Prompt TeV Emission from Cosmic Rays Accelerated by Gamma Ray Bursts Interacting with Surrounding Stellar Wind

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ABSTRACT

Protons accelerated in the internal shocks of a long duration gamma ray burst can escape the fireball as cosmic rays by converting to neutrons. Hadronic interactions of these neutrons inside a stellar wind bubble created by the progenitor star will produce TeV gamma rays via neutral meson decay and synchrotron radiation by charged pion-decay electrons in the wind magnetic field. Such gamma rays should be observable from nearby gamma ray bursts by currently running and upcoming ground-based detectors.

Subject headings: gamma rays: bursts—gamma rays: theory—radiation mechanisms: nonthermal

1. Introduction

TeV γ-rays have not been yet convincingly detected from a gamma ray burst (GRB). The data from GRB 970417a reported by the Milagrito water Cherenkov detector (Atkins et al. 2000) and from GRB 971110 reported by the GRAND air shower array (Poirier et al. 2003) lack one of the most crucial pieces of information about those GRBs, namely their redshifts. A redshift is necessary to estimate the burst energetics and to properly take into account attenuation of TeV γ-rays in the extragalactic background radiation (EBL) fields. Moreover, their detection is at the $\approx 3\sigma$ level and hence statistically not very significant. A detection at higher significance level has been reported by the TIBET air shower array by stacking data for a large number of GRB time windows (Amenomori et al. 2001). Currently, several imaging air Cherenkov telescopes (IACTs) such as MAGIC and VERITAS are capable of slewing to the GRB direction in the sky prompted by burst alert network. The successor

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of the recently decomissioned Milagro detector, namely the High Altitude Water Cherenkov detector HAWC[1], has a high duty cycle and is particularly suitable to detect $\gtrsim$TeV γ-rays from GRB. Their observations have provided upper limits on γ-ray fluence from several GRBs (Atkins et al. 2005; Albert et al. 2006). More powerful detectors covering a wider energy range such as AGIS (Krawczynski et al. 2007) and CTA[2] are being planned.

Theoretical models do not predict TeV γ-rays from the internal shocks of a GRB because of a high opacity to $e^{\pm}$ pair production with observed keV–MeV energy γ-rays unless the Lorentz factor of the relativistic bulk motion is very large (Razzaque, Mészáros & Zhang 2004). In the external shock with larger shock radii, TeV γ-rays formed by Compton scattering of shock-accelerated electrons may avoid $e^{\pm}$ pair production (Dermer, Chiang & Mitman 2000; Wang, Dai & Lu 2001; Zhang & Mészáros 2001). Photohadronic cascades induced by shock-accelerated protons (Böttcher & Dermer 1998) requires intense internal soft photon fields that will strongly attenuate TeV γ-rays in the EBL.

In this Letter we propose a hadronic mechanism to produce TeV γ-rays at the same time as the prompt keV–MeV emission. If protons are accelerated in the internal shocks of a GRB (Waxman 1995), they are expected to interact with observed keV–MeV photons to produce neutrons ($p\gamma \to n\pi^+$) which may escape the shock region as cosmic-rays (Waxman & Bahcall 1997; Rachen & Mészáros 1998; Dermer & Atoyan 2003). A fraction of these cosmic rays will interact with particles in a surrounding dense stellar wind as the progenitor star is expected to undergo substantial mass loss before explosion (Chevalier & Li 1999). Neutral pions from secondary nuclear production promptly decay to produce very high energy γ-rays, while charged pions decay to produce electrons which emit synchrotron radiation in the magnetic field of the stellar wind. These γ-rays at TeV energy could be detected if they avoid substantial absorption in the source environment as well as

We find that TeV γ-rays formed by nuclear interactions of escaping neutrons with stellar wind particles may be detected from a nearby GRB by current and upcoming γ-ray Cherenkov telescopes.

