Interpretation and implication of the non-detection of GeV spectrum excess by Fermi $\gamma$-ray Space Telescope in most GRBs

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ABSTRACT

Since the launch of the Fermi Gamma-ray Space Telescope on 11 June 2008, significant detections of high energy emission have been reported only in six Gamma-ray Bursts (GRBs) until now. In this work we show that the lack of detection of a GeV spectrum excess in almost all GRBs, though somewhat surprisingly, can be well understood within the standard internal shock model and several alternatives like the photosphere-internal shock (gradual magnetic dissipation) model and the magnetized internal shock model. The delay of the arrival of the $>100$ MeV photons from some Fermi bursts can be interpreted too. We then show that with the polarimetry of prompt emission these models may be distinguishable. In the magnetized internal shock model, high linear polarization level should be typical. In the standard internal shock model, high linear polarization level is still possible but much less frequent. In the photosphere-internal shock model, the linear polarization degree is expected to be roughly anti-correlated with the weight of the photosphere/thermal component, which may be a unique signature of this kind of model. We also briefly discuss the implication of the current Fermi GRB data on the detection prospect of the prompt PeV neutrinos. The influences of the intrinsic proton spectrum and the enhancement of the neutrino number at some specific energies, due to the cooling of pions (muons), are outlined.

Key words: gamma rays: bursts — polarization — radiation mechanism: nonthermal — acceleration of particles — elementary particles: neutrino

1 INTRODUCTION

Gamma-ray Bursts (GRBs) are the most extreme explosion discovered so far in the universe. With the discovery of the afterglows and then the measurement of the redshifts in 1997 (see van Paradijs et al. 2000, for a review), the cosmological origin of GRBs has been firmly established. The modeling of the late ($t > 10^3$ s) afterglow data favors the external forward shock model (see Piran 1999; Mészáros 2002; Zhang & Mészáros 2004, for reviews). The radiation mechanisms employed in the modeling are synchrotron radiation and synchrotron self-Compton (SSC) scattering. In the early time the prolonged activity of the central engine plays an important role in producing afterglow emission too, particularly in X-ray band (e.g., Katz et al. 1998; Fan & Wei 2005; Nousek et al. 2006; Zhang et al. 2006). The radiation mechanisms, remaining unclear, are assumed to be the same as those of the prompt soft gamma-ray emission. It is expected that in the Fermi era the origin of the prompt emission can be better understood. This is because the Large Area Telescope (LAT) and the Gamma-ray Burst Monitor (GBM) onboard Fermi satellite (http://fermi.gsfc.nasa.gov/) can measure the spectrum in a very wide energy band (from 8 keV to more than 300 GeV), with which some models may be well distinguished. For example, in the standard internal shock model the SSC radiation can give rise to a distinct GeV excess while in the magnetized outflow model no GeV excess is expected.

Motivated by the detection of some $>100$ MeV photons from quite a few GRBs by the Compton Gamma Ray Observatory satellite in 1991–2000 (e.g., Hurley et al. 1994; Fishman & Meegan 1995; González et al. 2003), the prompt high energy emission has been extensively investigated and most calculations are within the framework of the standard internal shocks (e.g., Pilia & Loeb 1998; Pe’er & Waxman 2004; Gupta & Zhang 2007; Bosnjak et al. 2009, cf. Giannios 2007). The detection prospect for LAT seems very promising (see Fan & Piran 2008, for a recent review).

Since the launch of Fermi satellite on 11 June 2008, significant detections of prompt high energy emission from GRBs have been only reported in GRB 080825C (Bouvier et al. 2008), GRB 080916C (Abdo et al. 2009), GRB 081024B (Omodei 2008), GRB 090323 (Ohno et al. 2009a), GRB 090328 (Cutini et al. 2009), possibly and GRB 090217 (Ohno et al. 2009a) until now (5 May 2009). Though the detection of 3 prompt photons above 10 GeV from GRB 080916C at redshift $z \sim 4.5$ (Abdo et al. 2009).
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Greiner et al. (2009) is amazing and may imply a very high initial Lorentz factor of the outflow \( \Gamma_i > 1800 \) and an efficient acceleration of particles to very high energy (Zou et al. 2009), the non-detection of a significant > 100 MeV emission from most GRBs may be a better clue of the underlying physics. A delay in the onset of the > 100 MeV emission with respect to the soft gamma-rays, as detected in GRB 080825C, GRB 080916C, GRB 081024B and GRB 090323, may be the other clue of the GRB physics (Abdo et al. 2009, Ohno et al. 2009b). In this work we focus on these two novel observational features.

This work is structured as the following. In section 2 we discuss the constraint of the current Fermi GRB data on the standard internal shock model and several alternatives. In section 3 we look for distinguished signals in linear polarization of the prompt emission. In section 4 we briefly discuss the implication of the current Fermi results on the detection prospect of PeV neutrinos from GRBs. We summarize our results in section 5.

