
that the direction of the rotational axis essentially provides a preferred direction. First,
in the course of a prolonged kick, averaging about this axis will occur, and the resulting
velocity will be directed along it [26]. Second, the magnetic field generated by a dynamo
mechanism will also be oriented primarily along the rotational axis, while, in some models,
the appearance of the kick is due to asymmetrical neutrino radiation in strong magnetic
fields [26]. Third, in the magneto-rotational model of a supernova explosion, the kick
velocity is primarily directed along the rotational axis [27]. Finally, in a number of models
in which the kick is associated with the development of instabilities at the supernova
stage, the rotational axis also represents a preferred direction, and calculations reveal a
correlation between the direction of the kick velocity and this axis [28]. Observations of
radio pulsars present some very strong arguments suggesting that the directions of the
kick velocity and rotational axis coincide [29]-[31], while the rotational axis in binaries
may be expected to be perpendicular to the orbital plane.

Note that the kick may not only disrupt, but also bind some systems, which would
have decayed without the kick due to the large mass loss in the supernova explosion.
However, in most cases, increasing the kick velocity acquired by the neutron star during
its formation decreases the probability that a binary will be preserved.

2.2 Stellar Wind

Here, we use two evolutionary scenarios (A and C) that differ in the mass-loss rate for
non-degenerate stars. The stellar wind is an important evolutionary parameter, since it
specifies the masses of the remnants of the stellar evolution and the semi-major axes of
binary systems.
Evolutionary scenario A features a classical weak stellar wind (see [22], as well as evolutionary scenario A in [23]). On the main sequence and in the supergiant stage, a star loses no more than 10% of its mass in each of these stages, and in the Wolf-Rayet stage it loses 30% of its initial mass.

Evolutionary scenario C [23] features a higher mass-loss rate. In each stage of its evolution, a star fully loses its envelope, which may mean the loss of more than half its initial mass by the end of its evolution.

2.3 Angular Momentum of a Non-degenerate Core

The main basis for the model considered here is the acceleration of the rotation of a pre-supernova core in a close binary due to tidal synchronization of the rotation of its companion. In this case, we can formally assume that the synchronization occurs just before the collapse. The period of axial rotation of the newborn neutron star should then be approximately $10^{-6}$ of the orbital period of the binary at the time of the supernova explosion, since the radius of the core, whose mass before the collapse is approximately $1.5M_\odot$, is $\sim 10^9$ cm [32], while the characteristic size of the neutron star is $\sim 10^6$ cm. We assume that the rotational angular momentum of this core is conserved during the collapse.

However, the lifetime of the core of a star in the carbon-burning stage is $\sim 10^4$ years [32], while, as a rule, the time for the tidal synchronization of components is no less than $\sim 10^4$ yrs, even in very close systems [33]. Thus, we can take the synchronization of the axial rotation of the core with the orbital rotation of the companion to occur at the carbonburning stage, or at the end of the helium-burning stage [13]. During the stage of the burning of carbon and subsequent elements, the period of axial rotation of the core is shorter than the orbital period of the system. In this case, the rotational period of the newborn neutron star will be approximately $10^{-8}$ of the orbital period of the binary when the components’ rotation becomes synchronized: the radius of a CO core with an approximate mass of $1.5M_\odot$ is $\sim 10^{10}$ cm [32], while the characteristic size of the neutron star is $\sim 10^6$ cm. It is assumed that the rotational angular momentum conserved the core has possessed at the onset of the carbon-burning stage.

We decided to call a magnetar a neutron star that has originated in a close binary, with an initial period of axial rotation that does not exceed 5 ms. Such rapid rotation should make it possible to increase the magnetic field substantially due to the dynamo mechanism. Consequently, if we suppose that the synchronization of the rotation occurs before the collapse, then the maximum orbital period at the epoch when the orbital rotation of the components becomes synchronized with the rotation of the core of the future collapsar should not exceed $\sim 10$ days.

If the formally defined rotational period of the newborn neutron star is shorter than 0.001 s (the limiting minimum rotational period for neutron stars), we consider the period of the neutron star to be equal to this value. It seems to us that the excess angular momentum may lead to additional peculiarities of supernova explosions in such close binaries.
2.4 Other Parameters of the Evolutionary Scenario

In this section, we present some parameters of the evolutionary scenario that are not yet known accurately, and so can be adopted as free parameters in the population synthesis carried out using the “Scenario Machine”. The maximum mass of the neutron star (the Oppenheimer-Volkov limit) that can be attained via accretion is taken to be $M_{OV} = 2.0M_\odot$, and the initial masses of the young neutron stars to be distributed randomly in the interval $1.25 - 1.44M_\odot$.