2. GRB internal shocks and cosmic-ray escape

The GRB internal shocks take place over a wide range of fireball radii, depending on the γ-ray variability time scale $t_v \sim 10^{-3}$ s and the Lorentz factor of the bulk out-

[1]http://umdgrb.umd.edu/hawc/

[2]http://www.mpi-hd.mpg.de/hfm/CTA/

flow $\Gamma_b \gtrsim 10^{2.5}\Gamma_{b,2.5}$ for typical long GRBs. For observed non-thermal emission, the radii where the internal shocks occur need to be larger than the jet photospheric radius $r_{\rm ph} \cong (\sigma_T L_{\gamma,{\rm iso}})/(4\pi\epsilon_e\Gamma_b^3 m_p c^3) \approx 3.7\times10^{11} L_{\gamma,51}\epsilon_{e,-1}^{-1}\Gamma_{b,2.5}^{-3}$ cm, at which the fireball becomes optically thin to Thomson scattering. Here we use an isotropic-equivalent γ-ray luminosity of $L_{\gamma,{\rm iso}} = 10^{51} L_{\gamma,51}$ ergs s^{-1} and a kinetic luminosity of $L_{\rm k,iso} = L_{\gamma,{\rm iso}}\epsilon_e^{-1}$, where $\epsilon_e = 0.1\epsilon_{e,-1}$ is the fraction of kinetic energy converted to γ-rays (assuming a *fast-cooling* scenario). With these parameters we calculate a pre-shock electron and baryon number density of $n'_e \cong n'_p \cong L_{\gamma,{\rm iso}}/(4\pi\epsilon_e r_{\rm sh}^2\Gamma_b^2 m_p c^3)$ in the comoving frame. We denote the variables in the comoving plasma (observer's) frame with (without) primes.

For our modeling purpose, we assume a shock radius of $r_{\rm sh} = 10^{12} r_{\rm sh,12}$ cm. The turbulent magnetic field strength in the shock region, assuming that the magnetic energy density $B'^2_{\rm sh}/8\pi$ is a fraction $\epsilon_B = 0.1\epsilon_{B,-1}$ of the fireball's kinetic energy density $n'_p m_p c^2$, is

$$B'_{\rm sh} \approx 8.2\times10^5\ \epsilon_{B,-1}^{1/2} L_{\gamma,51}^{1/2}\epsilon_{e,-1}^{-1/2} r_{\rm sh,12}^{-1}\Gamma_{b,2.5}^{-1}\ {\rm G}. \quad (1)$$

The protons and electrons are assumed to be accelerated via a Fermi mechanism by this magnetic field.

Characteristic synchrotron photons radiated by the population of electrons with a minimum Lorentz factor $\gamma'_{e,\rm min} \simeq \epsilon_e(m_p/m_e)(\Gamma_{\rm rel}-1)$ is one of the leading models to produce observed γ-rays. With the parameters adopted here and a relative Lorentz factor between two colliding shells $\Gamma_{\rm rel}\approx 3$, the observed characteristic synchrotron photon energy is

$$\begin{aligned}\varepsilon_m &\cong (3/2)(B'_{\rm sh}/B_Q)\gamma'^2_{e,\rm min}\Gamma_b m_e c^2/(1+z)\\ &\approx 600(1+z)^{-1}\epsilon_{e,-1}^{3/2}\epsilon_{B,-1}^{1/2}L_{\gamma,51}^{1/2} r_{\rm sh,12}^{-1}\ {\rm keV}. \quad (2)\end{aligned}$$

Here $B_Q = m_e^2c^3/q\hbar \approx 4.414\times10^{13}$ G. The observed photon energy at the peak of the $\varepsilon F_\varepsilon$ spectrum, $\varepsilon_{\rm pk}$, varies from burst to burst, however, there exist several phenomenological relations connecting the peak photon energy to other burst parameters (e.g., Amati et al. 2002; Ghirlanda, Ghisellini & Lazzati 2004; Willingale et al. 2008). Here we adopt a relation between the peak γ-ray luminosity and a characteristic photon energy, which in turn is related to $\varepsilon_{\rm pk}$ as found by Willingale et al. (2008). We rewrite this relationship as

$$\varepsilon_{\rm pk} \approx 650(1+z)^{-1}L_{\gamma,51}^{0.27}\ {\rm keV}. \quad (3)$$

Note that this is close to the value of the synchrotron photon energy in equation (2).