2 INTERPRETING THE LACK OF GEV EXCESS IN MOST GRBS AND THE DELAY OF THE ARRIVAL OF THE > 100 MEV PHOTONS

In the leading internal shock model for the prompt emission (Narayan et al. 1992, Paczynski & Xu 1994, Rees & Mészáros 1994, Dai & Mochkovitch 1998), the ultra-relativistic outflows are highly variable. The faster shells ejected at late times catch up with the slower ones ejected earlier and then power energetic forward/reverse shocks at a radius \( R_{\text{int}} \sim 5 \times 10^{13} \left( \Gamma_i/300 \right) \left( \delta \tau/10 \text{ ms} \right) \) cm, where \( \Gamma_i \) is the initial Lorentz factor of the outflow and \( \delta \tau \) is the intrinsic variability timescale. Part of the shock energy has been used to accelerate electrons and part has been given to the magnetic field. If the outflow is magnetized (Usو 1992, Duncan & Thompson 1992, Lyutikov & Blandford 2003, Giannios & Spruit 2005b), we call the shocks generated in the collisions within the outflow the magnetized internal shocks (Spruit et al. 2001, Fan et al. 2004a). The synchrotron radiation of the shock-accelerated electrons may peak in soft gamma-ray band and then account for the observed prompt emission. This model has been widely accepted for the following good reasons: (1) For an ultra-relativistic outflow moving with an initial Lorentz factor \( \Gamma_i \), the velocity (in units of \( c \)) is \( \beta_v = \sqrt{1 - 1/\Gamma_i^2} \). A small velocity dispersion \( \delta \beta_v \sim \beta_v/(2 \Gamma_i^2) \) will yield a very different Lorentz factor. As a result, internal shocks within the GRB outflow seem inevitable. (2) In the numerical simulation of the collapsar launching relativistic outflow, people found highly variable energy deposition in the polar regions in a timescale as short as ~ 50 ms (MacFadyen & Woosley 1999). (3) This model can naturally account for the variability that is well detected in prompt gamma-ray emission (Kobayashi et al. 1997). On the other hand, this model usually predicts a fast cooling spectrum \( F_{\nu} \propto \nu^{-1/2} \) in the X-ray band. However, the data analysis finds a typical X-ray spectrum \( F_{\nu} \propto \nu^0 \) (Preece et al. 2000, Band et al. 1993). Such a divergence between the model and the observation data is the so-called “the low energy spectral index crisis” (Ghisellini & Celotti 1999). Another potential disadvantage of the internal shock model is its low efficiency of converting the kinetic energy of the outflow into prompt emission (e.g., Kumar 1999). Among the various solutions put forward, a plausible scenario is the photosphere-internal shock model (e.g. Rees & Mészáros 2003, Pe’er et al. 2006, Thompson et al. 2007). The idea is that the thermal emission leaking from the photosphere is the dominant component of the prompt sub-MeV photons (Thompson 1994, Mészáros & Rees 2003, Preece et al. 2007). The nonthermal high energy emission is likely the external inverse Compton (EIC) radiation of the internal shock-accelerated electrons cooled by the thermal photons from the photosphere (Rees & Mészáros 2003, Pe’er et al. 2005, 2006, Thompson et al. 2007). If the electrons are accelerated by gradual magnetic energy dissipation rather than by internal shocks, it is called the photosphere-gradual magnetic dissipation model (Giannios 2007). There is an increasing interest in these two kinds of models since: (1) In the spectrum analysis people did find evidences for a thermal emission component in dozens of bright GRBs (Ryde 2003, Ryde et al. 2006, Ryde & Pe’er 2009, McGlynn et al. 2009). (2) The emission from the photosphere can naturally account for the temporal behaviors of the temperature and flux of these thermal radiation (Pe’er 2008). (3) The overall spectrum of the prompt emission can be reasonably interpreted (e.g., Pe’er et al. 2006, Giannios 2007). (4) The GRB efficiency can be much higher than that of the internal shock model (see Ryde & Pe’er 2009, and the references therein).

In this section we test these four models with the current Fermi GRB data. It is somewhat surprisingly to see that none of these models have been ruled out.

2.1 Explaining the lack of GeV spectrum excess in most GRBs

2.1.1 The standard internal shock model

In this model, the outflow is baryonic and the thermal emission during the initial acceleration of the outflow is ignorable. The prompt emission is powered by energetic internal shocks. There are three basic assumptions. (i) \( \epsilon_e, \epsilon_B, \epsilon_p \) fractions of shock energy have been given to electrons, magnetic field and protons, respectively (note that \( \epsilon_e + \epsilon_B + \epsilon_p = 1 \)). (ii) The energy distribution of the shock-accelerated electrons is a single power-law. (iii) The prompt soft gamma-ray emission is attributed to the synchrotron radiation of the shocked electrons.

For internal shocks generating at \( R_{\text{int}} \), the typical random Lorentz factor of the electrons can be estimated as (see section 4.1.1 of Fan & Piran (2008) for details)

\[
\gamma_{e,m}^{'(ssc)} \sim 760 \left( 1 + Y_{\text{acc}} \right)^{1/4} L_{\text{syn},13}^{-1/4} m_{\text{int},13}^{1/2} (1+z)^{1/2} (\epsilon_p/300 \text{ keV})^{1/2},
\]

where \( \epsilon_p = h\nu_{\text{em}} \) is the observed peak energy of the synchrotron-radiation spectrum \((\nu F_{\nu})\), \( h \) is the Planck’s constant, \( L_{\text{syn}} \) is the synchrotron-radiation luminosity of the internal shock emission, \( Y_{\text{acc}} \sim 1 + \sqrt{1 + 4\epsilon_e/(1 + q^2\epsilon_B)} / 2 \) is the regular SSC parameter \( \gamma_{e,m}^{'(ssc)} \) (Sari & Esin 2001, Fan & Piran 2008, Piran et al. 2009), and \( \gamma_{e,m}^{'(ssc)} \sim \gamma_{e,m} \epsilon_e \Gamma_i/\Gamma e, \epsilon_p, \rho \). The SSC in the extreme Klein-Nishina regime \((g \gg 1)\) is very inefficient. If that happens the non-detection of GeV spectrum excess in most Fermi GRBs can be naturally explained. With the typical parameters adopted in eq. (1), we have \( g \sim 1 \), for which the SSC may still be important (i.e., \( Y_{\text{acc}} \gg 1 \)). In this work the convenience \( Q_s = Q/10^8 \) has been adopted in cgs units except for some specific notations.