We assume that main-sequence stars with initial masses in the range $10 - 25$ complete their evolution as neutron stars. There is some evidence that the progenitors of magnetars are the most massive stars among those forming neutron stars [34]; however, this is not a firm fact for all magnetars, and we do not take this possibility into account. It would be important to distinguish supernovae in which magnetars are formed (see, for example, [35]), but this question is likewise unclear.

Main-sequence components of close binaries that increase their masses as a result of mass exchange until their values appear in the above interval were also added to the progenitors of neutron stars. More massive stars evolve into black holes, and less massive stars to white dwarfs. In our present calculations, we assumed a uniform (flat) distribution of component-mass ratios for the initial binaries [32] and zero initial eccentricity for their orbits. We also adopted a flat distribution of the initial semi-major axes of the binaries, $d(lg a) = \text{const}$ in the interval $10 - 10^6 R_\odot$. The efficiency of the mass loss at the common-envelope stage is described by the parameter $\alpha_{CE} = \Delta E_b/ \Delta E_{orb} = 0.5$, where $\Delta E_b = E_{\text{grav}} - E_{\text{thermal}}$ is the binding energy of the ejected matter of the envelope and $\Delta E_{orb}$ the decrease in the orbital energy of the system as its components approach [32, 36].

3 Results

We note first that the synchronization of the core just before the collapse is essentially incompatible with the available observational data. The rate of formation of magnetars under this assumption would be $\sim 10^{-5}$ per year, which is more than two orders of magnitude below the lowest observational estimates (one per several hundred years). The binarity of magnetars if the synchronization of the core rotation occurs just before the collapse begins to differ substantially from unity only for very high kick velocities ($\sim 10^3$ km/s), which do not seem likely. Therefore, we consider further only the possibility that the core maintains the rotational angular momentum it possesses at the onset of the carbon-burning stage.

According to our computations, the rate of formation of rapidly rotating neutron stars (supposed to be magnetars) is approximately one per 400-500 yrs. This agrees with empirical estimates for the rate of formation of these objects (see the analysis and detailed discussion in [15]). Figures 1-4 present the results of our computations. All the curves in Figs. 1-3 assume that the angular momentum due to the axial rotation of the CO core is maintained, and, just before the collapse, the pre-supernova core rotates with a period shorter than the orbital period of the system at the time of the supernova. The maximum

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1 The period of axial rotation of a newborn neutron star is $10^{-6}$ of the orbital period before the collapse. We consider a magnetar to be a neutron star whose rotational period does not exceed 5 ms.
orbital period of the binary at the epoch when the rotation of the components becomes synchronized is 10 days.

We can clearly see in Fig. 1 that the binarity of magnetars remains too high if the magnitude of the kick velocity displays a Maxwell distribution, regardless of the other parameters of the evolutionary scenario, up to very high values $v_0 (> 700 \text{ km/s})$. The curves in Fig. 2 assume that the kick velocity has some specific value $v_0$ (it is a $\delta$ function). This makes it possible to reduce the predicted binarity of magnetars. The presence of a strong stellar wind (evolutionary scenario C) decreases the binarity (curves 2 and 4 in Figs. 1 and 2, and curve 2 in Fig. 3) compared to scenarios with a weak wind. If the kick is uniformly directed and the stellar wind is weak (evolutionary scenario A), consistency with observations can be reached for $v_0 \approx 700 \text{ km/s}$ (curve 1 in Fig. 2), even if the additional kick is represented by a $\delta$ function. With curves 3 and 4 in Fig. 2 and moderately large kick velocities (350-450 km/s), it is possible to reach a level of binarity for magnetars that corresponds to the current observational data (the fraction of binaries is $< 1/15$). This becomes possible if the kick is primarily directed along the rotational axis of the forming neutron star, perpendicular to the orbital plane of the binary at the time of the supernova (curves 3 and 4). A strong wind (curves 2 and 4) also decreases the predicted binarity of magnetars, but having the primary direction of the kick along the rotational axis of the newborn neutron star is preferably to achieve consistency between the computations and observations (curve 4).

