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Gamma-ray bursts, ultra-high-energy cosmic rays, and cosmic gamma-ray background

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Abstract

We argue that gamma-ray bursts (GRBs) may be the origin of the cosmic gamma-ray background radiation observed in the GeV range. It has theoretically been discussed that protons may carry a much larger amount of energy than electrons in GRBs, and this large energy can be radiated in the TeV range by synchrotron radiation of ultra-high-energy protons ($\sim 10^{20}$ eV). The possible detection of GRBs above 10 TeV suggested by the Tibet and HEGRA groups also supports this idea. If this is the case, most of TeV gamma-rays from GRBs are absorbed in intergalactic fields and eventually form GeV gamma-ray background, whose flux is in good agreement with the recent observation. © 1999 Elsevier Science B.V. All rights reserved.

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1. Introduction

In all wavelengths from radio to gamma-rays, the presence of a diffuse background radiation emanating from beyond our Galaxy is known. It is considered that the background radiation in different bands has different origins, and they may be truly diffuse processes or be superpositions of unresolved point sources. The background radiation in the highest energy range currently observed starts at around 30 MeV, and extends beyond 10 GeV with a clear single power-law spectrum. This extragalactic background radiation in the GeV range was first indicated by the SAS 2 satellite after removing the much stronger GeV background from our Galaxy [1], and recently a detailed observation was made by the EGRET detector on the Compton Gamma-Ray Observatory [2]. The EGRET observation revealed that this cosmic GeV background is very hard with a photon energy index of $\beta = 2.10 \pm 0.03$ ($dN/dE \propto E^{-\beta}$), compared with the background radiation in lower energy bands.

A large number of possible origins for the cosmic GeV background radiation has been proposed (see Ref. [2] for a review). Currently the most likely explanation is considered to be a superposition of unresolved active galactic nuclei of the blazar class. In fact, a large number of gamma-ray emitting blazars has been observed by the EGRET, and the average of the spectral index of these blazars is in good agreement with that of the cosmic GeV background. However, there is no clear evidence that the GeV background is actually produced by unresolved blazars. In fact, the majority of radio selected blazars is likely to have luminosities falling off above $\sim$ 10 GeV, and the observed GeV background extending to 100 GeV may be difficult to explain by blazars [3]. Recently,

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Mukherjee and Chiang [4] claimed that blazars can explain only 25% of the observed GeV background, based on the luminosity function and its evolution of EGRET blazars, and other sources of the GeV background must exist. Therefore, the origin of the cosmic GeV background radiation should still be considered as an open question.

In this paper we propose a new scenario which can explain the extragalactic GeV background radiation by the intergalactic cascade of TeV gamma-rays emitted from cosmological gamma-ray bursts (GRBs). Recently it has been pointed out that a very strong emission in TeV range is possible from GRBs by synchrotron radiation of protons accelerated up to 10^{20} eV [5,6]. There are also some recent observational suggestions for such strong emission of TeV gamma-rays from GRBs [7,8], and in fact they are well explained by the proton-synchrotron model [6].

In Section 2, we describe the proton synchrotron model of TeV gamma-ray emission from GRBs. We then discuss, in Section 3, the absorption of TeV gamma-rays in the intergalactic field and show that GRBs can make a significant contribution to the cosmic GeV background. In Section 4, we will discuss the spectrum of the GeV background radiation expected in this scenario and compare it to the observation. Conclusions are presented in Section 5.