Following the phenomenological broken power-law fits, we write the comoving photon spectrum as

$$n'_\gamma(\varepsilon') \cong n'_{\gamma,\rm pk}\Gamma_b/[\varepsilon_{\rm pk}(1+z)]$$

$$\times \begin{cases} (\varepsilon'_{\rm sa}/\varepsilon'_{\rm pk})^{-\alpha}(\varepsilon'/\varepsilon'_{\rm sa})^{3/2}; \ \varepsilon' < \varepsilon'_{\rm sa} \\ (\varepsilon'/\varepsilon'_{\rm pk})^{-\alpha}; \ \varepsilon'_{\rm sa} \le \varepsilon' \le \varepsilon'_{\rm pk} \\ (\varepsilon'/\varepsilon'_{\rm pk})^{-\beta}; \ \varepsilon'_{\rm max} > \varepsilon' > \varepsilon'_{\rm pk} \ , \end{cases} \tag{4}$$

where $(\varepsilon'_{\rm sa},\ \varepsilon'_{\rm max}) = (10^{-2.5},\ 10^6)$ keV are respectively the synchrotron self-absorption and maximum photon energies. The fitted values for the power-law indices are $(\alpha,\ \beta) = (1,\ 2.3)$. We calculate the peak photon number density $L_{\gamma,{\rm iso}}/(12\pi r_{\rm sh}^2 c\Gamma_b \varepsilon_{\rm pk})$, including a bolometric factor of ~ 3 and using equation (3), as

$$n'_{\gamma,{\rm pk}} \approx 2.7\times 10^{18}(1+z)L_{\gamma,51}^{0.73}\Gamma_{b,2.5}^{-1} r_{\rm sh,12}^{-2}\ {\rm cm}^{-3}. \tag{5}$$

The energy gained by the protons is proportional to the time $t'_{p,{\rm acc}} \simeq \phi E'_p/qB'_{\rm sh}c$, they spend in the shock region. The maximum energy is typically obtained by requiring that this time with $\phi \gtrsim 1$ to be equivalent to the smaller of the fireball expansion or dynamic time $t'_{\rm dyn} \simeq r_{\rm sh}/2c\Gamma_b$ and the energy loss time scale $t'_{p,{\rm loss}}$. The synchroton energy loss time scale $t'_{p,{\rm syn}} \cong 6\pi m_p^4 c^3/(\sigma_T m_e^2 E'_p B'^2_{\rm sh})$ is typically the shortest for internal shocks. A maximum cosmic ray proton energy can thus be obtained as

$$E_{p,{\rm max}} \approx 7\times 10^{10}\epsilon_{e,-1}^{1/4}\Gamma_{b,2.5}^{3/2} r_{\rm sh,12}^{1/2}\epsilon_{B,-1}^{-1/4}L_{\gamma,51}^{-1/4}\ {\rm GeV}, \tag{6}$$

for $t'_{\rm acc} = t'_{\rm syn}$. The differential spectrum (e.g., in units of cm^{-2} s^{-1} GeV^{-1}) of cosmic ray protons, if they could escape freely from the fireball at a luminosity distance d_L, may be written as

$$J_p(E_p) \cong L_{\gamma,{\rm iso}}/[4\pi d_L^2 \epsilon_e E_p^2\ \ln(E_{p,{\rm max}}/\Gamma_b m_p c^2)], \tag{7}$$

where we have assumed a typical $N(E) \propto E^{-2}$ spectrum generated in a mildly relativistic shock.

