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Letter to the Editor

Formation of a gravitationally bound object after binary neutron star merging and GRB phenomena

G.V. Lipunova[1] **and V.M. Lipunov**[2]

[1] Sternberg Astronomical Institute, Moscow State University, Universitetskii pr. 13, Moscow, 119899 Russia (e-mail: galja@sai.msu.su)
[2] Sternberg Astronomical Institute, Moscow State University and Milano University (e-mail: lipunov@sai.msu.su)

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Abstract. The stages that follow the merging of two neutron stars are discussed. It is shown that if a rapidly rotating gravitationally bound object is formed after the merging (a spinar or a massive neutron star), then the characteristic time of its evolution is determined by a fundamental value

$$t_{spin} = 3k\frac{m_p e^2 \hbar^{1/2}}{m_e^3 c^{5/2} G^{1/2}} \approx 10^3 s \cdot \kappa \ ,$$

where the dimensionless value $\kappa = 100 \div 1000$ depends on the exact equation of state of nuclear matter. The hypothesis is discussed as to whether the residual optical emission of the gamma-ray bursts is pulsar-like and its evolution driven by magnetodipole energy losses. It is shown that binary neutron star mergings can be accompanied by two gravitational wave burst separated either by the time of spinar's collapse t_{spin} or neutron star cooling time ($\sim$ 10 s), depending on the masses of neutron stars.

Key words: stars: neutron — gamma rays: bursts

1. Introduction

The detection of optical and X-ray emission after the gamma ray bursts GRB 970228, GRB 970508 (Groot et al. 1997a; Groot et al. 1997b; Metzger et al. 1997b; Costa et al. 1997b; Sahu et al. 1997; Bond 1997; Galama et al. 1997; Djorgovski et al. 1997a; Metzger et al. 1997c; Schaefer et al. 1997; Djorgovski et al. 1997b; Djorgovski et al. 1997c; Groot et al. 1997; Donahue et al., 1997) may be interpreted in terms of the formation of a transient rapidly rotating gravitationally bound object — a heavy neutron star (NS) or spinar — an object with the equilibrium maintained either by the fast rotation ("cool" spinar, CSP) or by both rotation and pressure ("hot" spinar, HSP).

Let us assume that two neutron stars with masses M_1 and M_2 are merging. The following state of the after-merging object is determined by the ratio of the resulting total mass and the Oppenheimer–Volkoff limit. Two different scenarios may be envisaged as follows:

$$M_1 + M_2 \geq M_{OV} \tag{A}$$

$$M_1 + M_2 < M_{OV} \tag{B}$$

Here and below we interpret the Oppenheimer–Volkoff limit not as the standard value derived for the cold equation of state of baryonic matter for a non–rotating neutron star, but as a modified one. In the general case the Oppenheimer–Volkoff limit is a function of the angular spin velocity of the object, its entropy, and the specific equation of state: $M_{OV} = M_{OV}(\omega, S, EqSt)$.

Each neutron star can have a mass lying between the limits:

$$M_{min} < M_1, M_2 < M_{OV}$$

The value of $M_{min} \sim 0.2 M_\odot$ was derived by Landau (1938). In a standard modern scenario, it is commonly suggested that $M_{min} \sim 1.2 M_\odot$. Thus we can expect the different evolutionary tracks depending on the specific masses of NS.

2. Mergingology

2.1. Case (A)

In this case, we can expect that after the merging a black hole results from a direct collapse during the time $\sim 10^{-5} s$ and that the most energy is emitted in the gravitational wave burst. This scenario is discussed more frequently in the literature, and GRB phenomenon can be related with the relativistic particle ejection in the form of a Fireball (Rees & Meszaros, 1992) or a beam of protons (Shaviv & Dar, 1996). In addition, a certain fraction

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Send offprint requests to: G.V. Lipunova of radiated energy can be related with the pulsar mechanism (Lipunov & Panchenko 1996; Lipunova 1997). No gravitationally bound object can be formed in this case outside the horizon. We can present these stages by the following way:

$$NS + NS \rightarrow BH + GWB + GRB + \nu B$$

(GWB - gravitational waves burst; νB - neutrino burst).

From our point of view the more interesting scenario is the Case (B).

2.2. *Case (B):* $M_1 + M_2 < M_{OV}$

This variant can be realized if either two merging neutron stars have small masses or the Oppenheimer-Volkoff limit is very large.

