Gamma-ray burst interaction with dense interstellar medium

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Abstract. Interaction of cosmological gamma ray burst radiation with the dense interstellar medium of host galaxy is considered. Gas dynamical motion of interstellar medium driven by gamma ray burst is investigated in 2D approximation for different initial density distributions of host galaxy matter and different total energy of gamma ray burst. The maximum velocity of motion of interstellar medium is $1.8 \cdot 10^4$ km/s. Light curves of gamma ray burst afterglow are calculated for set of non homogeneous density, distribution gamma ray burst total energy, and different viewing angles. Spectra of gamma ray burst afterglow are modeled taking into account conversion of hard photons (soft X-ray, hard UV) to soft UV and optics photons.

Keywords: gamma ray burst, optical afterglow,

1. Introduction.

Although gamma-ray bursts (GRBs) were discovered more than thirty years ago (Klebesadel, 1973), their origin is still unclear. The most extensive data on the detection of GRBs have been obtained by the Compton Gamma Ray Observatory BATSE experiment (Briggs, 1995; Fishman, 1995; Meegan, 1992). Analysis of the GRBs detected showed that their apparent distribution on the sky was isotropic, but that there was a significant departure of their ($\log N - \log S$) curve from the $N \sim S^{-3/2}$, low corresponding to a spatially uniform source distribution (Briggs, 1995; Kouveliotou, 1994).

Observation of optical afterglows of GRB, following after identification of GRB with a transient X-ray source by Beppo-SAX, and discovery of large (up to $z = 4.5$) redshifts in the spectra of optical transients had confirmed the cosmological origin of long GRB.

The cosmological model suggests that the GRB source are located in distant galaxies (within $\sim 10^3$ Mpc). In the framework of this model, the observed fluxes $\sim 10^{-4}$ erg s$^{-1}$ require the release of enormous amounts of energy ($\sim 10^{51} - 10^{53}$ erg) within a fairly short time interval (of the order of several tens of seconds). Such a powerful energy release should have a strong effect on a large volume of matter around the parent galaxy and should give rise to the formation of GRB counterpart at other wavelengths. Without specifying the mechanism for GRB
formation, we assume only the existence of a strong flux gamma radiation and consider the interaction of this radiation with the interstellar medium on large spatial and temporal scales.

We investigate the response of an interstellar medium of standard chemical composition to the passage of a short-term powerful pulse of gamma radiation (that is, the dynamical behaviour and radiative cooling after heating by the gamma rays).

The spherical symmetric model was investigated by Bisnovatyi-Kogan and Timokhin (1997), 2D model, permitting to study different matter distribution and reaction to anisotropic GRB had been studied by Barkov and Bisnovatyi-Kogan (2004a, 2004b) using numerical simulations by PPM method. In what follows we represent the results from Barkov and Bisnovatyi-Kogan (2004a, 2004b).

2. The main equations

We solve the system of hydrodynamic equations, describing the motion of matter, together with thermal processes in axially symmetric case

\[
\frac{\partial \rho}{\partial t} + \nabla (\rho \vec{v}) = 0, \tag{1}
\]

\[
\frac{\partial (\rho v_r)}{\partial t} + \frac{\partial (\rho v_r^2 + P)}{\partial r} + \frac{1}{r} \frac{\partial (\rho v_r v_\theta)}{\partial \theta} + \frac{2 \rho v_r^2 - \rho v_\theta^2 - \rho v_r v_\theta \cot \theta}{r} = \rho F_\gamma, \tag{2}
\]

\[
\frac{\partial (\rho v_\theta)}{\partial t} + \frac{\partial (\rho v_r v_\theta)}{\partial r} + \frac{1}{r} \frac{\partial (\rho v_\theta^2 + P)}{\partial \theta} + \frac{3 \rho v_r v_\theta + \rho v_\theta^2 \cot \theta}{r} = 0, \tag{3}
\]

\[
\frac{\partial}{\partial t} \left( \frac{\rho v_r^2}{2} + \rho \varepsilon \right) + \nabla \left\{ \rho \vec{v} \left( \frac{v_r^2}{2} + \varepsilon + \frac{P}{\rho} \right) \right\} = \rho H_\gamma - \rho C_\gamma. \tag{4}
\]

Here \( \rho, P, \varepsilon, v_r, \) and \( v_\theta \) are density, pressure, internal specific energy and two velocity components, respectively. The gamma ray pulse is considered as instant one having total energy \( \Gamma \) and luminosity

\[
L = \Gamma \delta \left( t - \frac{r}{c} \right). \tag{5}
\]

We are interested in the behaviour of the gas heated by GRB, which is taken as fully ionized one.
Consider flat spectrum of GRB

\[ \frac{dL}{dE} = \frac{L}{E_{\text{max}}} e^{-E/E_{\text{max}}} \] (6)