Shock-accelerated protons are expected to be confined in the GRB fireball by the magnetic field. Particles can, however, escape directly from the internal shock region when protons convert to neutrons through $p\gamma \to n\pi^+$ interaction. The rate of $p\gamma$ scattering with observed γ-rays, assumed to be isotropically distributed in the GRB fireball, is given by

$$K_{p\gamma}(\gamma'_p) = \frac{c}{2\gamma'^2_p}\int_{\varepsilon'_{\rm th}}^{\infty} d\varepsilon'_r \varepsilon'_r \sigma_{p\gamma}(\varepsilon'_r)\int_{\frac{\varepsilon'_r}{2\gamma'_p}}^{\infty} d\varepsilon' \frac{n_\gamma(\varepsilon')}{\varepsilon'^2}. \tag{8}$$

Here $\varepsilon'_r = \gamma'_p \varepsilon'(1-\beta_p\cos\theta)$ is the photon energy evaluated in the proton's rest frame for the angle θ between the directions of the energetic proton and target photon, and $\varepsilon'_{\rm th} = m_\pi c^2 + m_\pi^2 c^2/2m_p$ is the threshold photon energy for pion production. The dominant neutron production channel is $p\gamma \to n\pi^+$ with an intermediate $\Delta(1232)$ baryonic resonance production. The cross section formula may be written in the Breit-Wigner form (Mücke et al. 2000) as $\sigma_\Delta(\varepsilon'_r) = \sigma_0 \Gamma_\Delta^2 (s/\varepsilon'_r)^2 [\Gamma_\Delta^2 s + (s - m_\Delta^2)^2]^{-1}$, where $s = m_p^2 c^4 + 2\varepsilon'_r m_p c^2$, $\sigma_0 = 3.11 \times 10^{-29}$ cm^2 and the peak cross section is given by $\sigma_{\rm pk} = 4.12 \times 10^{-28}$ cm^2 at $\varepsilon'_{r,{\rm pk}} = 0.3$ GeV. The resonance width is $\Gamma_\Delta = 0.11$ GeV.

For the photon spectrum in equation (4), and taking an approximate cross section given by $\sigma_{p\gamma}(\varepsilon'_r) \cong \sigma_{\rm pk}$ for $\varepsilon'_{r,{\rm pk}} \le \varepsilon'_r \le \varepsilon'_{r,{\rm pk}} + \Gamma_\Delta$, the scattering rate in equation (8) simplifies to

$$K(\gamma'_p) \cong c\sigma_{\rm pk} n'_{\gamma,{\rm pk}} \times \begin{cases} \frac{2^\beta (\gamma'_p \varepsilon'_{\rm pk})^{\beta-1}}{(\beta^2-1)\varepsilon'^{\beta-1}_{r,{\rm pk}}} - \frac{\varepsilon'^{\beta-1}_{\rm pk} \varepsilon'^2_{r,{\rm pk}}}{4\gamma'^2_p \varepsilon'^{\beta+1}_{\rm max}(\beta+1)}; & \gamma'_p \le \frac{\varepsilon'_\Delta}{\varepsilon'_{\rm pk}} \\ \ln\left(\frac{\varepsilon'_{r,{\rm pk}}}{\varepsilon'_{\rm th}}\right) - \frac{\varepsilon'^2_{r,{\rm pk}}}{8\gamma'^2_p \varepsilon'^2_{\rm pk}}; & \frac{\varepsilon'_\Delta}{\varepsilon'_{\rm sa}} > \gamma'_p \ge \frac{\varepsilon'_\Delta}{\varepsilon'_{\rm pk}} \\ \frac{\varepsilon'^2_{r,{\rm pk}}}{2\gamma'^2_p \varepsilon'^2_{\rm sa}} - \frac{2^{1/2}\varepsilon'^{5/2}_{r,{\rm pk}}}{5\gamma'^{5/2}_p \varepsilon'^{5/2}_{\rm sa}}; & \gamma'_p > \frac{\varepsilon'_\Delta}{\varepsilon'_{\rm sa}} \ , \end{cases} \tag{9}$$