The SSC radiation will peak at

\[
h\nu_{\text{in,ssc}} \sim \frac{2\gamma_{e,m} \epsilon_p}{1 + 2g} \sim 220 \text{GeV (1 + 2g)}^{-1/2} \left( 1 + Y_{\text{acc}} \right)^{1/2} L_{\text{syn},13}^{-1/2} R_{\text{int},13} (1+z) (\epsilon_p/300 \text{ keV})^{1/2}.
\]

Taking into account the energy loss of the electrons via in-
verse Compton scattering on prompt soft gamma-rays, the cooling Lorentz factor can be roughly estimated as

$$\gamma_e' \sim \frac{0.03 L_{\text{syn},52} R_{\text{int},15} \Gamma_{2.5}^2}{h \nu_{\text{cut}}}.$$  (3)

In reality, $\gamma_e'$ is always larger than 1. The derived $\gamma_e' < 1$ just means that the electrons have lost almost all their energies and are sub-relativistic.

Prompt high energy photons above the cut-off frequency $h\nu_{\text{cut}}$ will produce pairs by interacting with softer photons and will not escape from the fireball. Following Lüthi & Sari (2001) and Fan & Piran (2008), we have

$$h\nu_{\text{cut}} \approx 2 \text{ GeV} (1 + z)^{-1} \left(\frac{e_0}{300 \text{ keV}}\right)^{(2-p)/p} L_{\text{syn},52}^{-1} \Gamma_{2.5}^{-2}/\delta \nu_c^{-1/2} \left(\frac{2(p+8)}{p}\right)^{1/2}.$$  (4)

The SSC radiation spectra can be approximated by $F_{\nu,\text{ssc}} \propto \nu^{-\frac{1}{2}}$ for $\nu_m < \nu < \nu_{\text{in,ssc}}$, and $F_{\nu,\text{ssc}} \propto \nu^{-p/2}$ ($F_{\nu,\text{ssc}} \propto \nu^{-p}$) for $\nu > \nu_{\text{in,ssc}}$ and $g \leq 1$ ($g \gg 1$). The energy ratio of the SSC radiation emitted below $h\nu_{\text{cut}}$ to the synchrotron radiation in the energy range $\nu_m < \nu < \nu_{\text{cut}}$ can be estimated as

$$\frac{R}{\nu_{\text{ssc},1/2}^{(2-p)/2} \int_{\nu_{\text{in,ssc}}}^{\nu_{\text{cut}}} \nu^{-1/2} d\nu} \approx \frac{(p-2)(\nu_{\text{cut}}/\nu_{\text{ssc},1/2})^{1/2} Y_{\text{ssc}}}{\nu_{\text{in,ssc},1/2} \int_{\nu_{\text{in,ssc}}}^{\nu_{\text{cut}}} \nu^{-2} d\nu}.$$  (5)

where $\nu_{\text{ssc}} \approx 30 \nu_s(1 + z)^{-1}$ MeV is the maximal synchrotron radiation frequency of the shocked electrons (Cheng & Wei 1996).

For $Y_{\text{ssc}} \sim 1$, $p \approx 2.5$ (corresponding to the typical $\gamma$--ray spectrum $F_\gamma \propto \nu^{-1.25}$ for $h\nu > e_0$) and $\nu_{\text{cut}} \leq \nu_{\text{in,ssc}}$, we have $R \ll 1$. Therefore there is no GeV excess in the spectrum, in agreement with the data. In other words, the non-detection of a significant high energy component is due to a too large $h\nu_{\text{in,ssc}} \sim \text{TeV}$ and a relative low $h\nu_{\text{cut}} \sim \text{GeV}$ (see Fig.1 for a schematic plot). The other possibility is that $1 + g^2 e_0 < 4e_0$, for which $Y_{\text{ssc}} \sim O(1)$, i.e., the SSC radiation is unimportant and can be ignored.

### Figure 1.

A possible interpretation of the non-detection of the SSC component by Fermi satellite in the internal shock model. The high energy photons with an energy $> h\nu_{\text{cut}}$ have been absorbed by the soft gamma-rays and energetic $e^+e^-$ pairs are formed. The pairs will lose their energy through synchrotron radiation and/or inverse Compton scattering and then produce soft gamma-rays.

2.1.2 The photosphere—internal shock model

Thompson (1994) proposed the first photosphere model for the prompt gamma-ray emission, in which the nonthermal X-ray and gamma-ray emission are attributed to the Compton upscattering of the thermal emission by the mildly relativistic Alfvén turbulence. The spectra of GRBs can be nicely reproduced (see also Pe’er et al. 2006; Giannios 2007). It is, however, difficult to explain the energy dependence of the width of the gamma-ray pulse (Fenimore et al. 1995; Norris et al. 1996). As shown in Thompson et al. (2007), such a puzzle may be solved in the photosphere—internal shocks model, in which the sub-MeV emission is dominated by the thermal emission of the fireball and the nonthermal tail is the EIC radiation of the electrons accelerated in internal shocks at a radius $R_{\text{int}} \sim 10^{14}$ cm (e.g., Mészáros & Rees 2004; Rees & Mészáros 2005; Pe’er et al. 2006). In this model the shock accelerated-electrons take a power-law energy distribution $dn/d\gamma_e \propto \gamma_e^{-p+1}$ for $\gamma_e \gg \gamma_{e,\text{in}} \sim 1$. Such an initial distribution can not keep if the electrons cool down rapidly. As shown in Sari et al. (1998), in the presence of steady injection of electrons, the energy distribution can be approximated by $N_{\nu_m} \propto \gamma_e^{-p+1}$ for $\gamma_e > \max(\gamma_{e,\text{in}}, \gamma_{e,m})$ and $N_{\nu_m} \propto \gamma_e^{-1}$ for $\gamma_{e,\text{in}} < \gamma_e < \gamma_{e,m}$. Under what conditions can shock acceleration generate a particle distribution with $\gamma_e \sim 1$, with a significant fraction of the outflow energy deposited in the nonthermal particles? There could be two ways. One is to assume that electron/positron pair creation in the outflow is so significant that the resulting pairs are much more than the electrons associated with the protons. As a result, the fraction of shock energy given to each electron/positron will be much smaller than that in the case of a pair-free outflow and a $\gamma_{e,m} \sim 1$ is achievable (Thompson et al. 2007). The other way is to assume that the particle heating is continuous. In the internal shock scenario, this could happen if an outflow shell consists of many sub-shells and the weak interaction between these sub-shells may be able to produce multiple shocks that can accelerate electrons continually with a very small $\gamma_{e,m}$.

