Interpretation and implications of the non-detection of GeV spectrum excess by the Fermi Gamma-ray Space Telescope in most gamma-ray bursts

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ABSTRACT
Since the launch of the Fermi Gamma-ray Space Telescope on 2008 June 11, 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 surprising, 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, a high linear polarization level should be typical. In the standard internal shock model, a 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 anticorrelated with the weight of the photosphere/thermal component, which may be a unique signature of this kind of model. We also briefly discuss the implications of the current Fermi GRB data on the detection prospects 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: acceleration of particles – elementary particles – neutrinos – polarization – radiation mechanisms: non-thermal – gamma-rays: bursts.

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, Kouveliotou & Wijers 2000, for a review) the cosmological origin of GRBs has been firmly established. The modelling of the late ($t > 10^4$ s) afterglow data favours the external forward shock model (see Piran 1999; Mészáros 2002; Zhang & Mészáros 2004, for reviews). The radiation mechanisms employed in the modelling are synchrotron radiation and synchrotron self-Compton (SSC) scattering. At early times the prolonged activity of the central engine plays an important role in producing afterglow emission too, particularly in the X-ray band (e.g. Katz, Piran & Sari 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 the 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. Pilla & Loeb 1998; Pe’ller & Waxman 2004; Gupta & Zhang 2007; Bosnjak, Daigne & Dubus 2009, cf. Giannios 2007). The detection prospect for LAT seems very promising (see Fan & Piran 2008, for a recent review).

Since the launch of the Fermi satellite on 2008 June 11, significant detections of prompt high-energy emission from GRBs have been reported only in GRB 080825C (Bouvier et al. 2008), GRB 080916C (Abdo et al. 2009), GRB 081024B (Omodei 2008), GRB 090323 (Ohno et al. 2009b), GRB 090328 (Cutini, Vasileiou & Chiang 2009), and possibly GRB 090217 (Ohno, McEnery & Pelassa 2009a) until now (2009 May 5). Though the detection of

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three prompt photons above 10 GeV from GRB 080916C at redshift $z \sim 4.5$ (Abdo et al. 2009; 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, Fan & Piran 2009), the non-detection of significant $>100$ MeV emission from most GRBs may be a better clue to 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 to 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 follows. 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 implications of the current Fermi results on the detection prospects 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, Paczyński & Piran 1992; Paczyński & Xu 1994; Rees & Mészáros 1994; Daigne & Mochkovitch 1998), the ultrarelativistic 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 $R_{\text{int}} \sim 5 \times 10^{13} (\Gamma_i/300)^2 (\delta t_i/10\text{ ms})$, where $\Gamma_i$ is the initial Lorentz factor of the outflow and $\delta t_i$ is the intrinsic variability time-scale. 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 (Duncan & Thompson 1992; Usov 1992; Lyutikov & Blandford 2003; Giannios & Spruit 2005), we call the shocks generated in the collisions within the outflow the magnetized internal shocks (Spruit, Daigne & Drenkhahn 2001; Fan, Wei & Zhang 2004b). The synchrotron radiation of the shock-accelerated electrons may peak in the 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 ultrarelativistic outflow moving with an initial Lorentz factor $\Gamma_i$, the velocity (in units of $c$) is $\beta_i = \sqrt{1 - 1/\Gamma_i^2}$. A small velocity dispersion $\delta \beta_i \sim \beta_i/(2 \Gamma_i^2)$ 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 collapsing launching relativistic outflow, people found highly variable energy deposition in the polar regions in a time-scale as short as $\sim 50$ ms (MacFadyen & Woosley 1999). (3) This model can naturally account for the variability that is well detected in prompt gamma-ray emission (Kobayashi, Piran & Sari 2007). 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 $F_{\nu} \propto \nu^0$ (Band et al. 1993; Preece et al. 2000). Such a divergence between the model and the observational data is the so-called ‘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 2005; Pe’er, Mészáros & Rees 2006; Thompson, Mészáros & Rees 2007; Ioka 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 2000; Ryde 2005). The non-thermal 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 (Pe’er, Mészáros & Rees 2005, 2006; Rees & Mészáros 2005; Thompson, Mészáros & Rees 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 evidence for a thermal emission component in dozens of bright GRBs (Ryde 2005; Ryde et al. 2006; McGlynn et al. 2009; Ryde & Pe’er 2009); (2) the emission from the photosphere can naturally account for the temporal behaviours of the temperature and flux of these thermal radiations (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 references therein).

