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Very High Energy Gamma Rays from Gamma Ray Bursts*

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Abstract Very high energy gamma rays from gamma ray bursts are explained by the expanding fireball model. The high energy gamma ray generation efficiency, the relativistic effect, and the absorption in cosmic background radiation are taken into account. It is shown that the ejection of gamma rays with the energies higher than 10GeV may happen at the very beginning of the fireball expansion ~ 10^{-5}s with a fluence up to 10^{-4}—10^{-6}cm^{-2} arriving at the earth.

Key words gamma ray burst, cosmic ray, fireball model

1 Introduction

Gamma ray bursts (GRBs), firstly detected by VELA satellite on July 2, 1967[1], has been a highlight in astrophysics for thirty years. On CGRO, BATSE[2] identified GRB's isotropic distribution and, in consequence, supported GRB's origin of [illegible] in 1997 observed X-ray afterglow so as to positon GRBs even in a few arcminutes, further confirming some cosmological countparts. Gamma rays of energies higher than a few 10GeV from GRBs, however, has not been observed, for which several experiments, e.g., L3 + C[5] and Tibet ASγ[6], are searching at present, and some other experiments, e.g., ARGO-YBJ[7] will search soon. To explain the origin of GRBs, the expanding fireball model was raised. A fireball is a huge energy lepton ball and expands relativistically[8,9]. In the fireball the prolific creation of e^+e^- pairs will inhibit the escape of photons until their energies have been degraded below the pair production threshold[10]. According to this model, after 10^3s from the beginning of the fireball expansion, internal shocks may generate gamma rays of energies 10keV—10GeV, and after months or weeks external shocks generate afterglow in X, radio and optical bands[11—13]. It was even figured out that during the expansion there exists backflow where electrons can be accelerated with very high efficiency[14]. In brief, during expansion, the fireball cools down and photon energy decreases. It hints that higher energy gamma rays might be generated at the much earlier stage of the fireball expansion. In this paper, we will deduce the generation time and the fluence of gamma rays with the energies higher than 10GeV from GRBs and estimate results of some ongoing experiments on high energy gamma rays from GRBs.

2 Very high energy (≥10GeV) gamma ray fluence

2.1 Fireball: black-body radiation

During very early expansion, the fireball radiation is thermal and optically thick, so it can be considered as a black-body radiation. The fireball temperature T can be calculated by[15]:

$$kT = \left(\frac{E \cdot (hc)^3}{2.75 \cdot R^3}\right)^{1/4} \tag{1}$$

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where k is Boltzmann constant, h is the reduced Planck constant, c is light speed, E is fireball energy and R is fireball radius. The photon number density between E_1 and E_2 is then

$$n(E_1 < E_\gamma < E_2, kT) = \int_{E_1}^{E_2} n_x \mathrm{d}x, \tag{2}$$

where E_γ is photon energy,

$$x = \frac{E_\gamma}{kT}, \tag{3}$$

and

$$n_x = \frac{(kT)^3}{\pi^2 (hc)^3} \frac{x^2}{(e^x - 1)}. \tag{4}$$

Supposing that the fireball is compact to be its initial radius $R_0 \sim 10^6$cm. At the beginning, in a very short time, the expansion is relativistic and the efficiency factor to emit photons might be supposed to be $C_2 \sim 10^{-3}$. After that about 10^3s, observed GRB photons are mostly generated by synchrotron radiation during internal shocks, of which the efficiency factor is $C_1 \sim 10^{-2}$, and GRB energy E_{GRB} is calculated up to 10^{50}—10^{54} erg assuming an isotropic emission. In consequence the initial fireball energy E_0 is

$$E_0 = E_{\mathrm{GRB}} \cdot C_1^{-1} \cdot C_2^{-1}. \tag{5}$$

If $E_{\mathrm{GRB}} = 10^{54}$ erg, the initial temperature $kT_0 = 0.0058$erg, and photons with higher energies have lower density (Fig.1). Supposing that the expansion is adiabatic, which means RT = constant, R increases and T, E and n decreases as a function of time t.

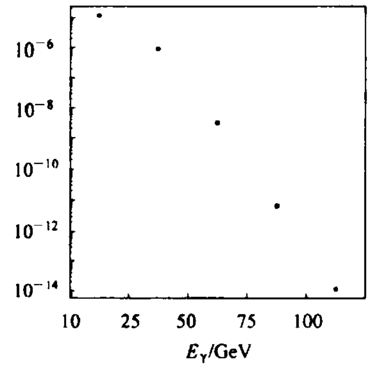

Fig.1. Relation between photon energy and density when $kT_0 = 0.0058$erg.

