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DELAYED MeV–GeV GAMMA-RAY PHOTONS IN GAMMA-RAY BURSTS: AN EFFECT OF ELECTROMAGNETIC CASCADES OF VERY HIGH ENERGY GAMMA RAYS IN THE INFRARED/MICROWAVE BACKGROUND

L. X. CHENG
Institute of High Energy Physics, Beijing 100039, China

AND

K. S. CHENG
Department of Physics, University of Hong Kong, Pokfulam Road, Hong Kong
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ABSTRACT

We show that the electromagnetic cascade of very high energy gamma-rays from gamma-ray bursts in the IR/microwave background will produce delayed MeV–GeV photons. Monte Carlo simulations have been performed to study this process. The distance of GB 940217 is estimated to be not less than 120 Mpc using our model, which supports a cosmological origin for this source. We also show that the time delays of gamma-ray photons are inversely proportional to their energy. Our model does not require the presence of intergalactic magnetic fields.
Subject headings: gamma rays: bursts — infrared: general

1. INTRODUCTION

The Energetic Gamma-Ray Experiment Telescope (EGRET) on board the *Compton Gamma Ray Observatory* (*CGRO*) has detected five gamma-ray bursts (GRBs) that have MeV–GeV emissions (Sommer et al. 1994; Dingus et al. 1994; Schneid et al. 1992; Kwok et al. 1993; Hurley et al. 1994). The durations of the MeV–GeV emission often seem to be longer than that of keV emission. An event occurred on 1994 February 17 (hereafter GB 940217) that clearly showed that the high-energy emission persisted for at least ∼5400 s, while the duration of low-energy emission was about 180 s (Hurley et al. 1994).

Delayed high-energy photon emission from GRB sources is now considered a well-established fact (Hurley et al. 1994). Plaga (1995), assuming a cosmological origin for GRBs, argued that the high-energy delay is evidence for the existence of intergalactic magnetic fields (IGMFs). Other theories suggest that this delay could be the consequence of the collapse of a compact object or coalescence of a compact binary, and is not necessarily a signature of cosmological origin (Mészáros & Rees 1994; Katz 1994).

We suggest here that, in the absence of IGMFs, photon-pair electromagnetic cascades of the very high energy photons from GRBs can produce delayed MeV–GeV photons, and that the amount of time delay suggests that the source distance of GB 940217 is larger than 120 Mpc.

2. MODEL

Gamma-ray photons emitted from extragalactic sources may collide with diffuse microwave or IR photons, leading to $e^{\pm}$ pair production. Among the active galactic nuclei detected by the *CGRO*, only Mrk 421 and Mrk 501, which are the nearest and weakest ones, have also been detected by the Whipple Observatory, indicating the presence of TeV gamma-ray emission (Punch et al. 1992; Quinn et al. 1995). This fact supports the suggestion that the absence of TeV gamma rays from the more distant sources is due to attenuation (Stecker, De Jager, & Salamon 1992).

For photons with energies in the range of several hundreds of GeV to 100 TeV, pair production should mainly involve IR background photons, although the intensity of such photons is still not known. The pairs produced will scatter off the background photons, the cross section for the scattering being approximately the same as that for the Thomson scattering of electrons/positrons with energies lower than 100 TeV. Since the number density of microwave background photons is significantly higher (∼400 $\mathrm{cm^{-3}}$) than that of IR photons (∼1) (Protheroe & Stanev 1993), many 2.7 K microwave radiation photons will be boosted to very high energy (MeV–GeV), so that a photon-pair electromagnetic cascade develops.

In the pair production process, the electron and positron move in opposite directions with equal energy in the center-of-mass system. So, in our laboratory frame, they deviate slightly from the direction of the original gamma-ray photon (with energy E_1) by an angle $\sim 1/\gamma$, where γ is the Lorentz factor of electron/positron. The direction of gamma-ray photons produced by inverse Compton scattering of electrons (positrons) on microwave photons also differs from the direction of the electrons (positrons). The scattered microwave photons will be boosted up to TeV energies and will deviate from the direction of the electron (positron) by an angle $\sim 1/\gamma$, which is comparable to the direction change for pairs. In addition to the transient high-energy (MeV–GeV) gamma rays that do not interact with background photons, we should observe delayed cascade photons that have to travel a longer distance to reach us than those arriving directly from the source.