Since both $\gamma_{e,m}$ and $\gamma_e' \sim 1$, the EIC spectrum should be $F_{\nu_m} \propto \nu^{-p/2}$ in the MeV-TeV energy range and there is no GeV excess for $p \sim 2.5$, consistent with the Fermi data.

### 2.1.3 The magnetized internal shock model

If the unsteady GRB outflow carries a moderate/small fraction of magnetic field, the collision between the fast and slow parts will generate strong internal shocks and then produce energetic soft gamma-ray emission. As usual, the ratio between the magnetic energy density and the particle energy density is denoted as $\sigma$. In the ideal MHD limit, for $\sigma \gg 1$ just a very small fraction of the upstream energy can be converted into the downstream thermal energy. Therefore the GRB efficiency is very low. That’s why peo-
ple concentrate on the internal shocks with a magnetization $\sigma \leq 1$ (Spruit et al. [2001], Fan et al. [2004b]). For the magnetized internal shocks with $\sigma \gg 1$, no significant high energy emission is expected since: (a) The SSC emission of the internal shocks is weak. Therefore there is no distinct GeV excess in the spectrum. (b) The synchrotron-radiation spectrum may be very soft, which renders the detection of GeV photons from GRBs more difficult. The reason is the following. For an isotropic diffusion and a relativistic shock, the electron energy distribution index can be estimated by (Keshet & Waxman [2005])

$$p \sim \frac{3\beta_0 - 2\beta_0\beta_i^2 + \beta_i^4}{(\beta_0 - \beta_i)} - 2.$$  \hspace{1cm} (6)

However, in the presence of a large scale coherent magnetic field, the diffusion is highly anisotropic rather than isotropic (Morlino et al. [2007a]). There are thus corrections to eq. (6). But as long as the scattering is not very forward- or backward-peaked, these corrections are small (Keshet [2004]). Taking into account the anisotropic correction, Morlino et al. (2007b) found a spectrum steep to $p \sim 3$ for $\sigma \sim 0.05$. In the ion-electron shock simulation, the acceleration of particles at the unmagnetized shock front is a lot more efficient than that with a $\sigma \sim 0.1$ (Sironi & Spitkovsky [2009]). Motivated by these two possible evidences, we adopt eq. (6) to estimate the spectral slope of accelerated particles at the magnetized shock fronts. The validity of our approach can be tested by the advanced numerical simulations in the future.

In the case of $\sigma = 0$, for an ultra-relativistic shock, $\beta_0 \rightarrow 1$ and $\beta_1 \rightarrow 1/\beta_0$, we have $p \rightarrow 2.22$. But for an ultra-relativistic magnetized shock, $\beta_0 \rightarrow 1$ and (e.g., Fan et al. [2004b])

$$\beta_1 \approx \frac{4}{6} \left(1 + \chi \sqrt{1 + 14\chi + \chi^2}\right).$$  \hspace{1cm} (7)

where $\chi \equiv \sigma/(1 + \sigma)$, please note that $\sigma$ is measured in the upstream. Note in this work we just discuss the ideal MHD limit, i.e., there is no magnetic energy dissipation at the shock front. For $0 < \sigma < 1$, we have $p \sim 4\beta_0^2/\beta_0 - 2 > 2.22$. For $\sigma \gg 1$, we have $\beta_1 \sim 1 - 1/2\beta_0$ and $p \sim 4\sigma - 1 \gg 2.22$. Correspondingly, the electron spectrum is very soft or even thermal-like. Adopting $\beta_1 \sim 1$ and substituting $\sigma \sim (1, 0.5, 0.1, 0.01)$ into eqs. (7), we have $p \sim (6.6, 4.5, 2.7, 2.3)$. The (very) soft high energy spectra of some GRBs (e.g., Preece et al. [2004]; see also our Fig. 2 for the Fermi GRBs) may be interpreted in this way.

If the high prompt high energy emission of GRBs is indeed attributed to the magnetization of the outflow, one can expect that the smaller the $p$, the stronger the high energy emission. The ongoing analysis of the LAT data will test such a correlation.

2.1.4 The photosphere—gradual magnetic dissipation model

**Giannios** [2007] calculated the emission of a Poynting-flux-dominated GRB outflow with gradual magnetic energy dissipation (reconnection). In his scenario, the energy of the radiating electrons is determined by heating and cooling balance. The mildly relativistic electrons stay thermal throughout the dissipation region because of Coulomb collisions (Thomson thick part of the flow) and exchange of synchrotron photons (Thomson thin part). Rather similar to Thompson [1994], the resulting spectrum naturally explains gamma-rays have an energy $\gamma'_e\varepsilon_0 \Gamma_\gamma \gg m_0c^2$, i.e., the SSC is in the extreme Klein-Nishina regime and is very inefficient. The non-detection of high energy emission from most GRBs is, of course, consistent with this model.

The observed sub-MeV break of the GRB emission and the spectral slopes. In this scenario, different from the magnetized internal shock model, the higher the initial $\sigma$, the harder the spectrum (see the Fig. 2 of Giannios [2007] for illustration). For an initial $\sigma \approx 40$ (corresponding to the baryon loading $L/\dot{M}c^2 \sim \sigma^{3/2} \approx 250$, where $M$ is the mass loading rate), the resulting $\Gamma > 10 \text{ MeV}$ spectrum is very soft (see also Drenkhahn [2002], Drenkhahn & Spruit [2002], accounting for the failed detection of the GeV spectrum excess in most GRBs.