In the lepton fireball, only photons in a thin shell of thickness λ_{tot}, total mean free path, on the fireball surface can escape from the fireball:

$$\lambda_{\mathrm{tot}} = \frac{1}{n\sigma_{\mathrm{tot}}}, \tag{6}$$

where σ_{tot} is the total interaction cross-section and n is the photon number density. There are four types of interactions among photons and electrons: double photon annihilation, inverse Compton scattering, e^+e^- scattering and e^+e^- annihilation. Double photon annihilation and e^+e^- scattering have so low interaction cross-sections and can be ignored. The cross-section of inverse Compton scattering is closed to, but a little larger than that of e^+e^- annihilation. High energy photons are generated mainly in λ_{an}, mean-freepath of e^+e^- annihilation, and

$$\lambda_{\mathrm{an}} = \frac{1}{n\sigma_{\mathrm{an}}}, \tag{7}$$

where σ_{an} is the interaction cross-section of e^+e^- annihilation.

Consequently, the high energy photon generation efficiency

$$\epsilon = \frac{\lambda_{\mathrm{tot}}}{\lambda_{\mathrm{an}}} \sim 0.4. \tag{8}$$

2.2 Expanding spheroid

The fireball expansion is calculated with the numercial method in Ref.[14] to obtain the fireball expansion velocity $\beta = v/c$ and Lorentz factor $\gamma = 1/\sqrt{1-\beta^2}$ (Fig.2). Due to the aberration, a distant observer sees an expanding radiation spheroid from the fireball[16]. The spheroid has a focus at the centre of the fireball, the semimajor axis $a = vt\gamma^2$ directing the observer, the semilatus rectum $p = vt$ and the eccentricity $e = \beta$ (Fig.3). Relativistically, the observer can only see photons within a polar angle θ of $1/\gamma$ in the observing direction, and the corresponding solid angle is $\Omega = 2\pi(1/\gamma)^2$. During a du-

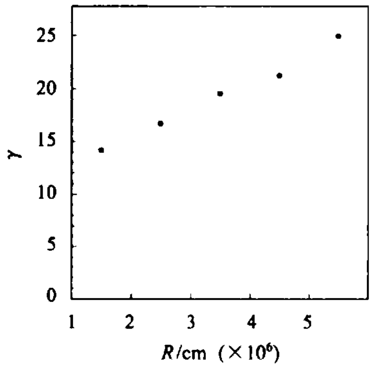

Fig.2. Relation between photon Lorentz factor γ and fireball radius R.

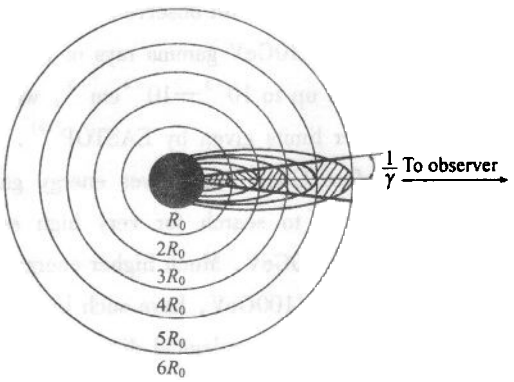

Fig.3. A fireball expands from R_0 to $6R_0$. A distant observer can only see an expanding radiation spheroid from the fireball within an polar angle θ of $1/\gamma$. The spheroid has a focus at the centre of the fireball, semimajor axis $a = vt\gamma^2$ directing observer, semi-latus rectum $p = vt$ and eccentricity $e = \beta$. The shaded areas are volume sending gamma rays which can be seen by observers in expanding periods.

ration (t_1, t_2), the volume of the fireball expansion in all direction is:

$$V = \frac{4\pi}{\Omega}\int_{w_1}^{w_2} \mathrm{d}p \int_0^{1/\gamma} \frac{2\pi p^2 \sin\theta}{(1-\beta\cos\theta)^3}\sqrt{\beta^2+1-2\beta\cos\theta}\,\mathrm{d}\theta . \tag{9}$$

When $\beta \to 1$,

$$V \quad \frac{4\pi}{9}\gamma^2 c^3 (t_2^3 \qquad \left(\frac{1}{\left(\cos\frac{1}{2\gamma}\right)^3} - 1\right) \tag{10}$$

2.3 Absorption in cosmic background radiation

High energy gamma rays emitted from GRBs might be absorbed partly in the intergalactic space due to Double-photon-annihilation with the cosmic background radiation. From Ref.[17], at optical depth $\tau_{\gamma\gamma} = 1$, between 10^{10}eV and 10^{12}eV, the relation between photon energy E_γ and redshift z of a gamma source can be taken approximately as

$$z = 10^{-0.85} E_\gamma^{\ 0.7}, \tag{11}$$

where the unit of E_γ is TeV. According to the relativistic Doppler effect equation,

$$\frac{v_u}{c} = \frac{(z+1)^2 - 1}{(z+1)^2 + 1}, \tag{12}$$

where v_u is the universe expansion velocity, and Hubble law,

$$l = \frac{v_u}{u}, \tag{13}$$

where l is the distance which photons can pass when $\tau_{\gamma\gamma} = 1$, and H_0 is Hubble constant ~ 75km·s^{-1}·Mpc^{-1}. So if z and E_γ are given, the remaining rate of photons with different energies after passing distance L can be obtained (Fig.4):

$$\eta = e^{-L/l} \tag{14}$$

Observed high energy GRBs, 10^{51}—10^{54}erg, have redshift from 0.43 to 4.5 [18] so here only three typical redshifts are taken into account as shown in Fig.4.