2. TeV gamma-ray emission from gamma-ray bursts

Gamma-ray bursts (GRBs) are widely believed as dissipation of kinetic energy of ultra-relativistic motion produced by an expanding fireball with a Lorentz factor of $\sim 10^2$–10^3 (see e.g. [9] for a review). The recently discovered afterglows following GRBs are also considered as similar phenomena, which are dissipation in the external shock generated by the collision with interstellar matter [10]. The radiation process of GRBs is generally considered as electron synchrotron. It has recently been pointed out that protons may carry a much larger amount of energy than electrons in the shock-heated matter by a factor of $\sim (m_p/m_e) = 2\,000$, and most of this energy is radiated as very high energy gamma-rays in TeV range by the synchrotron radiation of protons accelerated to $\sim 10^{20}$ eV [5]. Since the origin of the GRB energy is kinetic energy of ultra-relativistic motion, this situation is rather reasonable if the energy transfer from protons into electrons is inefficient. The shock acceleration in the internal shocks of GRBs can accelerate protons up to $\sim 10^{20}$ eV. Synchrotron photons of such ultra-high-energy protons are in the 1–10 TeV range when the magnetic field is in equipartition. The cooling time of such protons is sufficiently short ($\sim$ second), and hence a significant fraction of energy carried by protons can be emitted as TeV gamma-rays from GRBs, which would be much stronger emission than the electron synchrotron in the ordinary photon energy range of GRBs (keV–MeV) (see Ref. [5,6] for details). In fact, although further observational confirmation is necessary, the Tibet [7] and HEGRA [8] groups have independently suggested the existence of very strong emission above 10–20 TeV from some bright GRBs. If these signals are truly from GRBs, they are well explained by the above picture [6]. Hence the TeV gamma-rays from GRBs may be the evidence for the hypothesis that the ultra-high-energy cosmic rays (UHECRs) observed on the Earth are produced by GRBs [11–13].

Since a typical amount of energy emitted from GRBs in the ordinary soft gamma-ray range (keV–MeV) by electrons is $\sim 10^{52-53}(\Delta\Omega/4\pi)$ ergs [14,15], where $\Delta\Omega$ is the opening solid angle of GRB emission, a very large amount of energy ($\sim 10^{56}(\Delta\Omega/4\pi)$ erg) is required for the engine of GRBs. Although it seems too large at first glance, it is not theoretically impossible if GRB emission is strongly beamed. The energy available by some magnetic processes such as the Blandford–Znajek mechanism [16] is $\sim 10^{54}$ erg from mergers of compact objects or collapses of massive stars [17,18], which are currently considered as likely sources of GRBs. If the GRB emission is strongly beamed with $(\Delta\Omega/4\pi) \sim 10^{-2}$, the above energy can be explained. There are also some very energetic models of GRBs producing $\sim 10^{56}$ ergs, by collapses of supermassive stars [19,20]. Therefore, in the following of this paper, we assume the above picture of GRBs, i.e., (1) protons carry about a 2 000 times larger amount of energy than electrons in the shocked region, and (2) protons are accelerated to 10^{20} eV and most of the energy carried by the ultra-high-energy protons is radiated in the TeV range by a proton-synchrotron.

