The Magnetospheric Flare on Compact Magnetized Object (Neutron Star or White Dwarf)—Model for Cosmological Gamma-Ray Burst (GRB)

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Abstract

The SN explosion in the closed binary can give the magnetospheric flare possessing the properties of GRB. The SN shock, flowing around the magnetosphere of a magnetized neutron star or a white dwarf, produces a narrow magnetic tail $10^9 \text{cm}$ long, $10^8 \text{cm}$ wide and a magnetic field of $10^6 \text{Gauss}$. Fast particles ($\gamma \approx 10^4$), generated in the tail by reconnection processes, radiate gamma rays of the $100 \text{KeV}$ - $1 \text{MeV}$ energies. The duration of radiation $T < 1 \text{sec}$ corresponds to a short GRB. Apart, the powerful shock can tear and accelerate part of the tail. That is the relativistic ($\Gamma \approx 10^4$), strongly magnetized jet, producing gamma radiation and also X-ray and optic afterglow. That is a long ($T > 10 \text{sec}$) GRB. The duration of the afterglow is inversely proportional to the photon energy and is several months for optic.

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Identification of two tens of the long GRB ($T_{90} > 1 \text{sec}$) with the extragalactic objects located at cosmological distances ($z = 0.1–4$) raises a question about the source of energy release. For the spherical symmetry the energy yield is turned to be as abnormally large as $10^{53–54}$ ergs only in the band of thousands of $KeV$. Such energy release is comparable with that of a supernova explosion (SN), for which 90% of the energy is escaped by neutrinos during the first several seconds. To overcome the 'energy catastrophe' in the problem of GRB a hypothesis was suggested about a strong collimation of the gamma radiation in the narrow solid angle of $\Delta\phi \simeq 1^\circ$. This assumption gives a possibility to diminish the luminosity of GRB, needed for the explanation of the observed gamma-ray flux, by a factor of $(\Delta\phi/4)^2$ which for $\Delta\phi \simeq 1^\circ$ gives the gain of $10^5$. Such directivity can be explained by the radiation of a narrow jet of particles accelerated to relativistic energies. However, it is not clear now how this jet is formed when two compact objects merge or when one of them explodes. That is why there exists a large amount of models suggested for GRB explanation, [1]. In last years the model of strong anisotropic supernova explosion becomes very popular (see, for example, [2]), which demands extreme conditions for its realization.

Our model suggests the mechanism of origin of a narrow beam of gamma-rays when a shock of an SN explosion in the binary system, containing a magnetized neutron star or a white dwarf, is interacting with its magnetosphere. If the observer is placed in the plane of the orbit of such a binary system and at the moment of the origin of the magnetospheric tail the line of observation coincides with the tail direction, then a GRB will be observed. We give the estimations confirming that our model can explain the general properties of GRB, both long ($T > 1 \text{sec}$) – cosmological, and short ($T < 1 \text{sec}$) – possibly local. For the short GRB we consider the binary system in which one companion, as previously, is a neutron star or a white dwarf and another is a star of cataclysmic flare variable.

2 Model’s Parameters

As an example we discuss a binary stellar system with a distance between the companions of $a \simeq 10^{13} \text{cm}$. The system consists of a blue giant - supernova progenitor ($M = 20M_\odot, R = 50R_\odot$) and a magnetized neutron star ($M = 1.4M_\odot, R = 10^6\text{cm}, B = 10^{12}\text{Gauss}$) or a magnetized white dwarf ($M \simeq 1M_\odot, R = 10^9\text{cm}, B = 10^9\text{Gauss}$). According to the review [3] the parameters of the shock are
kinetic energy $E_{\text{kin}} \simeq 10^{47}\text{ergs},$

velocity $u \simeq 4 \cdot 10^9\text{cm/sec},$

density $\rho \simeq 10^{-8}\text{g/cm}^3 \simeq 10^{16}\text{protons/cm}^3,$

width $h \simeq 10^9\text{cm}.$

Under the impact of the shock on the dipole magnetic field of a neutron star or a white dwarf a magnetospheric tail forms, aligned along shock wave propagation. The magnetospheric magnetic field is amplified and compressed by the cumulative effect, forming the narrow tail. The dependencies of the magnitude of the magnetic field in the tail $B_t$ and the tail’s diameter $d_t$ on the distance to the center of the compact star $l$ follow from the condition of freezing of the magnetic field into the shock plasma and the conservation of the magnetic field flux

$$B_t(l) = B^* \left( \frac{l}{r^*} \right)^{1/2};$$
$$d_t(l) = r^* \left( \frac{l}{r^*} \right)^{-1/4}. \quad (1)$$

