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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 energies 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 of 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.

Key words. gamma ray burst: optical afterglow

1. Introduction

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

Observations of optical afterglows of some GRB, following the identification of these GRB with transient X-ray sources on the satellite Beppo-SAX, and a 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 sources are located in galaxies at distances up to $\sim 10^3$ Mpc. In the framework of this model, the observed fluxes $\sim 10^{-4}$ erg cm^{-2} require a 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 surrounding matter in the parent galaxy, and should give rise to formation of the GRB counterpart at other wavelengths. Without specifying the mechanism for the GRB origin, we assume only the existence of a strong flux of the gamma ray radiation, and consider the in-

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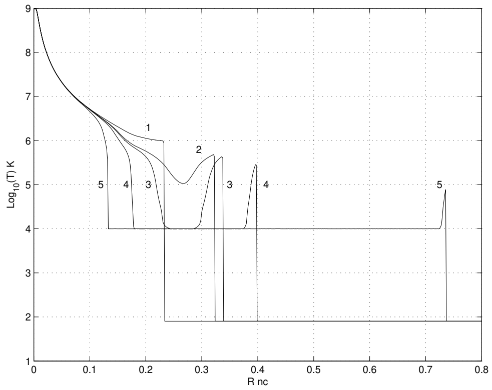

Fig. 1. The evolution of temperature distribution in the cloud with the time is represented for the GRB burst in the center of a spherically symmetric uniform cloud with a radius $R = 1.5$ pc, concentration $n_H = 10^5$ cm^{-3}, $\Gamma = 10^{52}$ erg, $E_{max} \geq 1/6$ MeV. The curves are marked by numbers corresponding to the following time moments after the GRB: 1) 0.76 year, 2) 1.054 year, 3) 1.103 year, 4) 1.30 year, 5) 2.40 year.

teraction of this radiation with the interstellar medium on large spatial and temporal scales.

We investigate a response of an interstellar medium of a standard chemical composition to the passage of a short-term powerful pulse of gamma radiation, that is the dynamical behavior, and radiative cooling of matter heated by the gamma rays pulse. The spherical symmetric model was investigated by Bisnovatyi-Kogan and Timokhin (1997). 2D model which allows to study different matter distributions and reaction to the anisotropic GRB, had been studied by Barkov and Bisnovatyi-Kogan (2005a, 2005b), using numerical simulations by PPM method. In what follows we represent the results from Barkov and Bisnovatyi-Kogan (2005a, 2005b).

2. The main equations

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

$$\frac{\partial \rho}{\partial t} + \nabla(\rho \boldsymbol{v}) = 0, \tag{1}$$

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

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

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

Here $\rho, P, \varepsilon, v_r$, and v_θ are density, pressure, internal specific energy and two velocity components, respectively. The gamma ray pulse is considered as an instant one having the total energy Γ and the luminosity

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

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

$$\frac{dL}{dE} = \frac{L}{E_{max}} e^{-E/E_{max}} \tag{6}$$

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

$$H_\gamma = \frac{L}{4\pi r^2}\frac{\mu_e \sigma_T}{m_u} \frac{E_{max} f_h(E_{max}) - 4kT f_c(E_{max})}{m_e c^2}, \tag{7}$$

where

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

$$f_h(E_{max}) = \tag{8}$$

$$\frac{1}{E_{max}}\int_0^\infty W(E,E_{max})s(E)EdE.$$

We have considered GRB spectra with E_{max} = 0.6 MeV and 2 MeV. The functions $s(E)$ and $q(E)$, which include deviations from the Thompson cross section σ_T due to Klein-Nishina corrections (σ_{KN}), are taken from Beloborodov and Illarionov (1995). The functions are normalized so that $s(E) = q(E) = 1$ at $E \ll m_e c^2$. 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 caused by the electron scattering reads

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

where the function

$$f_f(E_{max}) = \tag{10}$$

$$\frac{1}{\sigma_T}\int_0^\infty W(E,E_{max})\sigma_{KN}(E)dE$$

takes into account KN corrections, $f_f = 0.5$ for $E_{max} = 0.6$ MeV and $f_f = 0.32$ for E_{max} = 2 MeV. Cooling of the gas is due to different radiative processes (ff, fb, bb).

We use optically thin plasma approximation for description of cooling. It is determined by the function C_γ, calculated by Kirienko (1993) and Raymond, Cox and Smith (1976).

$$C_\gamma = \frac{\Lambda(T)n^2}{\rho} \tag{11}$$

We approximate analytically the function $\Lambda(T)$ from Kirienko (1993) with a precision not worse than 5%.

It was shown by Barkov and Bisnovatyi-Kogan (2005a) that the heat conductivity may be neglected in this problem.

3. Numerical results

More then 10 variants had been calculated in the paper of Barkov and Bisnovatyi-Kogan (2005b) for different density distributions and GRBs beaming. We present here the main results of these calculations.

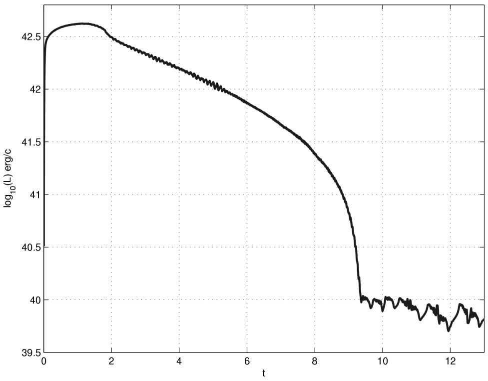

Fig. 2. The light curve for the sum of the optical and ultraviolet luminosity observed by the distant observer, for the same parameters as in fig.1. Time is given in years.