2.2 Interpreting the delay of the arrival of the $> 100 \text{ MeV}$ photons

In both the collapsar and the compact star merger models for GRBs (see Piran [1999], Mészáros [2002], Zhang & Mészáros [2004], for reviews), the early outflow may suffer more serious baryon pollution and thus have a smaller $\Gamma_1$ than the late ejecta (Zhang, Woosley & MacFadyen [2004]). This may explain the delay of the arrival of the $> 100 \text{ MeV}$ emission since as long as

$$\Gamma_i \leq \Gamma_{i,c} = 180 \left(1+z\right) \frac{\rho}{\rho_{\text{crit}}} \left(\frac{h\nu}{100 \text{ MeV}}\right)^\frac{\rho}{\rho_{\text{crit}}} \left(\frac{\varepsilon_p}{300 \text{ keV}}\right)^\frac{\rho+2}{\rho-2} \Gamma_{\text{esc}} \delta t_{\nu,2} \frac{1}{\Gamma_{i,c}},$$

the $>100 \text{ MeV}$ photons can not escape from the emitting region freely and thus can not be detected.

In the photosphere-gradual magnetic dissipation model, a small $\Gamma_1$ implies a low initial magnetization of the outflow, for which the high energy spectrum can be very soft (Drenkhahn & Spruit [2002], Giannios [2007]). In the magnetized internal shock model, the delay of the onset of the LAT observation indicates a larger magnetization of the early internal shocks if $\Gamma_i > \Gamma_{i,c}$.

In the collapsar scenario, before the breakout, the initial outflow is choked by the envelope material of the massive star (Zhang
et al. 2004). The ultra-relativistic reverse shock may be able to smooth out the velocity/energy-density dispersion of the initial ejecta. So the internal shocks generated within the early/breakout outflow may be too weak to produce a significant non-thermal radiation component. The early emission is then dominated by the thermal component from the photosphere and may last a few seconds (provided that the chocked material has a width comparable to that of the envelope of the progenitor). The outflow launched after the breakout of the early ejecta can escape from the progenitor freely and the consequent internal shocks can be strong enough to produce energetic non-thermal radiation. The photosphere-internal shock model therefore might be able to naturally account for the delay in the onset of the LAT observation.

In summary, before and after the onset of the $>100$ MeV emission, it seems the physical properties of the outflow have changed.

### 3 THE LINEAR POLARIZATION SIGNAL OF THE PROMPT $\gamma$-RAY EMISSION

As discussed in section 2, the failed detection of the GeV spectrum excess in most GRBs can be understood in either the standard internal shock model or several alternatives. Therefore we need independent probes to distinguish between these scenarios. Our current purpose is to see whether the polarimetry in gamma-ray band can achieve such a goal. In this section, we firstly investigate the linear polarization property of the photosphere-internal shock model (the results may apply to the photosphere-gradual magnetic dissipation model as well) since it has not been reported by others yet. We then briefly discuss the linear polarization signals expected in the magnetized internal shock model and in the standard internal shock model since they have been extensively discussed in the literature (e.g., Lyutikov et al. 2003; Granot 2003; Waxman 2003; Nakar et al. 2003; Fan et al. 2008; Toma et al. 2009).

#### 3.1 Linear polarization signal of the photosphere-internal shock model

In this work we assume an uniform outflow. At any point in the outflow there is a preferred direction, the radial direction, in which the fluid moves. We choose this $Z'$-direction of the fluid local frame coordinate to be in that direction. The $Y'$-direction is chosen to be within the place containing the line of sight (i.e., the scattered photon $k_0'$) and the $Z'$-axis (see Fig.3). In this frame, the incident photons ($k'$) are along the $Z'$-direction.

As usual, we assume that the electrons are isotropic in the comoving frame of the emitting region. The incident photons are the thermal emission from the photosphere and are unpolarized.

\[ A \equiv \frac{1}{2\pi} = \frac{1}{\gamma} \frac{1}{\gamma'} = \frac{2}{\gamma^2} \]

\[ B \equiv \frac{1}{\gamma^2} \frac{1}{\gamma'} = \frac{2}{\gamma^3} \]

\[ T_1 = \frac{1}{Q^2} \frac{1}{\gamma^2} \frac{1}{\gamma'} = \frac{2}{\gamma^4} \]

\[ T_2 = \frac{1}{Q^2} \frac{1}{\gamma^2} \frac{1}{\gamma'} = \frac{2}{\gamma^3} \]

\[ \theta \equiv \frac{1}{\gamma^2} \frac{1}{\gamma'} = \frac{2}{\gamma^3} \]

\[ \delta \equiv \frac{1}{\gamma^2} \frac{1}{\gamma'} = \frac{2}{\gamma^3} \]

Please note that $x$ ranges from $x_m$ to $x_m$ that are given by

\[ x_m = 1 + \frac{\sqrt{1 + x^2 - 2x \cos \theta'}}{1 - \cos \theta'} = \frac{1}{\gamma^2} \frac{1}{\gamma'} = \frac{2}{\gamma^3} \]

\[ \delta = \frac{1}{\gamma^2} \frac{1}{\gamma'} = \frac{2}{\gamma^3} \]

\[ \theta = \frac{1}{\gamma^2} \frac{1}{\gamma'} = \frac{2}{\gamma^3} \]

\[ \delta = \frac{1}{\gamma^2} \frac{1}{\gamma'} = \frac{2}{\gamma^3} \]

\[ P \approx \frac{A_0}{A_0^2} \frac{1}{B_0^2} \]