In this section we test these four models with the current Fermi GRB data. It is something surprising to see that none of these models has 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)

$$\gamma'_{\text{rms}} \sim 760(1 + Y_{\text{int}})^{1/4} L_{\text{syn},52}^{-1/4} R_{\text{int},13}^{1/2}(1 + z)^{1/2}(\epsilon_p/300 \text{ keV})^{1/2},$$

where $\epsilon_p = h\nu_{\text{syn}}$ is the observed peak energy of the synchrotron-radiation spectrum ($\nu F_{\nu}$), $h$ is Planck’s constant, $L_{\text{syn}}$ is the synchrotron radiation luminosity of the internal shock emission, $Y_{\text{int}} \sim [1 + \sqrt{1 + 4\epsilon_e/(1 + \gamma^2)}]/2$ is the regular SSC parameter (Sari & Esin 2001; Fan & Piran 2008; Piran, Sari & Zou 2009), and $g \sim \gamma'_{\text{rms}}^2 h\nu_{\text{syn}} R_{\text{int}}^{-1} \epsilon_p m_e c^2$. 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 equation (1) we have $g \sim 1$, for which the SSC may still be important (i.e. $Y_{\text{int}} \gtrsim 1$).

In this work the convention $Q_{\gamma} = Q/10$ has been adopted in cgs units except for some specific notations.

The SSC radiation will peak at

$$h
\nu_{\text{int,ssc}} \sim 2\gamma_{\text{rms}}^2 \epsilon_p \frac{1 + 2\gamma}{1 + \gamma^2} \times L_{\text{syn},52}^{-1/2} R_{\text{int},13}(1 + z)(\epsilon_p/300 \text{ keV})^2.$$

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

$$\gamma'_{\text{c}} \sim 0.03 L_{\text{syn},52}^{-1} R_{\text{int},13}^{1/2} \Gamma_2^{-3.5}.$$
In reality $\gamma_{\rm e}^*$ is always larger than 1. The derived electron energy is used almost all their energy and are subrelativistic.

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

$$h\nu_{\rm cut} \approx 2\,\text{GeV} \left(1 + z\right)^{-1} \left(\epsilon_p/300\,\text{keV}\right)^{(2-p)/p} L_{\text{syn}}^{-2/3} \times \Delta t_{\text{int}}^{-p/(2+p+b)/3} \frac{m_e c^2}{1.25}.$$  \hspace{1cm} (4)

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

$$\mathcal{R} \approx \frac{\nu_{\text{ssc}} Y_{\text{ssc}}^{(2-p)/2} \int_{\nu_{\text{m,ssc}}}^{\nu_{\text{max}}} \nu^{-1.25} d\nu}{\int_{\nu_{\text{m}}}^{\nu_{\text{cut}}} \nu^{-p/2} d\nu} \approx (p-2) \nu_{\text{cut}} / Y_{\text{ssc}}^{1.25},$$

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

For $Y_{\text{ssc}} \sim 1$, $p \sim 2.5$ (corresponding to the typical gamma-ray spectrum $F_{\nu} \propto \nu^{1.25}$ for $h\nu > \epsilon_p$) and $\nu_{\text{cut}} \ll \nu_{\text{m,ssc}}$, we have $\mathcal{R} \ll 1$. 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 the too large $h\nu_{\text{m,ssc}} \sim$ TeV and a relative low $h\nu_{\text{cut}} \sim$ GeV (see Fig. 1 for a schematic plot). The other possibility is that $(1+g^2)\epsilon_p > 4e_\gamma$, for which $Y_{\text{esc}} \sim \mathcal{O}(1)$, i.e. the SSC radiation is unimportant and can be ignored.

### 2.1.2 The photosphere internal shock model

Thompson (1994) proposed the first photosphere model for the prompt gamma-ray emission, in which the non-thermal 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 shock model, in which the sub-MeV emission is dominated by the thermal emission of the fireball and the non-thermal tail is the EIC radiation of the electrons accelerated in internal shocks at a radius $R_{\text{em}} \sim 10^{14}$ cm (e.g. Mészáros & Rees 2000; Rees & Mészáros 2005; Pe’er et al. 2006). In this model the shock accelerated electrons and/or positrons in the Poynting-flux dominated outflow (i.e. $\gamma_{\text{esc}} \lesssim 1$), Fermi GRBs: interpretation and implications