The curves in Fig. 3 assume that the kick is directed along the rotational axis of the forming neutron star and that the kick is represented by a $\delta$ function, but also depends on the orbital period at the time of the supernova as $v = v_0 \cdot 0.001/P_{\text{NS}}$, where $0.001 \text{ s} \leq P_{\text{NS}} \leq 0.005 \text{ s}$ is the period of the forming neutron star. The orbital period is restricted to approximately 10 days. The need for this computation stems from the following consideration. Our model assumes that the very strong magnetic field of the magnetar is generated as a result of the collapse of a very rapidly rotating core. In our present study, the maximum and minimum periods of magnetars differ by a factor of five. The kick velocity at the time of the collapse may depend on the magnetic field, while the predicted binarity of magnetars may depend on the orbital period at the time of the supernova. Figure 3 shows that curve 3 corresponds to observational data starting from $v_0 = 1700 \text{ km/s}$. For systems whose orbital periods at the time of tidal synchronization are, for example, 5 days, the kick velocity will not exceed 400 km/s, while the largest kick will be obtained by neutron stars forming in binaries with orbital periods $\lesssim 1 \text{ day}$. This graph may provide evidence against the basic model considered here.

We can see from Fig. 4 that the maximum orbital periods of binaries in which magnetars can form can be decreased to several days; however, they cannot be shorter than a day, since the rate of formation of rapidly rotating neutron stars would then be too low.

The potential companions in hypothetical binaries containing magnetars are also of interest. Most of these are main-sequence stars (49%) and black holes (46%). The remaining 5% are roughly equally divided among white dwarfs (2%), Wolf-Rayet stars (1%), stars filling their Roche lobes (0.7%), helium stars filling their Roche lobes (the BB stage), hot white dwarfs (0.7%), and neutron stars (0.6%).
Discussion

4.1 Alternatives

We were not able to obtain a sufficient number of single magnetars in our evolutionary scenario for binaries without making additional assumptions, for example, about the kick (recoil) velocity at the time of the supernova. This could be considered indirect argument against the generation of the magnetar magnetic field in rapidly rotating newborn neutron stars. In this connection, we will recall and briefly discuss alternatives to the considered scenario.

4.1.1 Relict magnetic field

One currently popular hypothesis suggests that the fields of magnetars are formed in the collapses of stellar cores with magnetic-flux conservation, when the progenitor star has a sufficiently strong magnetic field (see [16] and references therein). Some observations suggest that magnetars are related to the most massive stars among those giving rise to neutron stars [37]. According to some observational data, about a quarter of these massive stars display sufficiently strong magnetic fields (see [38] and references therein). In addition, studies of supernova remnants related to magnetars have not revealed any direct signs of intense energy release that could have been connected with the presence in them of rapidly rotating neutron stars with magnetic fields [39]. These studies can be considered indirect arguments against the hypothesis that the magnetar fields were generated in the course of a collapse. Simple population estimates [16] indicate that current estimates for the rate of formation of magnetars can be explained in this hypothesis.

However, there are serious objections against this hypothesis, some of them recently summarized by Spruit [40]. The simplest is that, even if there exists a strongly magnetized massive star, only 2% of its cross section (which is important when calculating the field during a collapse with flux conservation) will be included in the compact object.

The rate of formation of magnetars remains very uncertain. Recent detections of transient anomalous X-ray pulsars [41]-[43] and the detection of a new source of repeating GRBs [44, 45] suggest that the number of magnetars may exceed previous estimates. If true, this may raise the problem of the lack of sufficiently strongly magnetized massive stellar progenitors able to provide the high formation rate of magnetars. Finally, studies of stellar magnetic fields are able to probe only the surface fields. A compact object emerges from the stellar core, whose field is unknown.

Thus, to explain the origin of the fields of magnetars, it is difficult to get away without some mechanism for its generation. All the possible mechanisms [40] use the rotational energy of a newborn neutron star or collapsing core in some way; i.e., the question of what makes 10% to several tens of per cent of cores of massive stars rotate rapidly just before their collapse remains open.

4.1.2 Other channels of evolution in binaries

A more optimistic scenario than ours is considered in [20]. While here we consider only stars that rotate rapidly just before the collapse, several possible means for spinning
up stars in binaries are suggested in [20], neglecting the possible subsequent deceleration of the rotation. It is not surprising that this led, first, to a substantially higher rate of formation of rapidly rotating neutron stars, and second, to a fraction of preserved binaries that was much lower. Unlike the channels considered in [20], in the scenario considered above, rapidly rotating neutron stars originate only in very compact systems, and, in addition, the exploding star is often less massive than its companion.

There are a number of objections against the optimistic suggestion that a normal star spun up by accretion in an early stage of its evolution, or an object formed as a result of a merger, can maintain the high angular momentum of its core until its collapse. For example, three processes that can transfer the rotational angular momentum from one layer to another are considered in [13] convection, diffusion (shear diffusion), and meridional circulation. Convection tends to make the angular velocity constant, thereby transferring angular momentum from inner to outer layers of the convective zone. Diffusion weakens differential rotation and also transfers angular momentum outwards. Meridional circulation can transfer angular momentum both outward and inward in the star. Mass loss affects the angular momentum of the core in part indirectly, since it influences the rotational angular velocity of the star and the angular velocity gradient inside the star. The most important conclusions related to the evolution of the rotation listed in [13] are as follows (see also references therein):

- The angular momentum of the star decreases during the star’s evolution up to the supernova explosion.
- The largest loss of angular momentum occurs on the main sequence.
- After helium burning has finished, convection transfers angular momentum from inner parts of the convective zone to its outer layers, without involving the core; therefore, the rotational angular momentum of the core at the end of the helium-burning stage can be taken as a fairly reliable estimate of the rotational angular momentum of the collapsing core.