For the relativistic electrons (i.e., $\beta_0 \rightarrow 1$), eq. (8) and eq. (11) take the simplified forms

\[ \frac{dN_\gamma}{d\nu d\Omega} \approx \frac{3\pi c n_e\nu_e}{16\pi^2 M^2 c^2} \nu_{\text{esc}} \left[ 1 + \frac{1}{2(1 - \xi)} \frac{1}{B_0(1 - \xi)} + \frac{4\xi^2}{B_0^2(1 - \xi)^2} \right] \]

or

\[ \frac{dN_\gamma}{d\nu d\Omega} \approx \frac{3\pi c n_e\nu_e}{16\pi^2 M^2 c^2} \nu_{\text{esc}} \left[ 1 + \frac{1}{2(1 - \xi)} \frac{1}{B_0(1 - \xi)} + \frac{4\xi^2}{B_0^2(1 - \xi)^2} \right] \]

\[ \frac{dN_\gamma}{d\nu d\Omega} \approx \frac{3\pi c n_e\nu_e}{16\pi^2 M^2 c^2} \nu_{\text{esc}} \left[ 1 + \frac{1}{2(1 - \xi)} \frac{1}{B_0(1 - \xi)} + \frac{4\xi^2}{B_0^2(1 - \xi)^2} \right] \]
where $\xi \equiv h\nu/(\gamma'_e m_e c^2)$, $b_0 = 2(1 - \cos \theta')\gamma'_e h\nu'_e/(m_e c^2)$, and $h\nu'_e \ll h\nu \leq \gamma'_e m_e c^2b_0/(1 + b_0)$.  

Since the emitting region is moving relativistically, the angle $\theta'$ (in Fig. 4) corresponding to the line of sight (L.o.S) is given by

$$\cos \theta' = (\cos \theta - \beta)/(1 - \beta \cos \theta),$$

where $\theta$ is the angle between the line of sight and the emitting point (measured in the observer’s frame).

The azimuthal angle $\phi$ varying from 0 to $2\pi$ is defined in Fig. 4. The polar angle $\theta$ ranges from 0 to $\theta_v + \theta_e$. The angle between the vector $(\sin \theta \cos \phi, \sin \theta \sin \phi, \cos \theta)$ and the central axis of the ejecta (C.A. in Fig. 4) is denoted as $\Theta$ and is given by

$$\cos \Theta = -\sin \theta_v \sin \phi + \cos \theta_v \cos \phi.$$

Please bear in mind that in the following radiation calculation, the flux is set to be zero if $\cos \Theta < \cos \theta_v$ because these points $(\theta, \phi)$ are outside of the cone of the ejecta.

The EIC radiation flux in the observer frame is

$$F_{\nu,\text{EIC}} \propto \int D^3 h\nu' d\nu' d\Omega',$$

where $\nu = D\nu'/(1 + z)$, $D = [\Gamma_i(1 - \beta \cos \theta)]^{-1}$ is the Doppler factor, and $\Omega$ is the solid angle satisfying $d\Omega = \sin \theta d\theta d\phi$.

The polarized radiation flux is

$$Q_{\nu,\text{EIC}} \propto \int D^3 h\nu' P \cos 2\phi d\nu' d\phi,$$

where $P = |Q_{\nu,\text{EIC}}|/F_{\nu,\text{EIC}}$.  

The polarization degree of the EIC emission is

$$P_{\nu,\text{EIC}} = |Q_{\nu,\text{EIC}}|/F_{\nu,\text{EIC}}.$$
thermal components. The thermal component with the flux $F_{\nu, \text{th}}$ is expected to be unpolarized while the nonthermal EIC component may have a high linear polarization level. The observed polarization degree

$$P_{\nu, \text{obs}} = \frac{|Q_{\nu, \text{EIC}}|}{F_{\nu, \text{EIC}} + F_{\nu, \text{th}}}$$

should be strongly frequency-dependent. Roughly speaking, the linear polarization degree is anti-correlated with the weight of the thermal component. With an energy $\sim kT$, the emission is dominated by the thermal component and $P_{\nu, \text{obs}}$ is low. For $h\nu \gg kT$, the emission is dominated by the EIC component and $P_{\nu, \text{obs}} \sim P_{\nu, \text{EIC}}$, as illustrated in Fig.6. This unique behavior can help us to distinguish it from other models.

The probability of detecting a moderate/high linear polarization degree ($R_{\text{pol}}$), however, is not high (Please note that we do not take into account the weak events for which a reliable polarimetry is impossible). On the one hand, a high linear polarization level is achievable only for $\theta_e \gg 1/3\Gamma_i$. On the other hand, $\theta_e - \theta_i \leq 1/\Gamma_i$ is needed otherwise the burst will be too weak to perform the gamma-ray polarimetry. For $\Gamma_i \theta_i \gg 1$, we have

$$R_{\text{pol}} \sim 4/(3\Gamma_i \theta_i) \approx 5\% \Gamma_i^{-1} \theta_i^{-1}. \quad (20)$$

During the revision of this work, McGlynn et al. (2009) reported their analysis on the spectrum and the polarization properties of GRB 061122. They found out that the spectrum was better fitted by the superposition of a thermal and a non-thermal components and the photons in the “thermal” emission dominated energy range had a (much) lower polarization level than those in the higher energy band. These two characters are in agreement with the photosphere-internal shock model (or the photosphere-gradual magnetic dissipation model).

### 3.2 Linear polarization level expected in the standard internal shock model

In the standard internal shock model, the polarization of the synchrotron radiation depends on both the poorly known configuration of magnetic field generated in internal shocks and the geometry of the visible emitting region. Assuming a random magnetic field that remains planar in the plane of the shock, Waxman (2003) and Nakar et al. (2003) showed that a high linear polarization level can be obtained when a narrow jet is observed from the edge, like in the photosphere-internal shock model. For the jets on-axis ($\theta_e \leq \theta_i$), the linear polarization degree is low (see also Gruzinov 1999 and Toma et al. 2009). The detection probability of a moderate/high linear polarization degree can also be estimated by eq. (20).

### 3.3 High linear polarization degree expected in the magnetized internal shock model

For the magnetized internal shock model, the prompt soft $\gamma$-ray emission is attributed to the synchrotron radiation of the electrons in ordered magnetic field and a high linear polarization level

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4 For the synchrotron radiation of the electrons moving in a random magnetic field (the standard internal shock model) or in an ordered magnetic field (e.g., the magnetized internal shock model), before and after the peak of the spectrum, the polarization degree changes because the polarization properties depend on the profile of the spectrum. However, such a dependence is weak, as shown in Granot (2003).