For the Poynting-flux dominated outflow (i.e. $\gamma_{\text{esc}} \lesssim 1$), Usov (1994) proposed that $N_\nu \propto \nu^{-1}$ for $\gamma_{\text{esc}} \lesssim 1$ and $N_\nu \propto \nu^{-2}$ for $\gamma_{\text{esc}} > 1$. Such a different distribution cannot remain if the electrons cool down rapidly. As shown in Sari, Piran & Narayan (1998), in the presence of steady injection of electrons, the energy distribution can be approximated by $N_\nu \propto \nu^{2\eta_{\nu}}$ for $\gamma_{\text{esc}} \lesssim 1$ and $N_\nu \propto \nu^{-2}$ for $\gamma_{\text{esc}} > 1$. Under what conditions can shock acceleration generate a particle distribution with $\gamma_{\text{esc}} \sim 1$? With a large fraction of the outflow energy deposited in the non-thermal 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 $\gamma_{\text{esc}} \sim 1$ 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 subshells and the weak interaction between these subshells may be able to produce multiple shocks that can accelerate electrons continually with a very small $\gamma_{\text{esc}}$.

Since both $\gamma_{\text{esc}} < \gamma_{\text{cut}}$ and $\gamma_{\text{esc}} > 1$ are achieved, the EIC spectrum should be $F_\nu \propto \nu^{-p/2}$ 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 magnetohydrodynamics (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 is why people concentrate on the internal shocks with a sub-relativistic. The reason is the following. For an isotropic diffusion and soft, which renders the detection of GeV photons from GRBs more difficult. The reason is the following. For an isotropic diffusion and soft turbulence.

![Figure 1](https://academic.oup.com/mnras/article-abstract/397/3/1539/1077103/guest)
a relativistic shock, the electron energy distribution index can be
estimated by (Keshet & Waxman 2005)
\[ p \sim \frac{3\beta_u - 2\beta_u \beta_e^2 + \beta_e^2}{(\beta_u - \beta_e)^2} - 2. \] (6)
However, in the presence of a large-scale coherent magnetic field, the
diffusion is highly anisotropic rather than isotropic (Morlino,
Blasi & Vietri 2007a). There are thus corrections to equation (6).
However, as long as the scattering is not very forward or backward
peaked, these corrections are small (Keshet 2006). Taking into ac-
count the anisotropic correction, Morlino, Blasi & Vietri (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 \( \sigma \sim 0.1 \) (Sironi
& Spitkovsky 2009). Motivated by these two possible pieces of
evidence, we adopt equation (6) to estimate the spectral slope of
accelerated particles at the magnetized shock fronts. The validity
of our approach can be tested by advanced numerical simulations
in the future.

In the case of \( \sigma = 0 \), for an ultrarelativistic shock, \( \beta_u \rightarrow 1 \)
and \( \beta_e \rightarrow 1/3 \), we have \( p \rightarrow 2.22 \). However, for an ultrarelativistic
magnetized shock, \( \beta_u \rightarrow 1 \) and (e.g. Fan et al. 2004b)
\[ \beta_u \approx \frac{1}{6} \left( 1 + \chi + \sqrt{1 + 14\chi + \chi^2} \right), \] (7)
where \( \chi = \sigma / (1 + \sigma) \), please note that \( \sigma \) is measured in the up-
stream. Note in this work we just discuss the ideal MHD limit, i.e.
there is no magnetic energy dissipation at the shock front. For \( 0 < \sigma \ll 1 \), we have \( p \sim (4.22 - 2\sigma) / (1 - 2\sigma) \sim 2.22 \). For \( \sigma \gg 1 \),
we have \( \beta_u \sim 1 - 1/2\sigma \) and \( p \sim 4\sigma - 1 \sim 2.22 \). Correspondingly,
the electron spectrum is very soft or even thermal like. Adopting
\( \beta_u \sim 1 \) and substituting \( \sigma \sim (1, 0.5, 0.1, 0.01) \) into equations (6) and
(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. 2000, see also our Fig. 2
for the Fermi GRBs) may be interpreted in this way.

If the weak 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 elec-
trons 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 ex-
plains the observed sub-MeV break of the GRB emission and the
spectral slopes. In this scenario, different from the magnetized in-
ternal shock model, the higher the initial \( \sigma \), the harder the spec-
trum (see the fig. 2 of Giannios 2007 for illustration). For an initial
\( \sigma \leq 40 \) (corresponding to the baryon loading \( L/M_c^2 \sim \sigma^2/2 \leq 250 \),
where \( M_c \) is the mass loading rate), the resulting \( > 10 \) 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
\( > 100 \) 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 \( \Gamma_i \) than the late ejecta (Zhang,
Woosley & MacFadyen 2004). This may explain the delay of the arrival of
the \( > 100 \) MeV emission, since as long as
\[ \Gamma_i \leq \Gamma_{ic} = 180(1 + z)^{(p/2p+8)} \left( \frac{h_{\text{cut}}}{100 \text{ MeV}} \right)^{[(p/2p+8)]} \times \left( \frac{\epsilon_p}{\text{300 keV}} \right)^{(p-2)/(2p+8)} L_{\text{sys,52}}^{-1/2} \delta_{e^-,-2}, \]
the \( > 100 \) MeV photons cannot escape from the emitting region freely
and thus cannot be detected.