Is it possible that the Oppenheimer–Volkoff limit exceeds $3M_\odot$? First, it is known (Friedman & Ipser, 1987) that the fast rotation (which is naturally expected after the merging) increases the Oppenheimer–Volkoff limit to the value $\sim 3M_\odot$ for hard equations of state. Second, the object formed is not degenerate due to its high temperature and the equilibrium is maintained both by fast rotation and entropy ("hot" spinar). And last, Oppenheimer-Volkoff limit can be high because of relativistic behavior of nuclear forces.

Thus we can present these three sub-scenarios as follows:

$$NS + NS \rightarrow HSP + GWB + GRB + \nu B$$

$$NS + NS \rightarrow CSP + GWB + GRB + \nu B$$

$$NS + NS \rightarrow NS + GWB + GRB + \nu B$$

Let us consider the case of the HSP. Its lifetime is completely determined by the cooling time which, according to different calculations, is of the order of $\sim$ 10 s (Shapiro & Teukolsky, 1983). Then, in the time interval t_{cool}, the collapse accompanied by the GWB, neutrino emission, and possible weak photon emission can be expected:

$$HSP \rightarrow BH + GWB + \nu B + \gamma$$

It seems very attractive to identify this cooling time with the mean characteristic gamma-ray burst duration $\sim 1 \div 10$ s!

Second, the most interesting sub-scenario is when the centrifugal forces make the main contribution to the equilibrium ("cool" spinar). In this case the lifetime of the spinar is completely defined by the characteristic time of the angular momentum loss t_{spin} and evolutionary track looks like

$$CSP \rightarrow BH + GWB + \gamma + e^+ + e^- + \nu$$

Finally, there is a case of a high Oppenheimer-Volkoff limit for the cool non–rotating object.

$$M_1 + M_2 < M_{OV} \quad \text{always !}$$

This variant leads to the formation of a very powerful pulsar (maybe without pulsation) with the maximum spin rotation.

$$NS + NS \rightarrow PSR$$

The characteristic time t_{spin} of its evolution is governed by the momentum loss rate.

3. The rate of the angular momentum losses

In both cases of a cool spinar (Lipunova 1997) and of a fast–rotating NS, the specific time of their evolution is determined by the rate of magnetodipole energy loss

$$\frac{dI\omega}{dt} = -\frac{2}{3}\frac{\mu^2\omega^3}{c^3},$$

and

$$t_{spin} = \frac{\omega}{2\dot{\omega}} = \frac{2}{5}\frac{\mu c^3}{B_o^2 R_o^4 \omega^2}.$$

We assume:

the inertia moment $I = \frac{2}{5}MR^2$,

the mass $M = M_1 + M_2$,

the magneto–dipole moment $\mu = B_o R_o^3/2$.

The angular spin velocity of the post-merging object must be close to the limit:

$$\omega = (GM/R_o^3)^{1/2}.$$

Then we obtain:

$$t_{spin} \approx \frac{2}{5}\frac{c^3}{B_o^2 GR} \approx 10^5 \left(\frac{B}{B_{cr}}\right)^{-2} \left(\frac{R}{10^6 cm}\right)^{-1} \text{s}.$$

Thus, this duration is determined mainly by the magnetic field. If we assume that a gravitationally bound object magnetic field is equal to the critical value close to the Schwinger limit:

$$\hbar\frac{eB_{cr}}{m_e c} = m_e c^2, \quad B_{cr} \approx 4.3 \cdot 10^{13}\ \text{G}.$$

Expressing the radius and the mass of the NS in terms of fundamental constants we obtain the fundamental value for the lifetime of such an object:

$$T = \frac{m_p e^2 \hbar^{1/2}}{m_e^3 c^{5/2} G^{1/2}} \approx 1.2 \cdot 10^3 \text{s}.$$

Taking into account the real mass of NSs and specific equation of state, this time can be modified as

$$t_{spin} = T \cdot \kappa,$$

where $\kappa \approx 100 \div 1000$. This duration accords with the specific fundamental value of luminosity.

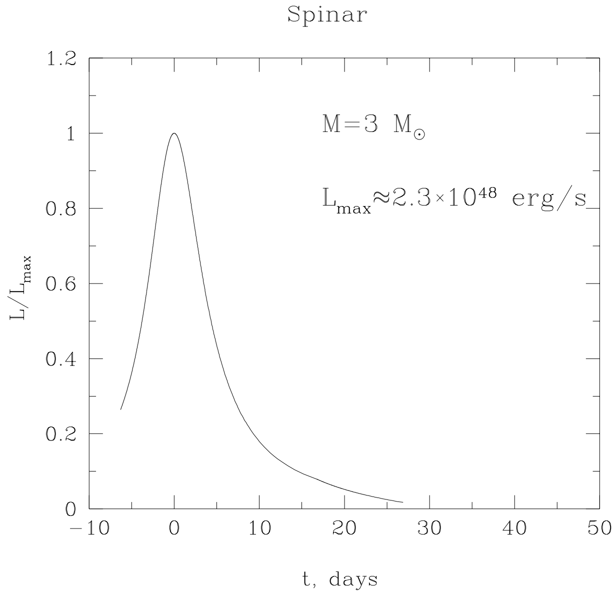

Fig. 1. The spinar luminosity evolution. The magnetic field $B = 4.3 \cdot 10^{13}$ Gs at $R = 20$ km.