In the fig.1 (Barkov and Bisnovatyi-Kogan, 2005b) the evolution of the 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^{-3}, $\Gamma = 10^{52}$ erg, $E_{max} \geq 1/6$ MeV. It was shown by Barkov and Bisnovatyi-Kogan (2005b), that for $E_{max} \geq 1/6$ MeV, at a big distance from the GRB ($r \geq 0.05$ pc) heating depends only on the GRB energy Γ, and does not depend on E_{max}. The temperature inversion is developed at middle radia ($r = 0.15 \div 0.7$ pc), where the gas is heated up to $T \sim 10^6$ K, and cooling is the most effective. The cooling front is propagating outwards with a superluminal speed, and inward with a subluminal speed (phase velocities). The light curve for sum of a optical and ultraviolet luminosity, observed by the distant observer is represented in fig. 2 (Barkov and Bisnovatyi-Kogan, 2005b).

GRB heating of the cloud is a most intensive in the central parts and leads to a formation of the shock wave propagating outwards. The speed of the shock is about 2×10^8 cm/s for the uniform spherical cloud. It is much less than the speed of light. Therefore, the cloud is heated mainly by the light signal from GRB. Effects connected with the formation of a central shock do not influence the integral light curve, except the radiation in the hard X-ray

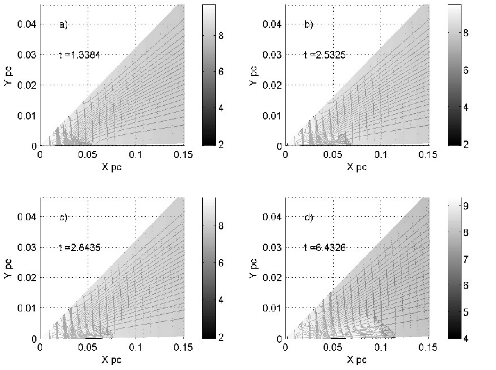

Fig. 3. The evolution of the velocity field is represented for the conical density distribution in the cloud.

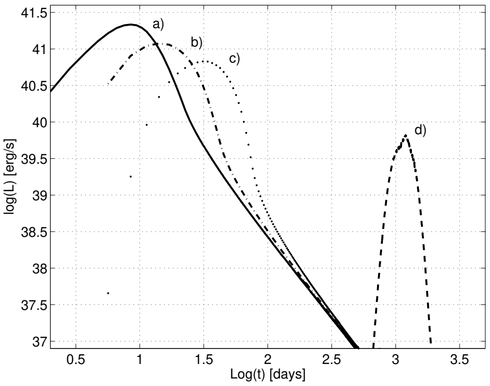

Fig. 4. Light curves of the collimated GRB, situated on 1 pc from the center of the molecular cloud. Time is in years. The observer is situated on the line (GRB - MC, case a); on the deviation from this line: by the angle $\alpha = 0.1$ radian (case b), by the angle $\alpha = 0.2$ radian (case c), by the angle $\alpha = \pi/2$ radian (case d).

band produced in the close vicinity of GRB explosion. In the case, when the GRB explosion takes place between two dense clouds, or in the cavity, produced by a 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 increases up to $\sim 2 \times 10^9$ cm/s.

In the fig.3 from Barkov and Bisnovatyi-Kogan (2005a) the evolution of the velocity field is represented for the case of the density distribution in the cloud as $n = 10^5 e^{-2 - 2\cos(10\theta)}\mathrm{cm}^{-3}$, the cloud radius 1.5 pc, for the energy of the isotropic GRB $\Gamma = 1.6 \times 10^{53}$ erg, and $E_{max} \geq 1/6$ MeV. The calculations had 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 the GRB, so the pressure gradient is developed inside the cavity inducing the motion of the matter to the axis of the cone. Collision of the flows at the cone axis produces a cumulative effect, and leads a matter acceleration along the axis up to velocity $\sim 2 \times 10^9$ cm/s (Barkov and Bisnovatyi-Kogan, 2005a). The accelerated matter has a form of the bullet in this case. In the case of the explosion in the space between two spherical clouds, the ejected matter should have a form of an expanding ring.

In the case of anisotropic GRB explosion in the nonuniform gas cloud the observed light curve is different for distant observers at different angular distances from the symmetry axes. Such light curves are represented in fig 4. from Barkov and Bisnovatyi-Kogan (2005b). Here the anisotropic GRB is considered, with the angular dependence of luminosity inside the beam as $\Gamma(\theta) = 10^{52} e^{-(\vartheta/\vartheta_0)^2}$, $\theta = 0.1$ rad, the total energy of GRB $\Gamma_{tot} = 2.5 \times 10^{49}$ erg, the density distribution $n = 10^5 e^{-(r/r_0)^2}$ cm^{-3}, $r_0 = 0.2$ pc. The explosion takes place at a distance 1 pc from the center of the cloud. The shortest optical burst of few days duration, with the 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 (~ 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

The optical afterglow, connected with the reradiation of the GRB by the dense enough molecular cloud could be observed as an optical transient. Indications that GRB explosions take place in the regions of star formation filled with dense gas clouds (Sokolov et al. 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 (2005b) show, that dust can be evaporated by the GRB pulse in the cloud along the GRB pulse direction, or in the whole cloud by isotropic GRB with $R \sim 1$ pc. In this case it does not influence the light curve of optical, UV and X-ray GRB afterglows. The parts of the cloud outside the GRB beam are not heated, and dust is not evaporated there. Therefore, the observer situated at large angle from the beam axis, would see only the orphan infrared transient source due to the dust reradiation. If the dust cloud is situated at larger distances where it cannot be evaporated by the GRB pulse, the main afterglow radiation is expected in the infrared region for all kind of observers.

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