Here $r^*$ is the Alfven radius

$$r^* = R \left( \frac{B^2}{4\pi \rho u^2} \right)^{1/6}; \quad (2)$$

where the magnetic field pressure is equal to the pressure of the shock matter; $B^*$ is the value of the magnetic field on the Alfven radius

$$B^* = \left( 4\pi \rho u^2 \right)^{1/2}. \quad (3)$$

The length of the tail $L$ is of the order of shock’s width $h,$

$$L \simeq h.$$ 

Thus, a stretched ($d_t << L$), magnetized ($B^* \simeq 10^6\text{Gauss}$), almost parallel magnetospheric tail forms with a stored magnetic energy

$$\epsilon_B = \int B_t^2/8\pi \cdot \pi d_t^2 dl,$$

$$\epsilon_B = \frac{1}{8} B^{1/2} B^*^{3/2} (Rh)^{3/2}. \quad (4)$$

For neutron stars and for white dwarfs the values of $\epsilon_B$ are equal to
\[ \epsilon_B^{n.s.} = 4 \cdot 10^{36} \left( \frac{B}{10^{12} G} \right)^{1/2} \left( \frac{B^*}{10^6 G} \right)^{3/2} \left( \frac{R^*}{10^6 \text{cm}} \right)^{3/2} \left( \frac{h}{10^9 \text{cm}} \right)^{3/2} \text{ergs,} \]

\[ \epsilon_B^{w.d.} = 4 \cdot 10^{39} \left( \frac{B}{10^9 G} \right)^{1/2} \left( \frac{B^*}{10^6 G} \right)^{3/2} \left( \frac{R^*}{10^9 \text{cm}} \right)^{3/2} \left( \frac{h}{10^9 \text{cm}} \right)^{3/2} \text{ergs,} \]

respectively. We see that for a not very compact pair \((a \approx 10^{13} \text{cm})\) a part of the energy caught from the total kinetic energy of the shock of the SN explosion is \(10^{-8}\) and \(10^{-11}\) for the white dwarfs and the neutron stars \(^1\). The energy caught increases as \(a^{-3/2}\) for a closer binary system.

For the narrow directivity of gamma radiation \(\Delta \phi \approx 10^{-4}\) from the relativistic particles \((\gamma \approx 10^4)\), when the magnetospheric tail is directed to the observer, it is natural to obtain the effective power needed for the cosmological GRB. The rate of GRB of \(300 \text{year}^{-1}\) for a total number of \(10^{11}\) galaxies of a visible Universe gives the rate per one galaxy of the order of \(3 \cdot 10^{-9} \text{year}^{-1}\). If we assume the rate of SN explosions in one young galaxy as \(1 \text{SN} \text{year}^{-1}\), then we obtain that approximately \(10^8\) SN explosions result in one GRB. This corresponds to the directivity of gamma radiation of \(\Delta \phi \approx 10^{-4}\).

The lifetime of the tail is defined by the annihilation of its magnetic field \(\tau = L/v_a \equiv h/u\) (\(v_a\) is the Alfven velocity) and is equal to the time of its forming \(h/u\). It is 1 sec. The non-stationarity and the reconnection of the magnetic field in the tail (note that the magnetic field is antiparallel at the opposite sides of the tail) lead to the appearance of a strong electric field

\[ E = \frac{d_i}{c \tau} B_t \approx 10^{-2} B^*, \]

accelerating particles. Their mean Lorentz factor \(\gamma\) can be estimated from the equilibrium between the acceleration rate and synchrotron losses of fast particles in the magnetic field \(B^*\),

\[ \gamma = 10^4 \left( \frac{r^*}{10^8 \text{cm}} \right)^{1/2} \left( \frac{u}{4 \cdot 10^9 \text{cm/sec}} \right)^{1/2} \left( \frac{h}{10^9 \text{cm}} \right)^{-1/2} \left( \frac{B^*}{10^6 G} \right)^{-1/2}. \]

The characteristic value of the Lorentz factor of accelerated electrons (and positrons) is \(10^4\). In the magnetic field \(B^* \approx 10^6 \text{Gauss}\) particles of such energies radiate at the frequency \(\nu \approx \omega_c \gamma^2\), which corresponds to the photon energy \(500 \text{KeV}\), typical of a gamma burst.

\(^1\) We assume \(E_{\text{kin}} \approx 10^{47} \text{ergs}\), that is typical of a compact SN of Ib/c type. For the Ia type \(E_{\text{kin}}\) may \(10^{3-4}\) times larger.
In some cases the magnetospheric tail produced by the interaction of a SN shock with a magnetosphere of a magnetized companion can be torn due to a global reconnecton of its magnetic field lines (tearing instability). Such kind of phenomenon is observed during intense chromospheric flares on the Sun. As a result, part of the tail can be torn off and obtain high kinetic energy. It will move with a Lorentz factor $\Gamma$, which is almost equal to the factor $\gamma$, estimated early in (7), $\Gamma \approx 10^4$. Thus, a narrow, magnetized, relativistic jet is moving towards the observer.

