Infrared afterglow of GRB041219 as a result of reradiation on dust in a circumstellar cloud.

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Abstract

Observations of gamma ray bursts (GRB) afterglows in different spectral bands provide a most valuable information about their nature, as well as about properties of surrounding medium. Powerful infrared afterglow was observed from the strong GRB041219. Here we explain the observed IR afterglow in the model of a dust reradiation of the main GRB signal in the envelope surrounding the GRB source. In this model we do not expect appearance of the prompt optical emission which should be absorbed in the dust envelope. We estimate the collimation angle of the gamma ray emission, and obtain restrictions on the redshift (distance to GRB source), by fitting the model parameters to the observational data.

1 Observational data

Observations of gamma ray bursts (GRB) afterglows in different spectral bands provide a most valuable information about their nature, as well as about properties of surrounding medium. Powerful infrared afterglow was observed from the strong GRB041219, recorded by INTEGRAL and SWIFT [1, 2]. By lucky chance IR observations started as soon as 2.4 minutes after GRB registration, during the GRB itself (second such case after GRB990123), which lasted 520 seconds, and was very strong $F_\gamma \sim 10^{-4}$ erg/cm$^2$. The IR flux (K - band) corresponded to $K = 15.5^m$ 2.4 minutes after registration [3], $K = 14.9^m$ after 0.8 hour, $K = 15.5^m$ after 1.55 hours [4], and $K = 16.5^m$ after 1.01 day [5]. Observations 47.25 hours after the burst had shown $K = 17.6^m$, $H = 18.9^m$, and $J = 19.9^m$ [6]. No optical afterglow was registered 74 seconds after registration up to 17.2$^m$ (unfiltered) [7], and the limiting value $R = 19.4^m$ was obtained in [8] for the prompt optical emission of this burst. A weak growing radio emission at 4.9 GHz was detected from this GRB, with fluxes 205 microJy 1.75 days after the burst [9], and 349 microJy 2.74 days after GRB [10].

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2 Model

The plot for the observed IR flux on the time $L_{IR}(t)$ is represented in Fig.1. The IR flux in $K = 14.9^{m}$ is equivalent to $2.4 \times 10^{-13}$ erg/(s $\cdot$ cm$^2$). Accepting the duration of IR emission during 1 day we obtain the IR fluence $\sim 10^{-8}$ erg/cm$^2$, what corresponds to $10^{-4}$ of the total energy of GRB. With account of the limited spectral range of SWIFT data, we expect the total fluence to be $F_\gamma \approx 2 \cdot 10^{-4}$ erg/cm$^2$. Suppose that the observed IR emission is formed due to interaction of the GRB main pulse with the surrounding dust envelope. The mechanism of this formation is the following. Gamma photons with energy exceeding 10 keV interact with the matter, including dust, mainly due to Compton scattering. The photons with energies $E_\gamma = 10 - 100$ keV interact with the electron inside the dust grain, transferring $\xi_e$ of its energy to this electron. The electron is absorbed inside this grain, the dust grain reradiate this energy in IR, and gamma ray photon is flowing away. We consider only sufficiently distant regions of the dust envelope, where the dust evaporation is not important. IR reradiation is produced effectively only in such condition [11, 12, 13].

The dust formed by heavy elements contains about 1% of the whole mass of the gas for solar abundances. XMM observations of GRB011211 and GRB030227 had indicated [14], that abundances of light elements (Mg, Si, S) in the X - radiating matter more than 10 times exceed the Solar ones. Taking 10% for the mass of the dust component, the amount of energy absorbed in the surrounding envelope due to Compton scattering would be 10 times larger than that absorbed by the dust. As a result the IR emission should be equal
to $\alpha_D \sim 0.1$ of the total energy absorbed in the surrounding cloud, $E_{abs} \sim 10^{-7}$ erg/cm$^2$. The total absorption optical depth of the envelope would be equal to $\tau_{abs} \sim 5 \cdot 10^{-4}$, if the gamma ray and IR photons were radiated in the same body angle. For a small gamma ray beam $\Theta \ll 4\pi$ and isotropic IR reradiation the absorption of gamma ray emission should be $4/\Theta^2$ times larger, and the total depth of the envelope to the Compton interaction should be equal to

$$\tau_c \sim \frac{2 \cdot 10^{-3}}{\xi_e \Theta^2}, \quad \tau_{IR} = \alpha_D \tau_c \sim \frac{2 \cdot 10^{-4}}{\xi_e \Theta^2},$$

where $\tau_{IR}$ is the optical depth of the dust component. The surface number density $\Sigma_e$ for Thompson cross-section $\sigma_T$, and $\xi_e = 0.25$ for the characteristic GRB spectrum [15], is equal to

$$\Sigma_e = \frac{\tau_c}{\sigma_T} \sim \frac{3.2 \cdot 10^{21}}{\Theta^2} \text{cm}^{-2}.$$  