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#### Fermi GRBs: Interpretation and Implication

| Model                              | Unique Polarization Property | $R_{\text{pol}}$ |
|------------------------------------|------------------------------|------------------|
| Standard internal shocks           |                              | $\lesssim 10\%$  |
| Photosphere-internal shocks\(^1\)  | Strongly frequency-dependent$^\ddagger$ | $\lesssim 10\%$  |
| Magnetized internal shocks         |                              | $\sim 100\%$    |

\(^1\)In the photosphere-gradual magnetic dissipation model, very similar polarization properties are expected.

\(^\ddagger\)As shown in Fig.6, the polarization degree is anti-correlated with the weight of the photosphere/thermal component.

As summarized in Table 1, for the magnetized internal shock model, a high linear polarization level should be typical, while for two other models a moderate/high linear polarization degree is still possible but much less frequent. So the statistical analysis of the GRB polarimetry results may be able to distinguish the magnetized internal shock model from the others (see also Toma et al. 2009). In the photosphere-internal shock model the polarization degree is expected to be strongly frequency-dependent. Such a remarkable behavior, if detected, labels its physical origin.

Indeed there were some claims of the detection of high linear polarization degree in the soft $\gamma$-ray emission of GRB 021206 (Coburn & Boggs 2003; however see Rutledge & Fox 2004), GRB 930131, GRB 960924 (Willis et al. 2005), GRB 041219A (McGlynn et al. 2007; Gotz et al. 2009), and GRB 061122 (McGlynn et al. 2009). These results are consistent with each other as the errors are very large. The situation is inconclusive and additional data is needed to test these results. Measuring polarization is of growing interest in high energy astronomy. New technologies are being invented, and several polarimeter projects are proposed, such as, in the gamma-ray band, there are the Advanced Compton Telescope Mission (Boggs et al. 2008), POET (Hill et al. 2008) and others (see Toma et al. 2009 for a summary). So in the next decade reliable polarimetry of GRBs in gamma-ray band may be realized and we can impose tight constraint on the models. At present, the most reliable polarimetry is in UV/optical band (e.g.,
The optical polari
ty of the prompt emission and the reverse shock emission require a quic
c response of the telescope to the GRB alert. This is very challeng
ing. Mundell et al. (2007) reported the optical polarization of the afterglow, at 203 sec after the initial burst of $\gamma$-rays from GRB 060418, using a ring polarimeter on the robotic Liverpool Tele
scope. Their robust (90% confidence level) upper limit on the per
centage of polarization, less than 8%, coincides with the fireball deceleration time at the onset of the afterglow. Such a null detect
tion is, however, not a surprise because for this particular burst the reverse shock emission is too weak to outshine the unpolarized for
tward shock emission (Jin & Fan 2007). Quite recently, the robotic Liverpool Telescope performed the polarimetry measurement of the reverse shock emission of GRB 090102 (Kobayashi 2009, private communication). Following Fan et al. (2002), Zhang et al. (2003) and Kumar & Panaitecu (2003), it is straightforward to show that the reverse shock of GRB 090102 is magnetized. Consequently the optical flash is expected to be highly polarized. If confirmed in the ongoing data analysis, the magnetized outflow model for some GRBs will be favored.

4 IMPLICATION ON THE DETECTION PROSPECT OF PEV NEUTRINO EMISSION

The site of the prompt $\gamma$-ray emission may be an ideal place accelerating protons to ultra-high energy (Vietri 1995; Waxman 1995). These energetic protons can produce high-energy neutrinos via photomeson interaction, mainly through $\Delta$-resonance (Waxman & Bahcall 1997). The resulting neutrinos have a typical energy $E_{\nu, obs} \sim 5 \times 10^{14} E_{\gamma, 2000} \Gamma_{sh}^{-2} \left[ 1 + z \right] \epsilon_{\gamma, obs} / 1 \text{MeV}^{-1}$. Significant detections are expected if GRBs are the main source of ultra-high energy cosmic rays (Waxman & Bahcall 1997). The underlying assumption is that the proton spectrum is not significantly softer than $dN/dE \propto E^{-2}$. The current Fermi observations do not provide an observational evidence for such a flat particle spectrum. Below we discuss the detection prospect of PeV neutrinos implicated by the non-detection of high energy emission from most GRBs. In the magnetized outflow model, the accelera
tion of a significant part of protons to energies $\gtrsim 10^{19}$ eV is highly questionable because of the resulting soft proton spec
trum. In the photosphere-internal shock model, $\gamma_{\epsilon, m} \sim 1$ is needed (Thompson et al. 2007). The efficiency of accelerating protons to very high energy depends on the mechanism of the particle heating. For example, in the case of multiple internal shocks, each pair of internal shocks are expected to be very weak since $\Gamma_{sh} - 1 \sim 0.04 \left[ \gamma_{\epsilon, m} / 5 \right] \left[ \epsilon_{\gamma, 0} / 0.2 \right]^{-1} \left[ 3p - 2 \right] / \left[ p - 1 \right]^{-1}$, where $\Gamma_{sh}$ is the Lorentz factor representing the strength of the shock ($\Gamma_{sh} \sim 1$ for Newtonian shocks). So the acceleration of the protons to ultra-high energy is less efficient than the standard internal shocks. This is particularly the case if the acceleration is mainly via second-order Fermi process, in which the acceleration of particles depends on the shock velocity sensitively.