for $\alpha = 1$. Here $\varepsilon'_\Delta = (\varepsilon'_{r,{\rm pk}} - \Gamma_\Delta) m_p c^2$. The rate $K(\gamma'_p)$ times the dynamical time $t'_{\rm dyn} \simeq r_{\rm sh}/2c\Gamma_b$ represents the opacity $\tau_{p\gamma}(\gamma'_p)$ for $p\gamma$ scattering. For target photons with energies below ε'_{pk}, the $p\gamma$ scattering rate of high-energy protons is almost constant with energy when $\alpha = 1$. Therefore $\tau_{p\gamma}(\gamma'_p) \approx K(\gamma'_p) t'_{\rm dyn} \sim 1$ in this plateau region of γ'_p, where $K(\gamma'_p)$ refers to the accurate rate, equation (8), or the approximate rate, equation (9), respectively.

The flux $J_n(E_n)$ of neutrons from $p\gamma$ interactions depends crucially on the shocked-fireball radius, as discussed above. Assuming that they don't interact further in the fireball,

$$J_n(E_n) \cong J_p(E_n/y) t'_{\rm dyn} K(E_n/y\Gamma_b)/2y \ , \tag{10}$$

where $y = E_n/E_p \approx 0.8$ is the fraction of proton energy given to a secondary neutron, where a mean inelasticity is used. The injected primary proton flux (topmost thick dashed line) and escaping neutron flux are plotted for the full numerical calculation (thin solid line overlayed on dots) and for the approximate expression (dots) in Fig. 1.

3. Cosmic ray interaction with stellar wind

Massive stars such as GRB progenitors lose mass by blowing a spherically symmetric and steady wind. We assume a nominal mass loss rate of $\dot{M}_w = 10^{-4.5} M_{w,-4.5} M_\odot$ yr^{-1} and a wind velocity of $v_w = 10^8 v_{w,8}$ cm s^{-1}. The volume density of particles in the wind is $\dot{M}_w/(4\pi r^2 v_w m_p)$ and the column density at a radius $r = r_{\rm sh} = 10^{12} r_{12}$ cm is

$$\Sigma_w \approx 9.5 \times 10^{23} \dot{M}_{w,-4.5} v_{w,8}^{-1} r_{12}^{-1} \ {\rm cm}^{-2}. \tag{11}$$

The stellar wind may have high magnetic field, as has been suggested by many authors (e.g., Völk & Biermann 1988; Biermann & Cassinelli 1993). We assume for simplicity that this field is in equipartition with the wind kinetic luminosity $\dot{M}_w v_w^2/2$ (Wang et al. 2007), so that

$$B_w \approx 141\ w_{B,-1}^{1/2} \dot{M}_{w,-4.5}^{1/2} v_{w,8}^{1/2} r_{12}^{-1}\ \mathrm{G}\ , \tag{12}$$

where $w_B = 0.1 w_{B,-1}$ is the equipartition parameter.

Cosmic ray neutrons escaping from the GRB internal shocks can interact with dense stellar wind particles and produce secondary pions, kaons, and higher-order resonances through pn interactions. The neutron decay radius is $\gg c\tau_\beta \Gamma_b \approx 10^{16}\Gamma_{b,2.5}$ cm, so that neutrons that do interact with wind particles do so before they decay, and will therefore make beamed secondaries that would be directed along the GRB jet. Neutral pion and eta mesons decay almost instantaneously to produce ultrahigh energy γ-rays.

The γ-ray flux from pn interactions of neutrons with stellar wind can be calculated from the expression

$$J_\gamma(E_\gamma) = \Sigma_w \int_0^1 \frac{dx}{x} J_n \left[\frac{E_\gamma}{x}\right] \sigma_{pp} \left[\frac{E_\gamma}{x}\right] Y_\gamma(x; E_\gamma). \tag{13}$$