4.2 Possible Observational Manifestations of Magnetars in Binary Systems

In our scenario, with an isotropic kick, an appreciable fraction of magnetars remain in bound binaries. In this connection, we should discuss possible manifestations of close binaries with magnetars.

Since the magnetic fields of magnetars apparently rapidly decrease to values typical for common radio pulsars (see, for example, [46] and references therein), the considered stage will be short. The secondary component does not have sufficient time to undergo substantial evolution (the characteristic time of the decay for the magnetar field lies in the interval from several thousand years to several tens of thousand years). Possible configurations can be identified in which some feature of a magnetar, such as its strong magnetic field, will be manifest in a critical way.

One example of a close binary system with a magnetar may be provided by the central object in the supernova remnant RCW 103 [47]. This object displays variability with a
period of 6.7 h. One possible interpretation of the observations is that the secondary is situated within the magnetosphere of the magnetar [47, 48]. In this case, 6.7 h is the orbital period of the system. The binary is similar to polars, in which the compact object is a white dwarf whose magnetic moment is approximately equal to that of the magnetar. In the classification suggested by Shvartsman and Lipunov [49], such systems are called magnetors. We are planning to estimate the number of such objects in the Galaxy.

5 Conclusion

We have considered the hypothesis that GRBs and magnetars originate during the evolution of massive stars in close binary systems, which spins up the core of the presupernova. The statistics for the expected rate of formation of magnetars are in satisfactory agreement with observational estimates. However, this scenario predicts a large fraction of binary magnetars, whereas all known magnetars or magnetar candidates are single. This problem may be solved by introducing an additional component of the kick velocity acquired during the formation of the neutron star, perpendicular to the orbital plane (i.e., along the direction of the magnetic-dipole axis of the newborn compact object), and requiring that the magnitude of the kick not be small ($\lesssim 400$ km/s). The presence of a moderately strong stellar wind (evolutionary scenario C) also promotes a decrease in the predicted binarity of potential magnetars; the requirement that the kick velocity be high is mandatory, but it should be preeminently directed perpendicular to the orbital plane of a system.

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Figure 1: The fraction of binary neutron stars formed in very close binaries as a function of the characteristic kick velocity $v_0$ acquired during the formation of a neutron star. The kick velocity is distributed according to (1). The vertical axis plots $N_b/(N_b + N_s)$, where $N_s$ is the number of singular neutron stars and $N_b$ the number of neutron stars in binaries that originated in the course of the computations. The numbers on the graph denote the curves calculated for the following scenarios: (1) equiprobable directions for the kick, type A evolutionary scenario; (2) equiprobable directions for the kick, type C evolutionary scenario; (3) kick always perpendicular to the plane of axial rotation of the star, type A evolutionary scenario; (4) kick always perpendicular to the plane of axial rotation of the star, type C evolutionary scenario; (5) upper limit for binarity according to observations ($\approx 1/15$).
Figure 2: Same as Fig. 1 for a $\delta$-function distribution for the kick velocity. The numbers on the graph denote the curves calculated for the following scenarios: (1) equiprobable kick-velocity direction, type A evolutionary scenario; (2) equiprobable kick-velocity direction, type C evolutionary scenario; (3) kick velocity directed along the rotational axis of the star, type A evolutionary scenario; (4) kick directed along the rotational axis of the star, type C evolutionary scenario; (5) upper limit for binarity according to observations ($\approx 1/15$).
Figure 3: Same as Fig. [I] for a $\delta$-function kick-velocity distribution with the kick directed along the rotational axis of the star; the absolute value of the kick also depends on the initial rotational period of the young neutron star (see text for the details). The numbers on the graph denote the curves calculated for the following scenarios: (1) type A evolutionary scenario, (2) type C evolutionary scenario, (3) upper limit for binarity according to observations ($\approx 1/15$).
Figure 4: Distribution of orbital periods just before the collapse in the systems in which neutron stars originate. If a neutron star originates in a disrupted system, the orbital period at the time of disruption is taken into account. The type A evolutionary scenario is adopted (a weak stellar wind).