The main GRB photons have energies larger than ionization energies of most electrons, so we consider energy exchange of GRB with the gas due to Compton and inverse Compton processes only. The function \( H_\gamma \) in (4) is written as

\[ H_\gamma = \frac{L}{4\pi r^2} \frac{\mu_e \sigma_T}{m_u} E_{\text{max}} f_h(E_{\text{max}}) - 4kT f_c(E_{\text{max}}), \] (7)

where

\[ f_c(E_{\text{max}}) = \int_0^\infty W(E, E_{\text{max}}) q(E) dE, \]

\[ f_h(E_{\text{max}}) = \frac{1}{E_{\text{max}}} \int_0^\infty W(E, E_{\text{max}}) s(E) E dE. \] (8)

We have used GRB spectra with \( E_{\text{max}} = 0.6 \) MeV and 2 MeV. The functions \( s(E) \) and \( q(E) \), which take into account deviations from Thomson cross section \( \sigma_T \) due to Klein-Nishina correction \( \sigma_{KN} \), are taken from (Beloborodov and Illarionov, 1995). They are normalized so that \( s(E) = q(E) = 1 \) at \( E \ll m_c^2 \). In our cases \( f_h = 0.19; f_c = 0.33 \) for \( E = 0.6 \) MeV, and \( f_h = 0.065; f_c = 0.16 \) for \( E = 2 \) MeV.

The radiation force due to electron scattering is written as

\[ F_\gamma = \frac{1}{c} \frac{L}{4\pi r^2} \frac{\mu_e \sigma_T}{m_u} f_f(E_{\text{max}}), \] (9)

where the function

\[ f_f(E_{\text{max}}) = \frac{1}{\sigma_T} \int_0^\infty W(E, E_{\text{max}}) \sigma_{KN}(E) dE \] (10)

takes into account KN corrections, \( f_f = 0.5 \) for \( E_{\text{max}} = 0.6 \) MeV and \( f_f = 0.32 \) for \( E_{\text{max}} = 2 \) MeV. Cooling of the gas is due to different radiative processes (ff, fh, bb). For optically thin plasma, which is used for description of cooling, the function \( C_\gamma \) was calculated in Kirienko (1993), Raymond, Cox and Smith (1976)

\[ C_\gamma = \frac{\Lambda(T)n^2}{\rho}, \] (11)
where \( \Lambda(T) \) from Kirienko (1993) was approximated analytically with a precision not worse then 5%:

\[
\Lambda(T) = \begin{cases} 
0, & T < 10^{4} K \\
10^{-48.8} T^{6.4}, & 10^{4} < T < 10^{4.25} \\
10^{-16.5} T^{-1.2}, & 10^{4.25} < T < 10^{4.5} \\
10^{-27.48} T^{1.24}, & 10^{4.5} < T < 10^{5} \\
10^{-21.03} T^{-0.05}, & 10^{5} < T < 10^{5.4} \\
10^{-13.6698} T^{-1.413}, & 10^{5.4} < T < 10^{5.86} \\
10^{-22.8378} T^{-0.1515}, & 10^{5.86} < T < 10^{6.19} \\
10^{-13.1969} T^{-1.406}, & 10^{6.19} < T < 10^{6.83} \\
10^{-22.2877} T^{-0.075}, & 10^{6.83} < T < 10^{7.5} \\
10^{-26.6} T^{0.5}, & 10^{7.5} < T 
\end{cases}
\] 

(12)

It was shown in Barkov and Bisnovatyi-Kogan (2004a) that the heat conductivity may be neglected in this problem.

### 3. Numerical results

In the paper of Barkov and Bisnovatyi-Kogan (2004b) more then 10 variants with different density distribution and GRB beaming have been calculated. Here we represent the main results of these calculations.

In the fig. 1 from Barkov and Bisnovatyi-Kogan (2004b) the evolution of temperature distribution in the cloud with time is represented for the GRB exploding in the center of a spherically symmetric uniform cloud with a radius \( R = 1.5 \) pc, concentration \( n_H = 10^5 \) cm\(^{-1} \), \( \Gamma = 10^{52} \) erg, \( E_{\text{max}} \geq 1/6 \) MeV. It was shown by Barkov and Bisnovatyi-Kogan (2004b), that for \( E_{\text{max}} \geq 1/6 \) MeV, the heating at big distance from GRB \( (r \geq 0.05 \) pc) depends only on the GRB energy \( \Gamma \) and does not depend on \( E_{\text{max}} \). The temperature inversion is developed in the middle radiuses \( (r = 0.15 \div 0.7 \) pc), where after heating \( T \sim 10^6 \) K, and the cooling is the most effective. The cooling front is propagating outward with superlight speed, and inward with sublight speed (phase velocities). The light curve for optical and ultraviolet luminosity, observed by the distant observer is represented in fig. 2 from Barkov and Bisnovatyi-Kogan (2004b).