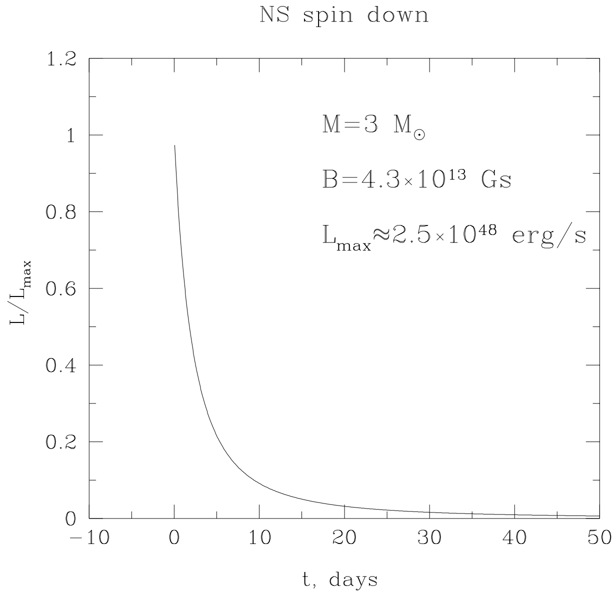

Fig. 2. The neutron star spindown rate and luminosity evolution. $R = 30$ km, $\nu_{max} = 660$ Hz.

4. GRB light curve

Here we present the alternative model to the now frequently discussed model of GRB — the radiation of a Fireball (see Meszaros & Rees 1997). We admit that the models of fast–rotating pulsar or spinar with extremely high magnetic fields do not wholly substitute the model of Fireball (especially, concerning the gamma burst itself) but accompany the process of radiation and, possibly, at later stages of GRB afterglow, dominate in a GRB spectrum. Note, that these mechanisms can supply the emission in a wide range of wavelengths, as radiopulsar studies confirm.

We suggest that part of the observed optical and X-ray afterglow of a GRB can relate to the pulsar mechanism. As an emission from Fireball decreases to the undetectable level, the pulsar mechanism can become the main contribution to the afterglow.

We can construct the luminosity evolution for a cool spinar collapse (Lipunova, 1997) and for a pulsar spin down.

Supposing that the optical emission is produced by the pulsar mechanism acting with the critical magnetic field, one can derive:

$$L \approx 2 \cdot 10^{45}\mathrm{erg/s}\left(\frac{B}{B_{cr}}\right)^2 R_6^6 P_{1.5}^{-4}\ K(t,\nu)\ \times$$
$$\times\left(\frac{t}{3\cdot10^7\ \mathrm{s}}\left(\frac{B}{B_{cr}}\right)^2 R_6^4 P_{1.5}^{-2} M_3^{-1} + 1\right)^{-2},$$

where $R_6 = \left(R/10^6 cm\right)$, $P_{1.5} = \left(P/1.5ms\right)$, $M_3 = \left(M/3M_\odot\right)$. The coefficient $K(t,\nu)$ is the ratio of optical radiation to the total energy loss by a pulsar. Of course, it is hard to expect the ratio of optical radiation to the total rotational energy loss to be constant, as evidenced by radiopulsar studies. As it is, the real power of time dependence can vary from -2.

Fig. 1 shows the characteristic times of luminosity decreasing to be in a rather good correlation with the observed ones (see Groot et al. 1997a; Groot et al. 1997b; Metzger et al. 1997b Costa et al. 1997b; Sahu et al. 1997; Bond 1997; Galama et al. 1997; Djorgovski et al. 1997a; Metzger et al. 1997c; Schaefer et al. 1997; Djorgovski et al. 1997b; Djorgovski et al. 1997c; Groot et al. 1997; Donahue et al., 1997). The model of a neutron star spin down is calculated for the initial angular velocity $\nu = 660$ Hz, which corresponds to the minimum spin period observed in millisecond pulsars.

The lack of optical counterparts to other GRBs may be explained by another relation between the total mass of the system before merging and the Oppenheimer-Volkoff limit and, as a result, by another scenario of neutron star coalescence.

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