In the case of GB 940217, EGRET detected 10 MeV–GeV photons within the keV burst, and the count rate in this burst period is around 4 times the count rate in the whole delay period. The energy spectrum of the 10 high-energy photons within the keV burst shows no sign of a high-energy turnoff. We thus assume that high-energy photons with energies up to TeV are emitted from the source within 180 s, and the delayed MeV–GeV photons should be the result of the electromagnetic cascade and inverse Compton scattering.

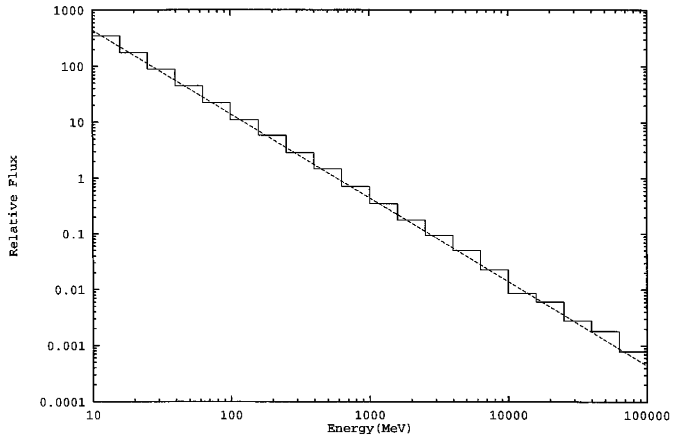

FIG. 1.—The solid line is the energy spectrum of secondary (scattered) photons when monoenergetic electrons are injected into the microwave field. The dashed line is a power function with index -1.5.

3. MONTE CARLO SIMULATION

Once a TeV gamma-ray photon is absorbed by the IR field and generates an $e^{\pm}$ pair, the electron and positron will scatter on the microwave photons for as many as several thousands of times until the secondary gamma-ray energy falls below the EGRET detection range. The total flight path of $e^{\pm}$ in these scatterings is negligible compared with the cosmological source distance (Plage 1995). We use Monte Carlo simulation for the scattering process to study how much the secondary photons with different energies will deviate from the direction of the original electron. The microwave background is taken as the 2.7 K blackbody radiation. Monoenergetic electrons are injected into the microwave field, and, as the energy of the electrons is transferred to microwave photons via inverse Compton scattering, the energies of generated photons should cover the entire energy range of EGRET. The energy loss of an electron in each scattering is $dE_e/dN \propto E_e^{-2} \propto E_2^{-1}$, where E_e is the energy of the electron and E_2 is the energy of the secondary photons. Thus, the energy spectrum of scattered photons should be $dN/dE_2 = dN/dE_e(dE_e/dE_2) \propto E_2^{-1}(dE_e/dE_2) \propto E_2^{-1.5}$ (Blumenthal & Gould 1970). Figure 1 shows the spectrum of scattered photons obtained in our simulation. Figure 2*a* shows the mean angular deviation of secondary photons with different energies.

In GB 940217, an 18 GeV photon was detected ~4500 s after the keV burst. If we assume 18 delayed MeV–GeV photons observed by EGRET are scattered microwave photons, less than 0.05 photons are expected to be scattered IR photons within EGRET observation. The probability of EGRET observing one or more scattered IR photons in the whole observation is less than 10^{-4}.

The fluence of the delayed emission was measured to be 7×10^{-6} ergs cm^{-2} (30–30,000 MeV) by Hurley et al. (1994). According to our model, photons in this energy range should come from primary photons with energies between 0.5 and 18 TeV, whose fluence is estimated to be 1.3×10^{-5} ergs cm^{-2} based on an extrapolation of the power-law fit by Hurley et al. (1994) on undelayed emission. Since the primary photons between 0.5 and 18 TeV may not be totally absorbed by IR photons, the above fluence is an upper limit for delayed emission. We use the IR background given by Stecker et al. (1992) to estimate the fluence of delayed emission. Assuming a distance of 120 Mpc, we find the fluence of delayed emission should be in the range of $(7\text{–}9.5) \times 10^{-6}$, which is consistent with the measurement. In estimating the delayed flux, we have assumed that the original emission is isotropic. If the original emission is beaming, then our estimated delayed flux is still valid, unless the beaming angle is much less than 10^{-6}. Therefore, the beaming caused by the relativistic bulk motion with a Lorentz factor of nearly 10^3, which plays an important role to reduce the $\gamma - \gamma$ opacity in the source, should not affect our estimation.