Here $\sigma_{pp}(E_p)$ is the inelastic pp cross-section, $x = E_\gamma/E_n$ is the fractional γ-ray energy and $Y_\gamma(x; E_\gamma)$ is the γ-ray yield function from neutral meson decays. We use the $Y_\gamma(x; E_\gamma)$ as recently parametrized by Kelner, Aharonian & Bugayov (2006) of the SIBYLL code which include γ-ray production from both π^0 and η^0 decays. Note that the charged lepton flux from pion decays may also be calculated using equation (13) with a change of subscript $\gamma \to e$ and using the appropriate yield function. The γ-ray (thin dash-dotted line) and electron (thin dashed line) source fluxes are plotted in Fig. 1

Comparing the synchrotron cooling time scale $t_{e,\rm syn} = (3/2)\hbar^2 (B_\perp/B_Q)^{-2} (r_e m_e c E_e)^{-1}$ for $\pi^\pm$ decay $e^\pm$ in the wind magnetic field given by equation (12), with the observed γ-ray variability time $t_v \simeq r_{\rm sh}/2\Gamma_b^2 c$, we find that electrons with $E_{e,\rm min} \gtrsim 8 \times 10^4$ GeV radiate away a large fraction of their energy. Here r_e is the classical electron radius, and we let the perpendicular magnetic field $B_\perp \cong B_w$. The total synchrotron power emitted by an electron is given by $P = (2/3)(r_e/\hbar^2)(B_\perp/B_Q)^2 E_e^2 m_e c$ with a characteristic photon energy $E_c = (3/2)(B_\perp/B_Q)E_e^2/m_e c^2$, similar to the expression in equation (2). To a good approximation we can assume that the total power $4\pi d_L^2 t_v P E_e J_e(E_e)$ is emitted in photons of energy E_c. The corresponding synchrotron flux by the electrons is therefore given by

$$E_\gamma^2 J_{\rm syn}(E_\gamma) \cong \frac{t_v r_e c^4 E_\gamma^{3/2}}{(3/2m_e)^{5/2}\hbar^2} \left(\frac{B_w}{B_Q}\right)^{1/2} J_e(\xi). \tag{14}$$

Here $\xi = [(2/3)(B_w/B_Q)E_\gamma m_e c^2]^{1/2}$. Note that the synchrotron energy loss formula assumed here applies in the classical limit defined by the parameter $\chi = (3/2)(B_\perp/B_Q)(E_e/m_e c^2) \ll 1$. Thus the minimum and maximum synchrotron photon energies for the parameters adopted here may be calculated as $E_{\gamma,\rm min} \simeq (27/2)(B_Q/B_w)^3\hbar^4\Gamma_b^4/[m_e^3c^2r_e^2r_{\rm sh}^2] \approx 60$ GeV and $E_{\gamma,\rm max} \simeq (2/3)(B_Q/B_w)\chi^2 m_e c^2 \approx 10^4\chi_{-2}^2$ GeV, assuming $\chi = 10^{-2}\chi_{-2}$. The synchrotron flux is plotted in Fig. 1 with an exponential cutoff above $E_{\gamma,\rm max}$.

Compton losses on the scattered stellar radiation field can be shown to be small compared with synchrotron losses. The energy density of scattered stellar photons from the pre-burst star is $\approx L_*\tau_w/4\pi r^2 c \cong 260\ L_{*,38}\tau_w/r_{12}^2$ ergs cm^{-3}, where $L_* = 10^{38}L_{*,38}$ ergs s^{-1} is the pre-burst stellar luminosity and τ_w is the Thomson depth of the wind. This is smaller than the magnetic field energy density $B_w^2/8\pi$ given from the expression for B_w in equation (12), even for a luminous pre-burst star. Klein-Nishina effects will make the Compton losses even smaller. TeV γ rays might also produce $e^\pm$ pairs with the stellar photons through $\gamma\gamma$ interactions. The optical depth of TeV photons to $\gamma\gamma$ pair production with stellar photons with mean energy $\bar{\epsilon}_*$ can be written as $\tau_{\gamma\gamma} \simeq (\sigma_{\rm T}/3)n_{ph}(\bar{\epsilon}_*)r \simeq 4\times 10^{-5}L_{*,38}\tau_{\rm T}/[r_{12}(\bar{\epsilon}_*/{\rm eV})]$. As can be seen, this process can be neglected.