GRB heating of the cloud is most intensive in central parts and leads to formation of the shock wave propagating outwards. The speed of the shock is about \( 2 \times 10^8 \) cm/s for the uniform spherical cloud, what is much less then the light speed. Therefore, the cloud is heated mainly by the light signal from GRB, and effects connected with the formation of central shock do not influence the integral light curve, except the
Figure 1. The evolution of temperature distribution in the cloud with time is represented for the GRB burst in the center of a spherically symmetric uniform cloud with a radius $R = 1.5$ pc, concentration $n_H = 10^5$ cm$^{-1}$, $\Gamma = 10^{52}$ erg, $E_{\text{max}} \geq 1/6$ MeV; curves marked by number correspond to the following time moments after GRB: 1) 0.76 year, 2) 1.054 year, 3) 1.103 year, 4) 1.30 year, 5) 2.40 year.

Figure 2. The light curve for optical and ultraviolet luminosity for same parameters, as in fig. 1, observed by the distant observer. Time is in years.
radiation in the hard X-ray band produced in close vicinity of GRB explosion.

In the case, when GRB explosion takes place between two dense clouds, or in the cavity, produced by strong anisotropic stellar wind, the hydrodynamic effects may be much stronger than in the case of the uniform cloud, and the speed of the shock increase up to $\sim 2 \times 10^9$ cm/s.

In the fig. 3 from Barkov and Bisnovatyi-Kogan (2004a) the evolution of the velocity field is represented for the case of the density distribution in the cloud as $n = 10^5 e^{-2 - 2 \cos(10\theta)} \text{cm}^{-3}$, cloud radius 1.5 pc, for the energy of isotropic GRB $\Gamma = 1.6 \times 10^{53}$ erg, and $E_{\text{max}} \geq 1/6$ MeV. The calculation have been performed in the region $0 \leq \theta \leq \pi/10$, with the condition $v_\theta = 0$ on the boundaries. The temperature of the heated gas depend only on the distance from GRB, so pressure gradient is developed inside the cavity inducing the motion of the matter to the axis of the cone. Collision of the flow at the cone axis produces a cumulative effect, leading to matter acceleration along the axis up to velocity $\sim 2 \times 10^9$ cm/s Barkov and Bisnovatyi-Kogan (2004a).

The accelerated matter in this case have a form of the bullet. In the case of the explosion in the space between two spherical clouds, the ejected matter should have the form of an expanding ring.

In the case of anisotropic GRB exploded in the uniform gas cloud the observed light curve is different for distant observer with differ-
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Figure 4. Light curves for collimated GRBs situated on 1 pc from center of the molecular cloud, time in years. Observer’s situated on the line GRB - MC, case a); deviation from this line by the angle $\alpha = 0.1$ radian, case b); by the angle $\alpha = 0.2$ radian, case c); by the angle $\alpha = \pi/2$ radian, case d).

Different angular distances from the symmetry axes. Such light curves are represented in fig. 4 from Barkov and Bisnovatyi-Kogan (2004b). Here anisotropic GRB is considered with angular dependence of luminosity $\Gamma(\theta) = 10^{52}e^{-\left(\theta/\theta_0\right)^2}$, $\theta = 0.1$ rad, the total energy of GRB $\Gamma_{tot} = 2.5 \times 10^{49}$ erg, density distribution $n = 10^5e^{-\left(r/r_0\right)^2}$ cm$^{-3}$, $r_0 = 0.2$ pc, when the explosion takes place at the distance 1 pc from the center of the cloud. The shortest optical burst of few days with largest luminosity $\sim 10^{41.5}$ erg/s is seen by the observer, situated at the symmetry axis on the continuation of the line cloud center — GRB.

The observer on the line which is perpendicular to the symmetry axis is observing much longer optical afterglow ($\sim 1000$ days), but with accordingly lower luminosity. All these differences are connected with the kinematic of the light propagation from the nonuniformly and nonsimultaneously heated gas cloud.

4. Discussion

Optical afterglow, connected with the reradiation of the GRB by the dense enough molecular cloud could be observed as optical transient. Indications that GRB explosions take place in the region of star formation filled with dense gas clouds (Sokolov, 2001; Paczynski, 1999) make
this possibility as very probable. Observation of plato in the optical afterglow of GRB 030329 during a month between 64 and 94 days after GRB detection (Ibrahimov et. al., 2003) may be connected with such kind of reradiation.

The dense molecular clouds have very low temperature, at which dust is formed. Estimations made by Barkov and Bisnovatyi-Kogan (2004b) show, that dust is evaporated by GRB pulse in the cloud near GRB impulse direction, or in the whole cloud by isotropic GRB with \( R \sim 1 \) pc, and does not influence the light curve of optical, UV and X-ray GRB afterglows.

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