3. Cascade of TeV gamma-rays and the cosmic GeV background

Most of TeV gamma-rays emitted from GRBs would however be absorbed in the intergalactic space because of the $e^{\pm}$ creation with the cosmic infrared background radiation [21]. The TeV gamma-rays observed by the Tibet and HEGRA arrays are considered to be a very tiny fraction of the original flux from nearby GRBs ($z \lesssim 0.2$) [6]. On the other hand, the $e^{\pm}$ pairs created by the TeV photons in intergalactic fields, whose energy is also about TeV, would scatter the 2.7 K cosmic microwave background (CMB) photons by the inverse-Compton process, and the energy of the secondary photons is $\epsilon_\gamma = 0.6\varepsilon_{\gamma,\mathrm{TeV}}^2$ GeV, where $\varepsilon_\gamma = 10^{12}\varepsilon_{\gamma,\mathrm{TeV}}$ eV is the energy of primary photons. (For simplicity, we neglect the redshift dependence of particle energies.) It should be noted that created pairs would also scatter other low-energy background photons such as the infrared band, but energy density of background radiation is dominated by CMB and hence most of the energy of created pairs is lost in scattering the CMB photons. It is uncertain whether we can directly observe these secondary photons because the $e^{\pm}$ pairs would be bent by intergalactic magnetic fields. The created pairs run about $l = 0.35\varepsilon_{\mathrm{e,TeV}}^{-1}$ Mpc before they cool down by the inverse-Compton scattering of CMB photons, where $\varepsilon_{\mathrm{e}} = 10^{12}\varepsilon_{\mathrm{e,TeV}}$ eV is the energy of created pairs. The Larmor radius of pairs is given by $r_L = 1.1\varepsilon_{\mathrm{e,TeV}}B_{-12}^{-1}$ kpc, where $B = 10^{-12}B_{-12}$ G is the intergalactic magnetic field. In order to observe the inverse-Compton photons within a time delay of about day, a very small bending angle of $(l/r_L) \lesssim 10^{-6}d_3^{-1/2}$ rad, i.e. $B \lesssim 10^{-20}$ G, is required, where $d = 3000d_3$ Mpc is the distance to the source. This value is much smaller than the current upper limits on the intergalactic magnetic fields, $B_{\mathrm{IGM}} \lesssim 10^{-9}(L_{\mathrm{rev}}/\mathrm{Mpc})^{-1/2}$ G, where L_{rev} is the field reversal scale [22]. At least a magnetic field of order $\sim 10^{-20}$ G is expected in intergalactic fields during the structure formation in the universe by thermoelectric currents [23]. If the intergalactic magnetic field is still at this level at the present time, the secondary GeV gamma-rays may be marginally observable. On the other hand, it should also be noted that a magnetic field of $\sim 10^{-12}$ G is necessary in the intergalactic field for the hypothesis that GRBs are the origin of UHECRs, in order to make the arrival time of UHECRs on the Earth sufficiently dispersed (i.e., not like a burst) [11]. In our model, protons are accelerated to 10^{20} eV in order to emit TeV gamma-rays from GRBs, and if these ultra-high-energy protons also explain UHECRs, it seems difficult to observe the secondary GeV photons.

In any case, such secondary GeV photons should form a uniform cosmic background radiation at the present time. In the following we show that the flux and spectrum predicted by our scenario are consistent with the recent observations of the cosmic GeV background by the EGRET experiment [2]. First we give an order-of-magnitude estimation for the GeV background flux. The observed energy density of GeV background photons is $\sim 6 \times 10^{-18}$ erg cm^{-3} in 30 MeV–30 GeV [2]. In our scenario this energy density is a sum of the energy emitted from all GRBs which have ever occurred in the universe. The occurrence rate of GRBs depends on the unknown distance scale of GRBs, and it is about $\sim 10^{-9}b$ yr^{-1}Mpc^{-3} [15,24] with typical distance scales of cosmological GRBs ($z_{\max} \sim 3$), where $b = 4\pi/\Delta\Omega$ is the beaming factor and $z_{\max}$ is the redshift of the most distant GRBs observed by the BATSE experiment [25]. By using this GRB occurrence rate and assuming the age of the universe as 15 Gyr, the total number of GRBs which have ever occurred is $\sim 15b$ Mpc^{-3}. (The evolutionary effect of GRB rate may somewhat change this estimate, but here we neglect it in this order-of-magnitude estimate.) Hence the total energy of GeV gamma-rays which should be produced by one GRB event becomes $\sim 10^{55}b^{-1}$ erg. Since we are now considering the case that the total GRB energy is $\sim 10^{56}b^{-1}$ erg, this energy can be supplied from GRBs. In fact, this energy is about 10^3 times larger than the conventional energy estimate of GRBs, $\sim 10^{52}b^{-1}$ erg. Therefore, it has been considered that GRBs cannot be the origin of the extragalactic GeV background. However, in the present model, protons carry $(m_p/m_e) \sim 2000$ times larger amount of energy than electrons, and significant fraction of this energy will be emitted as TeV gamma-rays and eventually converted into GeV photons. Hence the shortage of energy is just compensated by the proton–electron mass ratio, and now the energy production of GRBs is in agreement with that of the cosmic GeV background.