We suppose that GRB is a result of processes in the remnant of the evolution of a massive star (i.e., heavy disc falling into a massive black hole [16]), which had lost a considerable part $\geq 1/2$ of its matter which formed a massive cold envelope. The massive star is embedded into the dense interstellar cloud. Take for simplicity that the envelope is in the form of a thin spherical shell with a radius $R$, and thickness $h \ll R$. We take into account that the IR dust reradiation is very rapid, lasting less than one second [11], what is much less than all characteristic times inherent to GRB afterglow radiation. Therefore the IR reradiation may be taken as an instant process. The distant observer accepts at given moment the emission reradiated by the shell of the matter in the ring with the radius $r \approx \sqrt{2cRt}$, here $t$ is counted from the time of GRB detection, $r \ll R$, see Fig.2. The collimated gamma ray radiation illuminates only part of the shell with the radius $r_I = R\Theta$. The angular size $\theta$ of the ring from which the radiation is coming to the observer, is equal to

$$\theta \sim r/R = \sqrt{2ct/R}.$$ 

The observer will see the IR reradiation until $\theta$ reaches its maximal value $\Theta$, after with the IR radiation abruptly stopped in the thin shell model, but starts to drop more rapidly in the realistic case. Consider for simplicity, that gamma ray fluence, $\tau_c$, and $\tau_{IR}$ do not depend on the angle $\theta$ inside the beam. Let us introduce the values of the total energy of GRB $E_\gamma$ (erg), total energy of the infrared afterglow $E_{IR}$ (erg), observed fluence of the GRB $F_\gamma$ (erg/cm$^2$), observed fluence of the infrared afterglow $F_{IR}$ (erg/cm$^2$), observed infrared flux $L_{IR}$ (erg/cm$^2$/s). Here

$$E_{IR} = \tau_{IR} E_\gamma, \quad F_\gamma = \frac{E_\gamma}{\pi \Theta^2 l^2}, \quad F_{IR} = \frac{E_{IR}}{4\pi l^2}, \quad L_{IR} = \frac{E_{IR}}{4\pi l^2 l},$$

where $l$ is the distance from the source to the observer. The observed IR flux $L_{IR}(t)$ of reradiation as a function of time is determined as

$$L_{IR}(t) = \frac{1}{4\pi l^2} \frac{E_\gamma}{\pi \Theta^2} \tau_{IR} 2\pi \theta \frac{d\theta}{dt} = \frac{E_\gamma \tau_{IR}}{4\pi l^2} \frac{2c}{R \Theta^2} = \frac{1}{4\pi l^2} \frac{E_{IR}}{t_{IR}},$$
where \( t_{1R} \sim 1 \) day is the observed time of the IR radiation over which the IR flux may be taken almost constant, and which is uniquely connected with the collimation angle \( \Theta = \sqrt{2ct_{1R}/R} \). As follows from (5), the observed IR flux is constant in this simple model at \( t < t_{1R} = R\Theta^2/2c \), and becomes zero at larger \( t \). For nonuniform gamma ray fluence, and optical depth inside the beam the IR flux is variable at \( t < t_{1R} \), and does not become zero at \( t > t_{1R} \) for a thick dust shell.

### 3 Estimations of GRB041219 properties

Let us do quantitative estimations of the model parameters for GRB041219. Starting from the observed values \( F_{\gamma}, F_{1R}, t_{1R} \), and taking the optical depth as \( \tau_c = nR\sigma_T \), where \( n \) is the average concentration in the cloud, we obtain the expressions for \( \Theta, R, n \) and \( \tau_c \) as follows

\[
n = \frac{\tau_c\Theta^2}{2ct_{1R}\sigma_T} \approx 2 \cdot 10^6 \text{ cm}^{-3}, \quad \Theta = \sqrt{\frac{2ct_{1R}}{R}} \approx \frac{0.077}{\sqrt{R_{18}}} = \frac{4.4^o}{\sqrt{R_{18}}}, \quad \tau_c = \frac{4R_{18}}{3}, \quad (6)
\]

where \( R_{18} = R/10^{18}\text{cm} \). Note, that estimations of the collimation angle and properties of the media surrounding GRB source do not depend on the distance to GRB, and therefore on its energy production. The absence of the prompt optical emission could be connected with a strong absorption inside our Galaxy, because this GRB lies very close to the Galactic plane with \( b = 0.6 \) deg \([\text{6}]\), but we do not expect optical or soft X-ray afterglows because of their absorption in the remaining dust envelope. The afterglow IR flux, connected with a secondary reradiation of the X ray and optical quanta by dust, will be considerably fainter, than the direct IR afterglow produced by GRB itself. The matter heated by GRB gamma radiation up to temperatures \( 10^6 - 10^7 \) K has a cooling
time of the order of few weeks for the density (6), what is about 100 times larger than the duration of the prompt IR radiation accompanying heating of the dust by GRB pulse (17) (15). Therefore the IR flux at $t > t_{IR}$, due to this reradiation should be about $3^m$ magnitude fainter than in the prompt IR source. In our model the dust should not be evaporated by the GRB main pulse. According to (13). The critical gamma ray fluence which is destroying the dust grain is

$$F_{\gamma,cr} = \frac{E_{\gamma,cr}}{\pi \Theta^2 \varepsilon_{\gamma} R^2} = 4 \times 10^{21} \text{cm}^{-2},$$

(7)

where $\varepsilon_{\gamma} \approx 100$ keV is the average energy of the gamma ray quanta. Taking into account (6), we obtain the restriction in the GRB total power $E_{\gamma} \leq 1.3 \times 10^{49} R_{18}$ erg, and using the corrected observed gamma ray fluence $F_{\gamma} = 2 \times 10^{-4} \text{erg/cm}^{-2}$ and (6) we obtain the restriction to the distance $l$ and redshift $z$ of this GRB

$$l \leq 2 \times 10^{27} R_{18} \text{ cm} = 670 R_{18} \text{ Mpc}, \quad z \leq 0.16 R_{18}.$$  

(8)

Taking into account, that Compton interaction should not decrease considerably the GRB fluence, we put a restriction for $\tau_{c} \leq 1$, corresponding to about of $\xi_{c} = 0.25$ of the absorbed gamma ray fluence (13) (15), and obtain the following restrictions to GRB041219 parameters

$$R_{18} \leq 3/4, \quad z \leq 0.12, \quad E_{\gamma} \leq 10^{49} \text{erg}, \quad \Theta \geq 5^\circ.$$  

(9)

Note that these restrictions directly depend on the estimations of dust evaporation condition (7).

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