We now study the angular deviation of secondary photons in the energy range 16–20 GeV more quantitatively. Figure 2*b* shows the distribution of the angular deviation of the secondary photons in this energy range. We find that 90% of the photons deviate from the direction of the original electron by less than 7×10^{-7} rad. The total flight path of electrons/positrons in the microwave field is very small (<0.04 Mpc) (Plaga 1995), and the flight time difference of electron/positron on this path is negligible.

In the case where the mean free path of very high energy photons in the IR field is comparable to the source distance,

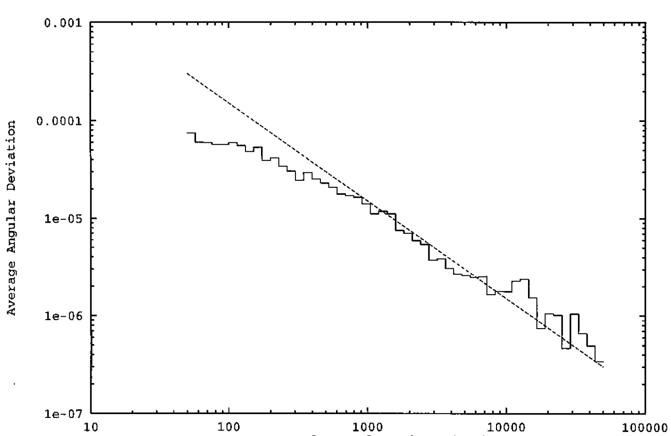

FIG. 2*a*

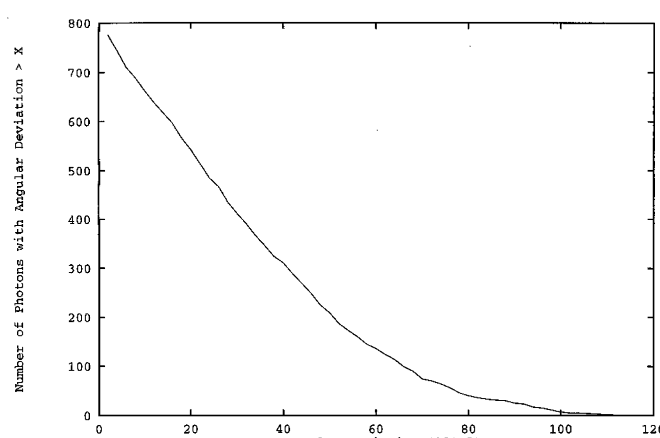

FIG. 2*b*

FIG. 2.—(*a*) The solid line is the simulation results of average angular deviation of secondary photons with different energies. The dashed line is a power function with index -1. The differences between the two curves at low energies arise from the low-energy cutoff in our simulation. (*b*) The number of photons (with energies between 16 and 20 GeV) with angular deviations larger than some value (X). As indicated in the text, most of the photons have deviation smaller than 7×10^{-7} rad.

the maximum time delay ($\delta t_{\max}$) for a deviation θ for a source distance d is (c is the speed of light)

$$\delta t_{\max} = \frac{\theta^2 d}{8c}. \tag{1}$$

Therefore, considering the angular deviation of the $e^{\pm}$ pair, we take $\theta = 1.1 \times 10^{-6}$ and conclude that the source distance should be larger than 120 Mpc with at least 90% confidence level. From the total fluence of this burst (6.6×10^{-4} ergs cm^{-2}), the total energy of this burst should be larger than 1.2×10^{51} ergs. This is consistent with the total energy of a typical cosmological gamma-ray burst (Paczyński 1986).

We now estimate the possible time delay for TeV photons. As indicated above, the maximum delay is proportional to θ^2 or γ^{-2}. As the energy of the secondary photon is roughly $E_2 = \gamma^2 E_{\rm MW}$, where $E_{\rm MW}$ is the energy of microwave photons, we have roughly $\delta t E_2 =$ constant. Assuming a source distance of 1 Gpc, 1 TeV secondary photons should have a maximum time delay of around 1600 s. Of course the TeV secondary photons could also come from the scattering of $e^{\pm}$ on IR photons, but the count rate of this kind of secondary photons should be around 1/400 of those from scattering on microwave photons. Another factor that will further reduce the time delay of TeV photons is the extremely high energy of the original gamma-ray photons (much larger than 10^{13} eV). Since the cross section is reduced by a factor of $1/E_\gamma$, the mean free path of photons with extremely high energy will be much longer than that of TeV photons. If the mean free path is significantly less than the source distance, the mean time delay ($\delta t_{\rm mean}$) should be

$$\delta t_{\rm mean} = \frac{\theta^2 \lambda}{2c}, \tag{2}$$

where λ is the mean free path of the original photons. In this case, $\delta t_{\rm mean}$ is restricted by λ and is independent of source distance.