It is also interesting to compare the energy production rate estimated above with that of UHECRs observed on the Earth. The energy production rate of UHECRs per one GRB is about $\sim 10^{54} b^{-1}$ erg (see Eq. (12) of Ref. [6]), and hence the energy production rate of the GeV background is somewhat larger than that of UHECRs. This suggests that the photons produced by the intergalactic cascade originated by UHECRs cannot be a dominant component of the GeV background. Instead, ultra-high-energy protons lose their energy mainly by synchrotron radiation in GRBs, and most of their energy is emitted as TeV gamma-rays. The dominant component of the GeV background is the secondary GeV photons produced by synchrotron TeV photons from GRBs, and only a small fraction of 10^{20} eV protons can escape from GRBs to be observed as UHECRs.

4. Spectrum of the cosmic GeV background

Next we consider the spectrum of the GeV background predicted by this model. It is not straightforward to calculate the spectrum of the GeV background generated by an intergalactic cascade of higher energy photons. The intergalactic optical depth of high energy gamma-rays changes significantly with the photon energy, depending on the flux, spectrum, and their evolution of the cosmic infrared background, which are still uncertain. It is known that the final spectrum of the gamma-ray background is generally insensitive to the original spectrum of gamma-rays emitted from the source [27]. Coppi and Aharonian [27] have made a realistic calculation of the spectrum of the GeV background produced by the cascade of TeV photons, taking into account various reaction processes in intergalactic fields and realistic properties of the cosmic infrared background. According to their calculation, most of the cascade energy produced by very high energy gamma-rays above $\sim$ TeV is contained in the background radiation in the EGRET range. The spectrum of the cascade photons becomes about $\beta \sim 1.8$–2 above the energy $\epsilon_b \sim [\epsilon_{\rm cut}(z_s)/1{\rm TeV}]^2$ GeV, where $\epsilon_{\rm cut}$ is the cutoff energy at which an observed spectrum of very high energy gamma-rays from a source at $z = z_s$ shows a cutoff due to the pair creation process. At $\epsilon_\gamma < \epsilon_b$, the spectral index becomes $\beta \sim 1.5$. Based on a recent realistic calculation [26], $\epsilon_{\rm cut} \sim 500$, 50, and 20 GeV for $z_s = 0.1$, 1, and 3, respectively. Therefore, for a typical cosmological GRBs with $z \gtrsim 1$, ϵ_b is well below 30 MeV at which the hard component of the cosmic GeV background starts. Therefore, the spectrum of the cascade photons becomes $\beta \sim 2$ in the EGRET range and it is fully consistent with the EGRET observation.

The cosmological evolution of GRB rate may also affect the spectrum of the GeV background through the cosmological redshift effect. A more detailed calculation including a realistic rate evolution of GRBs and various reaction processes in the intergalactic field is necessary to verify whether the GeV spectrum predicted by our scenario is consistent with the observation, and this point will be studied in future publications.

5. Conclusions

We have shown that the extragalactic background radiation in the GeV range can be explained by GRBs, by the intergalactic cascade of TeV photons from GRBs emitted by synchrotron radiation of 10^{20} eV protons. For this scenario, protons must carry about (m_p/m_e) times larger amount of energy than electrons, and it is a reasonable situation if the energy transfer from protons into electrons in shocked region is inefficient. In order to distinguish this scenario from other scenarios for the cosmic GeV background, a more precise estimate of the background spectrum is necessary both in the theoretical modeling and in observation. As we have mentioned earlier in this paper, the majority of radio selected blazars are likely to have luminosities falling off above ~ 10 GeV, and the observed GeV background extending to 100 GeV may be difficult to explain by blazars [3]. On the other hand, in our scenario the GeV gamma-ray background is a consequence of the cascade of much higher energy photons, and hence extension of the spectrum up to ~ 100 GeV is naturally expected. This point may be a crucial point to discriminate between the two scenarios.

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