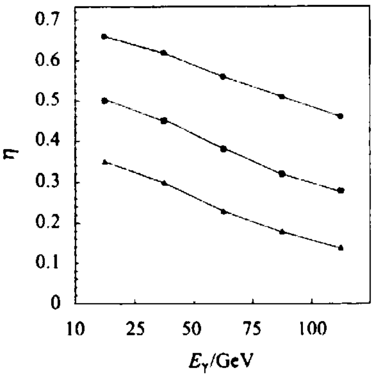

Fig.4. The remaining rate of photons with different energies in different cosmological distances L: circle, L = 1.5Gpc, z = 0.48; square, L = 2.5Gpc, z = 1.08; triangle, L = 3.8Gpc, z = 5.24.

2.4 Gamma ray fluence

The gamma ray fluence can be obtained now:

$$F = \frac{V \cdot n \cdot \epsilon \cdot \eta}{L^2}. \tag{15}$$

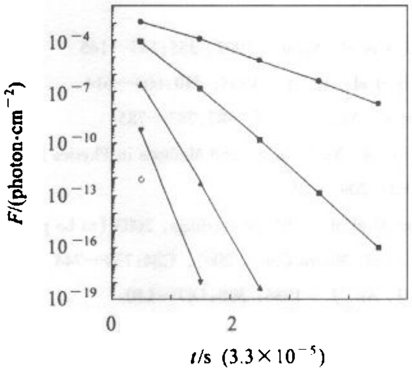

Fig.5. The fluence of photons with different energies changes with fireball expansion time: solid circle E_γ = 10GeV; square E_γ = 25GeV; triangle E_γ = 50GeV; inverse triangle E_γ = 75GeV; white circle E_γ = 100GeV.

Fig.5 shows the fluence of photons with different energies at different fireball expansion time. At the very beginning of expansion, about 10^{-5}s, the fluence of 10GeV gamma rays on the earth is up to 10^{-3}cm^{-2}, i.e., 10^{-5} erg·cm^{-2}. Very quickly, the number of gamma rays reduces many orders. Fig.6 is the spectrum of gamma rays in different cosmological distances. The spectrum is harder at the part of higher energies than lower ones.

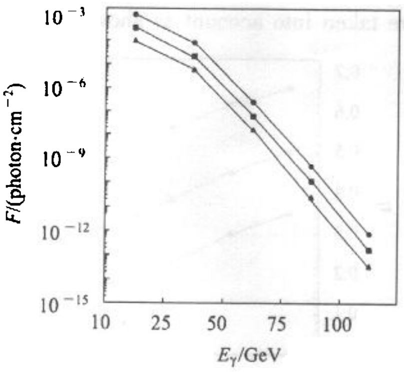

Fig.6. The spectra of gamma rays in different cosmological distnaces: circle, L = 1.5Gpc; square, L = 2.5Gpc; triangle, L = 3.8Gpc.

3 Discussion

At the beginning of expansion, in a very short duration, about 10^{-5}s, the GRB with observed energy 10^{54}erg may send out more than 10GeV gamma rays of which the fluence on the earth is up to 10^{-3}—10^{-4}cm^{-2}, which is compatible with upper limits given by EASTOP[19]. So it should be 10^3s before GRBs with lower energy gamma rays, 10keV—10GeV, to search for very high energy gamma rays larger than 10GeV. Much higher energy gamma rays, say, more than 100GeV, have such low fluence as not to be observed at a cosmological distance.

There are several ground cosmic ray experiments searching for high energy gamma rays from GRBs. One of them is L3 + C. The ratio of muons generated in atmosphere to original cosmic gamma rays at L3 + C is $\phi(E_\gamma \geqslant 40\text{GeV}) = 0.1\%$, and the detector area of L3 + C is $A = 100\text{m}^2$. If the fluence of gamma rays is $F = 10^{-3}$ cm^{-2}, L3 + C can only receive $N = F \cdot \phi \cdot A = 1$ muon generated by high energy gamma rays in a GRB.

Another experiment will be ARGO-YBJ. The ratio of showers generated in atmosphere to oringinal cosmic gamma rays at ARGO is $\phi(E_\gamma \geqslant 40\text{GeV}) = 1\%$, and the detector area of ARGO-YBJ is $A = 5000\text{m}^2$. If the fluence of gamma rays is $F = 10^{-3}$cm^{-2}, ARGO-YBJ can receive $N = F \cdot \phi \cdot A = 500$ photons generated by high energy gamma rays in a GRB.

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来自 γ 暴的甚高能 γ 射线*

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摘要　以膨胀火球模型解释来自 γ 暴的甚高能 γ 射线，其中考虑了高能 γ 射线产生效率，相对论效应以及宇宙背景辐射等因素．计算表明，大于 10GeV 的 γ 射线的喷射可能在火球膨胀开始后约 10^{-5}s 发生，其到达地面时的通量可达 10^{-4}—10^{-6}cm^{-2}．

关键词　γ 暴　宇宙线　火球模型

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