In the photosphere gradual magnetic dissipation model, a small
\( \Gamma_i \) 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 \( \Gamma_i > \Gamma_{ic} \).

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 ultrarelativistic 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
choked 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 emi-
sion, it seems the physical properties of the outflow have changed.

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**Figure 2.** The distribution of the high-energy power-law index (\( \beta_{\text{Band}} \)) of
GRBs detected by the Fermi satellite from 2008 August 10 to 2009 March
31. The data are taken from http://www.batse.msfc.nasa.gov/gbm/circulars/
(see also http://gcn.gsfc.nasa.gov/gcn3_archive.html) and are preliminary.
The GRBs having a single power-law spectrum in the GBM energy range
are excluded in the statistics. Following Preece et al. (2000) we take
\( \beta_{\text{Band}} = -4 \) for all bursts that can be better fitted by a power-law
function with an exponential high-energy cut-off rather than by the Band
function (Band et al. 1993). We find that a good fraction of bursts have a
\( p \sim 2(\beta_{\text{Band}} + 1) \sim 2.22 \), consistent with Preece et al. (2000). These
soft spectra may be attributed to the magnetized internal shocks.
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 the gamma-ray band can achieve such a goal. In this section, we first 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. Granot 2003; Lyutikov, Pariev & Blandford 2003; Nakar, Piran & Waxman 2003; Waxman 2003; Fan, Xu & Wei 2008; Toma et al. 2009).

3.1 Linear polarization signal of the photosphere internal shock model

In this work we assume a uniform outflow. At any point in the outflow there is a preferred direction, the radial direction, in which the fluid moves. We choose the $Z'$-direction of the fluid local frame coordinate to be in that direction. The $Y'$-direction is chosen to be within the plane containing the line of sight (i.e. the scattered photon $k'_s$) 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. The energies of the incident and the scattered photons are $h\nu'_s$ and $h\nu'$, respectively. As shown in Aharonian & Atoyan (1981) and Berestetskii, Lifshitz & Pitaevski (1982): (I) in the cloud of isotropic electrons of energies $\gamma'_e m_c c^2$, the spectrum of photons, upscattered at the angle $\theta'$ relative to the direction of the seed photon beam, can be approximated by

$$\frac{dN_{\nu'}}{d\Omega} \approx \frac{3\sigma_{\tau e}}{16\pi^2} \frac{n_{\nu'_s}}{v'_{\nu'_s}} \frac{x}{2\beta'_e} \left(4A_0^2 - 4A_0 + B_0\right),$$

where $\beta'_e = (1 - 1/\gamma'_e)^{-1/2}$ and

$$A_0 = \frac{1}{2\gamma'_{\nu'_s} x} \left(\frac{1}{T_1} - \frac{1}{T_2}\right),$$

$$B_0 = \frac{T_2}{T_1} + \frac{T_1}{T_2},$$

$$T_1 = (1 - \cos \theta') + x \cos \theta',$$

$$T_2 = (1 - \cos \theta') + x \cos \theta' + \delta,$$

$$Q \equiv \sqrt{1 + x^2 - 2x \cos \theta'},$$

$$Q' \equiv h\nu'_s / (\gamma'_e m_c c^2),$$

and $x \equiv \nu / \nu'_{\nu'_s}$.

Please note that $x$ ranges from $x_{m_i}$ to $x_m$, which are given by

$$x_{m_i} = 1 + \frac{A + \gamma'_e \beta'_e \sqrt{\gamma'^2(1 + \delta^2) - (1 - \cos \theta')^2 + \sin^2 \theta'}}{1 + 2\gamma'_{\nu'_s}(1 - \cos \theta') + \gamma'^2 \delta(1 - \cos \theta')},$$

where $A \equiv (1 - \cos \theta')\gamma'_{\nu'_s} [\beta'_e^2 - \delta^2(1 - \cos \theta')]$.