In the frame moving together with the jet, let the magnetic field strength be $B$, the particle density be $n$, the mean Lorentz factor of particles be $\gamma$. Due to synchrotron loses the value of $\gamma$ will decrease. Inside the jet microreconnection processes will support the equipartision between the magnetic energy and the particle energy, $B^2 = 8\pi mc^2\gamma n$. Besides, particles are frozen into the magnetic field, and their density is proportional to the magnetic field strength, $n = n_0B/B_0$. The index "0" is related to the initial values of the parameters. It follows that

$$B = 8\pi mc^2n_0\gamma/B_0.$$ 

During the adiabatic expansion of the jet’s diameter with the conservation of the magnetic flux, $d = d_0(B_0/B)^{1/2}$, the quantities $n$ and $B$ will decrease in time. Because of the optical depth with respect to the Thompson scattering is small $n_0L\sigma_T << 1$ for our parameters ($n_0 \approx 10^{13} cm^{-3}, L \approx 10^9 cm$) we can consider that the synchrotron radiation escapes freely. So, the jet’s cooling is associated with the synchrotron losses

$$mc^2\frac{d\gamma}{dt} = eEc - \frac{2e^4B^2\gamma^2}{3m^2c^3}.$$ 

(8)

Here $E$ is the induced electric field arising due to the change of the magnetic field, $E = -(r^*/c)dB/dt$. From (8) we obtain the equation describing the evolution of the mean particle energy

$$\frac{d\gamma}{dt}\left[1 + \frac{8\pi er^*n_0}{B_0}\right] = -\frac{2e^4}{3m^2c^5}\left(\frac{8\pi mc^2n_0}{B_0}\right)^2\gamma^4.$$ 

(9)

The second term in the left-hand side of (9) describes the betatron cooling of the particles with decreasing magnetic field

$$\frac{8\pi r^*en_0}{B_0} = \frac{2r^*\omega_{p0}^2}{c\omega_{c0}}.$$ 

$\omega_{p0}$ is the plasma frequency and $\omega_{c0}$ is the cyclotron frequency in the jet.
at the initial time $t = 0$. In our case for $\omega p_0^2 = 3 \cdot 10^{22}$ sec$^{-2}$, $\omega_c 0 = 2 \cdot 10^{13}$ sec$^{-1}$, $r^* = 10^8$ cm the value of $2r^* \omega p_0^2/ c \omega_c 0 >> 1$, and we can write the solution of equation (9) as

$$\gamma^{-3} - \gamma_0^{-3} = \frac{t}{\tau_0},$$

(10)

where the time $\tau_0 = r^* \omega_c 0 / 4 \omega p_0^2 r_e \simeq 2 \cdot 10^4$ years ( $r_e$ is the classic electron radius ). For not very small times in the frame of the jet, $t > \tau_0 \gamma_0^{-3}$, we have

$$\gamma = \left(\frac{t}{\tau_0}\right)^{-1/3},$$

$$B \propto \left(\frac{t}{\tau_0}\right)^{-1/3}.$$  

(11)

The characteristic frequency $\omega = \omega_c \gamma^2$, at which relativistic particles radiate synchrotron photons, will change in time

$$\omega = \frac{2 \omega p_0^2}{\omega_c 0} \left(\frac{t}{\tau_0}\right)^{-1} \propto \frac{1}{t}. $$

For such a dependence $\omega(t)$ the observed frequency $\omega' = \Gamma \omega$ and the time in the frame of observer $t' = t/\Gamma$ are related as

$$t' = \frac{2 \tau_0 \omega p_0^2}{\omega_c 0 \omega'} \propto \frac{1}{\omega'}. $$

We see that the time of glowing at a given frequency in the observer frame is

$$t' = \frac{2 \cdot 10^5 eV}{\hbar \omega' eV} \text{sec}. $$

For the photon energy $\hbar \omega' \simeq 0.3 MeV$, which is typical of a GRB, the time of glowing is 10 sec. This time just corresponds to the maximum of the distribution of long GRB over their duration ( at the level 90% from the peak luminosity - $T_{90}$ ). The observations showed that it is long GRB ( $T_{90} > 10$ sec ) that are sometimes accompanied the afterglow in X-ray and/or optic bands. According to our model the duration of the X-ray afterglow ( $\hbar \omega' \simeq 100 eV$ ) is several days, and that of the optic afterglow ( $\hbar \omega' \simeq 1 eV$ ) is several months. These estimations do not contradict the observations of GRB.

From our model we obtain also the estimations for the rate of the change of the afterglow intensity, $I(\omega') \propto \omega'^{4/3} \propto (t')^{-1.33}$. The observations show ( see, for example [1], [4] ) the dependence $I \propto (t')^{-1.2}$, which does not contradict our estimation.
Probably, if the energy of the shock from a SN is not enough to tear off the magnetospheric tail of magnetized component, then there will not be any jet and consequently no afterglow will be observed. This situation is more typical of a not energetic GRB and they will be short ( $T_{90} < 1\text{sec}$ ).

References