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Ultra-high energy cosmic rays and prompt TeV gamma rays from gamma ray bursts

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Abstract. Gamma ray bursts (GRBs) have been proposed as one possible class of sources of the ultrahigh energy cosmic ray (UHECR) events observed up to energies $\gtrsim 10^{20}$ eV. The synchrotron radiation of the highest energy protons accelerated within the GRB source should produce gamma rays up to TeV energies. Here we briefly discuss the implications on the energetics of the GRB from the point of view of the detectability of the prompt TeV γ-rays of proton–synchrotron origin in GRBs in the up-coming ICECUBE muon detector in the south pole.

Keywords. Gamma ray bursts; ultra-high energy cosmic rays; TeV gamma rays.

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1. Introduction

The origin of the observed ultra-high energy cosmic ray (UHECR) events with estimated energy in excess of 10^{20} eV [1] is unknown and is currently a subject of much discussions [2]. It is in general extremely difficult to accelerate particles to such high energies in most of the known astrophysical objects through conventional acceleration mechanisms. Gamma ray bursts (GRBs) have been proposed [3] as one possible class of sources which may be capable of accelerating particles to the requisite energies. If so, then synchrotron radiation of these protons in the magnetic field within the GRB source should produce prompt GeV–TeV γ-rays [4] whose detection may provide important clues as to the nature of GRBs. The predicted photon number flux at TeV energies is generally too low to be detected by the satellite-borne detectors which have limited sizes. However, ground-based detectors can in principle detect TeV photons from GRBs by detecting the secondary particles comprising the 'air showers' generated by these photons in the Earth's atmosphere.

Indeed, several ground-based γ-ray detectors employing different detection techniques [5] have independently claimed evidence, albeit not with strong statistical significance, for possible TeV γ-ray emission from sources in directional and temporal coincidence with some GRBs detected by BATSE. The estimated energy in TeV photons have been generally found to be significantly larger (by up to 4 orders of magnitude in some cases) than the corresponding sub-MeV energies measured by BATSE. Note that, since TeV photons are efficiently absorbed in the inter-galactic infrared (IR) background due to pair production [6], only few relatively close by (i.e., low red-shift) GRBs can be expected to be observed at TeV energies.

The high (GeV–TeV) energy component of proton–synchrotron origin we are considering here is distinct from and not a continuation of the low-energy (keV–MeV) component, the latter being due to synchrotron radiation of the electrons accelerated along with the protons in the same magnetic field within the GRB source. If the fundamental source of energy of the GRBs is indeed the kinetic energy of the ultra-relativistic bulk flow of matter as in the currently popular fireball model [7], then, at least initially, one would expect the total energy content in protons to be higher than that in electrons by a factor of $\sim m_p/m_e \sim 2000$, where m_p and m_e are proton and electron rest mass, respectively. The energy transfer from protons to electrons through Coulomb interaction is an inefficient process [8]. Immediately after dissipation of the kinetic energy of the bulk flow through formation of internal shocks, the total energy content of protons would, therefore, be higher than that of electrons. If the proton spectrum is sufficiently hard so that most of the total energy in the proton component lies at the highest energy end of the spectrum where the synchrotron emission process is efficient, and if the pair-production process for the resulting TeV synchrotron photons on the ambient low-energy photons within the GRB source is inefficient, then the bulk of the energy in the proton component (which is initially higher than that in the electron component) will escape from the source in the form of TeV photons, giving significantly higher total energy in the TeV photon component compared to that in the sub-MeV component.

2. Results and discussions

We have recently studied [9] the detectability of the possible TeV component of proton–synchrotron origin from GRBs in the up-coming ICECUBE muon detector [10] in the south pole which can detect TeV energy photons by detecting the muons produced by TeV photons in the Earth's atmosphere [11]. In figure 1 we show (see for details ref. [9]) the behavior of the minimum luminosity (assuming isotropic emission) in the high-energy component required for detection with a signal-to-noise ratio of 5 or larger in the ICECUBE detector, as a function of α_p, the differential spectral index of the accelerated protons within the GRB, for various values of the red-shift z of the GRB. The calculations include the effects of both the internal (i.e., within the GRB environment) as well as the external (i.e., in the inter-galactic medium) optical depth of TeV photons. The required isotropic luminosity of the high-energy photon component is upward of 10^{56} ergs/s (for reasonably hard proton spectrum) and are generally more than 3–4 orders of magnitude higher than typical estimated isotropic luminosities ($\sim 10^{53}$ ergs/s) in the keV–MeV BATSE energy band.

In order to explain the observed flux of UHECR, one needs a typical GRB to emit a total energy of $\sim$ few $\times\, 10^{53}$ erg (assuming isotropic emission) in UHE protons with energy $>10^{19}$ eV [12]. Note that the above number refers to the total energy *escaping* from the GRB source in the form of UHE protons. The total energy in

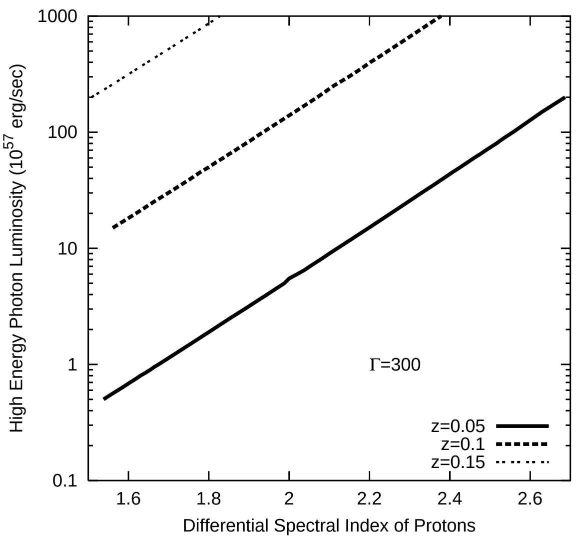

Figure 1. The minimum luminosity in the high-energy component required for detection with a signal-to-noise ratio of 5 or larger in an ICECUBE class detector, as a function of the power-law index (α_p) of the differential spectrum of protons accelerated within a typical GRB source, for various values of the red-shift z of the GRB. The values taken for other relevant parameters are as given in ref. [9].

the UHE proton component produced within the GRB may be significantly higher, depending on the various energy loss processes of the UHE protons within the GRB source. If synchrotron radiation is the dominant energy loss process for the UHE protons within the GRB source, and if the pair-production optical depth of the resulting GeV–TeV photons within the source is sufficiently small, then the escaping GeV–TeV photon luminosity of the source can be larger than the escaping UHE proton luminosity (see ref. [9]) for conditions on various parameters under which this can happen.

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