Even in the standard internal shock model, the generation of $10^{20}$ eV protons and the production of PeV-EeV neutrinos may be not as promising as that claimed in most literature adopting a proton spectrum $dN/dE \propto E^{-2.25}$ that is predicted in the relativistic shock acceleration model (the First-order Fermi mechanism), the kinetic energy of the ejecta needs to be $\sim 100$ times of the $\gamma$-ray radiation energy if GRBs are indeed the main source of the observed $\sim 10^{20}$ eV cosmic rays (see Dermer 2008, and the reference therein). In other words, the GRB efficiency should be as low as $\sim 1\%$. If correct, the number of protons at $E \sim 10^{16}$ eV will be quite a few times what assumed in Guetta et al. (2004). Correspondingly the PeV neutrino flux will be higher. However, the current afterglow modeling usually yields a typical GRB efficiency $\sim 10\%$ (e.g., Fan & Pirani 2006; Zhang et al. 2007), or larger (e.g., Panaitecu & Kumar 2003, Granot et al. 2006). Below we discuss a new possibility—The proton spectrum is curved. In the “low-energy” part, the spectrum may be steepened signif
icantly by the leakage of the very high energy cosmic rays from the ejecta (see Hillas 2003, and the references therein). The “high-energy” spectrum part may be a lot flatter. For example, in the numerical simulation of cosmic rays accelerated in some supernova remnants, a spectrum $dN/dE \propto E^{-1.7}$ at the high energy part is obtained (e.g., Volk et al. 2002, Berezhko et al. 2003). If holding for GRBs as well and GRBs are the main source of the $10^{20}$ eV cosmic rays, the PeV neutrino spectrum will be harder than that predicted in Guetta et al. (2004). For instance, the neutron spectra $\epsilon_{\nu} dN/d\epsilon_{\nu} \propto \epsilon_{\nu}^{-2}$ and $\epsilon_{\nu}^{-2} dN/d\epsilon_{\nu} \propto \epsilon_{\nu}^{-2}$ in Fig.3 will be hardened by a factor of $\epsilon_{\nu}^{-0.3}$. But the total flux may be just $\sim 10\%$ times that predicted in Guetta et al. (2004) because in this scenario the protons are not as many as that suggested in a flat spectrum $dN/dE \propto E^{-2}$ for $E \ll 10^{20}$ eV.

There is a process, ignored in some previous works, that can enhance the detection prospect a little bit. After the pions (muons) are generated, the high energy pions (muons) will lose energy via synchrotron radiation before decaying, thus reducing the energy of the decay neutrinos (e.g., Guetta et al. 2004). As a result, above $\epsilon_{\nu} \sim 10^{17}$ eV, $\epsilon_{\nu}^{-2} dN/d\epsilon_{\nu} \propto \epsilon_{\nu}^{-2}$, $\epsilon_{\nu}^{-2} dN/d\epsilon_{\nu} \propto \epsilon_{\nu}^{-2}$ in Fig.3 will be hardened by a factor of $\epsilon_{\nu}^{-0.3}$. But the total flux may be just $\sim 10\%$ times that predicted in Guetta et al. (2004) because in this scenario the protons are not as many as that suggested in a flat spectrum $dN/dE \propto E^{-2}$ for $E \ll 10^{20}$ eV.

A simple estimate suggests that the number of neutrinos in the energy range $(0.5, 1) \epsilon_{\nu}^{\epsilon_{\nu}}$ should be enhanced by a factor of $\sim 3$. A schematic plot of the muon neutrino spectrum in the standard internal shock model is shown in Fig.4.

5 CONCLUSION

In the pre-Fermi era, it is widely expected that significant GeV emission will be detected in a good fraction of bright GRBs if they are powered by un-magnetized internal shocks (e.g., Pilla & Loeb 1998, Pe’er & Waxman 2004; Gupta & Zhang 2007; Fan & Pirani 2008). The detection of a distinct excess at GeV-TeV energies, the SSC radiation component of such shocks, will be a crucial evidence for the standard fireball model. The non-detection of the GeV spectrum excess in almost all Fermi bursts (Abdo et al. 2009) is a surprise but does not impose a tight constraint on the models. For example, in the standard internal shock model, the non-detection can be attributed to a too large $h\nu_{\text{mic}} \sim \text{TeV}$ and a relative low $h\nu_{\text{cut}} \sim \text{GeV}$. Some alternatives, such as the photosphere-internal shock model, the magnetized internal shock model and the photosphere-gradual magnetic dissipation model, can be in agree-
The linear polarization level is expected only when the line of sight if detected, labels its physical origin. However, a moderate/high sensitivity with the data, too (see Tab.2 for a summary). We attribute the delay in the onset of LAT detection in quite a few Fermi bursts to perform the gamma-ray polarimetry. Consequently the detection prospect is not very promising.

In this work we have also briefly discussed the detection prospects of GeV spectrum excess in most Fermi bursts at the energies $dN/dE \propto E^{-2.5}$. The former, however, is uncertain. If the protons have an intrinsic spectrum $dN/dE \propto E^{-2.2}$ and have a total energy about ten times that emitted in gamma-rays, the detection prospect would be as good as, or even better than that presented in Guetta et al. (2004). If the proton spectrum traces that of the electrons, i.e., typically $dN/dE \propto E^{-2.5}$, the detection prospect would be discouraging.

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Figure 7. The schematic plot of the PeV muon neutrino spectrum in the standard internal shock model.

Table 2. The physical reasons for the lack of GeV spectrum excess in most GRBs.

| model                          | the physical reason          |
|-------------------------------|------------------------------|
| standard internal shocks      | $h(\nu_{\mu,ssc}, \nu_{cut}) \sim (\text{TeV, GeV})$ |
| photosphere-internal shocks   | very small $\gamma_{\mu,m}$ and $\gamma_{\mu,c}$ |
| magnetized internal shocks    | soft synchrotron spectrum and weak SSC |
| photosphere-gradual           | magnetic dissipation         | very small $\gamma_{\mu,m}$ and $\gamma_{\mu,c}$ |

Figure 8. The scheme of the PeV muon neutrino enhancement due to the cooling of pions in the standard internal shock model.
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