4. DISCUSSIONS

By now, very little is known about the IGMFs. Vallée (1990) gives an upper limit of 6×10^{-12} G, but the real strength might be much lower. Cheng & Olinto (1994) suggest that the "primordial" magnetic field, which might have been produced in the very early universe, could have decayed to $\lesssim 10^{-16}$ μG on scales of $\sim$1 pc today. This field could be the seed field of the intergalactic magnetic field. If this were indeed the case, the effect of IGMFs would be negligible on the megaparsec scale. However, if the IGMFs are comparable to Vallée's upper limit, the cascade of $e^{\pm}$ pairs would lose direction information and the secondary photons would have no position correlation with the point source.

Our results, based on a cosmological origin for GRBs, show that the electromagnetic cascade and subsequent inverse Compton scattering will produce delayed MeV–GeV photons from GRB sources. The IGMFs suggested by Plaga (1995) are not necessary for this delay.

Although the IR background has been estimated or measured by many scientists (Paresce & Jakobson 1980; Ressell & Turner 1990; De Jager, Stecker, & Salamon 1994), we still do

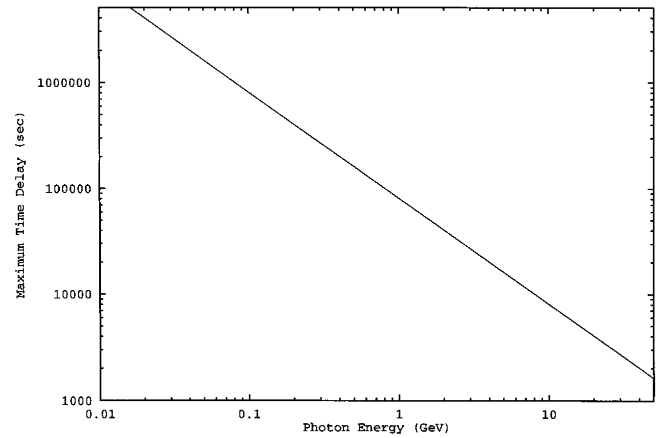

FIG. 3.—The maximum time delay of secondary photons with different energies.

not quite know its exact spectrum and intensity. Protheroe & Stanev (1993) assumed an IR background spectrum and simulated the cascade process. They found a pileup of photons around 1 GeV, which results in a significant flattening in the observed spectrum relative to the emission spectrum above 1 GeV, while the two spectra seem similar below this energy for low-redshift objects. Taking the Hubble constant H as 75 km s^{-1} Mpc^{-1}, the source distance of 120 Mpc gives $z = 0.06$. The delayed photon spectrum measured by EGRET seems to agree with the simulation results for the low-redshift case considered by Protheroe & Stanev (1993).

Although our model suggests that, in addition to the time delay of secondary MeV–GeV photons, soft photons tend to have larger amounts of delay, very long observation time is needed to detect this effect. Figure 3 shows the maximum delay of photons with various energies, assuming a distance of 120 Mpc. If the 18 GeV photon is excluded, the energies of EGRET observed photons are within 36–137 MeV and the lack of high-energy photons in this energy range should occur at around 10^6 s after the keV burst. Thus, no correlation between time delay and photon energy could be found in the EGRET observation.

It is difficult to give the absolute count rate and spectrum of the secondary photons by our model for two reasons. First, the original burst spectrum is not known at energies above several GeV. Second, the undetermined IR background makes it uncertain how much of the very high energy emission can be absorbed.

According to our calculations, the time delay of TeV photons should be much less than MeV–GeV photons. This would make it more difficult for very high energy telescopes to detect a GRB in the TeV range. However, future detection of TeV gamma rays from GRBs would provide a direct test for the photon-electron cascading process in intergalactic space.

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