High energy γ-rays are also subject to absorption with photons of the EBL while propagating from the source to Earth. The opacity $\tau_{\gamma\gamma} \sim 1$ for ≈ 600 GeV photons from a source at $z \approx 0.1$ (Razzaque, Dermer & Finke 2008). To calculate the opacity, we assumed that the background radiation field consists of three components—cosmic microwave background, infrared and optical photons—represented by a blackbody spectrum, a modified blackbody spectrum (Dermer 2007b) and a fit (Razzaque, Dermer & Finke 2008), respectively. The final emerging γ-ray spectrum (thick solid curve) is plotted in Fig. 1. The absorbed γ-rays can induce a pair cascade and give rise to a long duration component after the burst is over if the intergalactic magnetic field is sufficiently weak, $\lesssim 10^{-16}$ G (Razzaque, Mészáros & Zhang 2004).

4. Results and Discussion

Figure 1 shows the results of our study. We assumed a GRB luminosity distance of $d_L = 455$ Mpc ($z = 0.1$), with all scaling parameters equal to unity (most importantly, $r_{12} = 1$ and $M_{w,-4.5} = 1$). The "observed" γ-ray spectrum is calculated from the "e synchrotron" and "π^0, $\eta^0 \to \gamma$" components after taking into account absorption in the EBL. Also shown in Fig. 1 are the detection sensitivites of the MAGIC (Albert et al. 2006; Scapin et al. 2006) and HAWC (see footnote 4) detectors. For MAGIC, we used their 60 s 5σ GRB sensitivity of 5.8 Crab between 80 GeV – 350 GeV and 1.8 Crab between 350 GeV – 1 TeV. For HAWC we used their 10 s 5σ GRB sensitivity within 0–10 degrees of the azimuth.

As shown in Fig. 1, a typical long duration GRB inside a stellar wind environment may be detected by IACTs with rapid slewing capability such as MAGIC, VERITAS or HESS and by the upcoming HAWC detector. If all long duration GRBs within $z \sim 0.1$ have dense stellar wind as modeled here, then the expected detection rate in upcoming TeV detector would be $\gtrsim 1$ burst yr^{-1}, using a GRB rate of 2 Gpc^{-3} yr^{-1}. HAWC would be sensitive for GRBs with $z \lesssim 0.2$, when distance and EBL effects become important.

In the context of the internal shock model, a prompt TeV emission signal will result from the first pair of colliding shells that form neutrons which escape and then interact with particles in the wind. As the merged shell moves out along the GRB jet, it sweeps up wind material, so that subsequent escaping neutrons will no longer have target wind particles with which to interact. The column density of material does not however change, so that neutrons formed by further pairs of colliding shells still have a significant target column density with which to interact and make TeV radiation. Thus the duration of the prompt TeV signal in this model corresponds to the duration of the prompt phase associated with colliding shells.

Predicted TeV γ-ray emission in the early afterglow phase, either by hadronic interactions (Böttcher & Dermer 1998) or synchrotron self-Compton (SSC) emission (Dermer, Chiang & Mitman 2000; Wang, Dai & Lu 2001; Zhang & Mészáros 2001), is expected to last much longer than the prompt TeV emission considered here. A leptonic SSC origin of TeV radiation formed by an external shock will correlate with the lower energy synchrotron radiation with a peak energy that becomes smaller as the blast wave decelerates. By contrast, the TeV emission formed by the process considered here will end when the central engine becomes inactive. The TeV γ-ray flux predicted in this work should correlate with the activity of the central engine as reflected by the MeV emission from a GRB, though delays could arise from the time required to accelerate protons to ultra-high energies. High-energies neutrinos are formed directly from photopion-producing interactions in the internal shocks (in the TeV–PeV energy range), as well as from pn interactions (in the PeV–EeV energy range) in the stellar wind. Joint detection of prompt high-energy neutrinos and prompt TeV radiation would provide a new method to probe the environment in the vicinity of GRBs.

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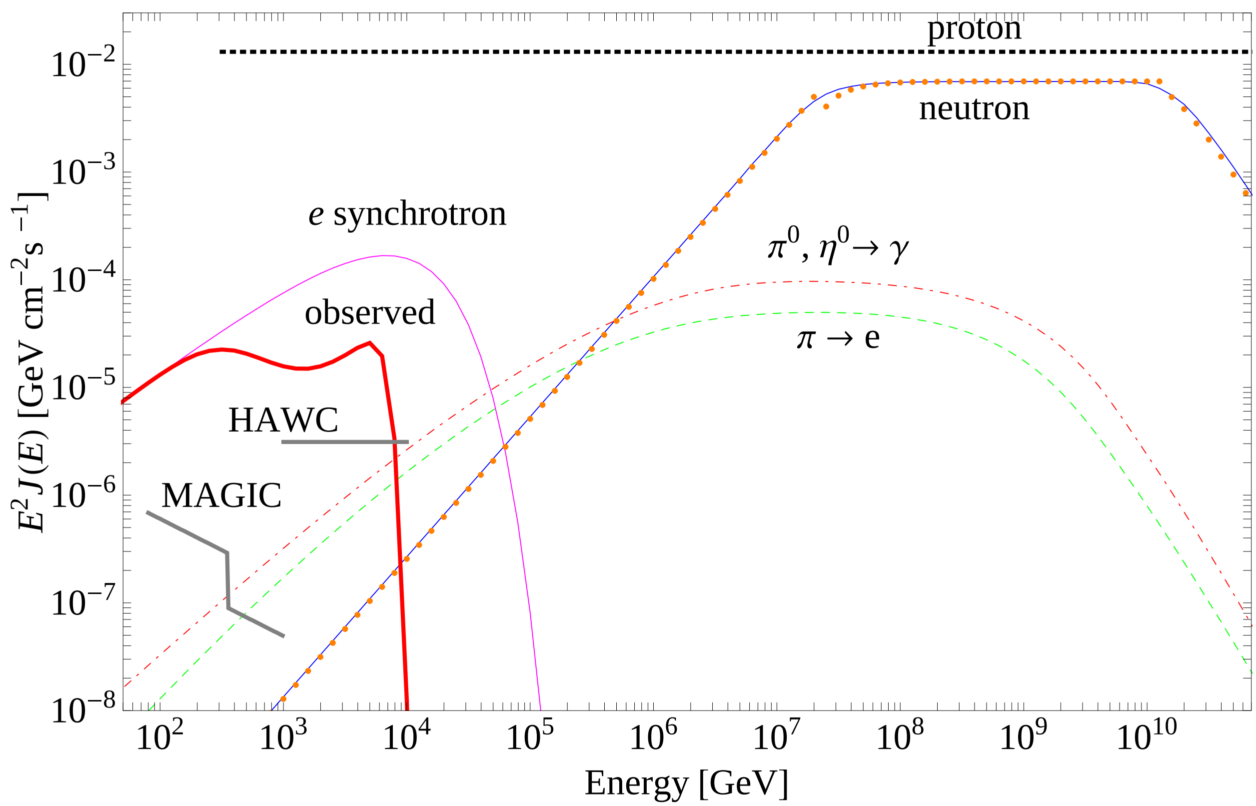

Fig. 1.— Spectra of shock-accelerated cosmic rays, neutrons escaping from the GRB fireball (thin solid line shows the numerical calculation using the full $p\gamma \to \Delta$ cross section formula, and the dots show equation (9) using a constant $p\gamma$ cross section), π^0 and η^0 decay γ-rays and $\pi^\pm$ decay electrons. The e synchrotron radiation is calculated from pion-decay electrons in the wind magnetic field, and the thick solid line is the emerging γ-ray spectrum after absorption in background radiation fields. Also plotted are the MAGIC and HAWC detector sensitivities.