(II) The polarization degree is

$$P \approx \frac{4(A_0 - A^2)}{B_0 - 4A_0 + 4A_0^2}.$$

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

$$\frac{dN_{\nu'}}{d\Omega} \approx \frac{3\sigma_{\tau e}}{16\pi^2} \frac{n_{\nu'_s}}{v'_{\nu'_s}} \left[\frac{1}{2(1 - \xi)} - \frac{\xi}{b_0(1 - \xi)}\right] + \frac{2\xi}{b_0^2 (1 - \xi)^2},$$

$$P \approx \frac{2\xi/b_0(1 - \xi) - [2\xi^2/b_0^2(1 - \xi)^2]}{1 + [\xi^2/2(1 - \xi)] - [2\xi/b_0(1 - \xi)] + [2\xi^2/b_0^2(1 - \xi)^2]}.$$
Figure 4. Sketch of the geometrical set-up used to compute the polarization signal. We take the LoS as the z-axis. The y-axis (x-axis) is within (perpendicular to) the plane containing the line of sight and central axis of the ejecta.

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

The EIC radiation flux in the observer frame is

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

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

The polarized radiation flux is

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

where $P$ is the linear polarization degree of the EIC emission is

$$P_{\nu, \text{EIC}} = \frac{|Q_{\nu, \text{EIC}}|}{F_{\nu, \text{EIC}}}.$$

One can see that a non-zero net polarization is expected as long as $\theta_i > 0$. In the numerical example, we assume that the seed photons have a thermal spectrum (as suggested in the photosphere model)

$$n_{\nu, \text{th}} \propto \frac{(h \nu)^2}{e^{h \nu/kT} - 1},$$

where $kT' \approx kT / 2 \Gamma_i$ is the temperature (measured in the rest frame of the emitting region) of the thermal emission. In the calculation we take $\Gamma_i \sim 300$ and $kT \sim 100$ keV. The electron distribution is taken as $N_{\nu_e} \propto \nu_e^{-4(1+q)} \propto \nu_e^{-3.5}$ for $\nu_e > 2$, otherwise $N_{\nu_e} = 0$. For comparison purposes we also consider the case of $N_{\nu_e} \propto \nu_e^{-2}$. The numerical results are presented in Fig. 5. One can see that the polarization degrees expected in these two representative cases are only slightly different. We also find that a moderate linear polarization level ($P_{\nu, \text{EIC}} > 10$ per cent) is achievable only for $\theta_i \gtrsim 1/3 \Gamma_i$.

Currently the prompt emission consists of thermal and non-thermal components. The thermal component with the flux $F_{\nu, \text{th}}$ is expected to be unpolarized while the non-thermal 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 anticorrelated 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 behaviour 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 reliable polarimetry is impossible.) On the one hand, a high linear polarization level is achievable only for $\theta_i \gtrsim 1/3 \Gamma_i$. On the other hand, $\theta_i \sim \theta_j \lesssim 1/\Gamma_i$ is needed otherwise the burst will be too weak to perform gamma-ray polarimetry. For $\Gamma_i \theta_j \gg 1$, we have

$$R_{\text{pol}} \approx 4/(3 \Gamma_i \theta_j) \approx 5 \text{ per cent} \Gamma_i^{-1} \theta_j^{-1}.$$

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 thermal and 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.

\(^4\) For the synchrotron radiation of 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).
band. These two characteristics 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, Nakar et al. (2003) and Waxman (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 ($\theta \lesssim \theta_i$), the linear polarization degree is low (see also Gruzinov 1999; Toma et al. 2009). The detection probability of a moderate/high linear polarization degree can also be estimated by equation (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 an ordered magnetic field and a high linear polarization level is expected (Granot 2003; Lyutikov et al. 2003). The physical reason is the following. The magnetic fields from the central engine are likely frozen in the expanding shells. The toroidal magnetic field component decreases as $R^{-1}$, while the poloidal magnetic field component decreases as $R^{-2}$. At the radius of the ‘internal’ energy dissipation (or the reverse shock emission), the frozen-in field is dominated by the toroidal component. For an ultrarelativistic outflow, due to the relativistic beaming effect, only the radiation from a very narrow cone (with half-opening angle $\leq 1/T_i$) around the LoS can be detected. As long as the line of sight is off the symmetric axis of the toroidal magnetic field, the orientation of the viewed magnetic field is nearly the same within the field of view. The synchrotron emission from such an ordered magnetic field therefore has a preferred polarization orientation (i.e. perpendicular to the direction of the toroidal field and the line of sight). Consequently, the linear polarization of the synchrotron emission of each electron could not be effectively averaged out and the net emission should be highly polarized. The detection prospects of a high linear polarization degree are very promising (i.e. $R_{\text{pol}} \sim 100$ per cent). The above argument applies to the reverse shock emission as well if the outflow is magnetized (Fan, Wei & Wang 2004a).

As summarized in Table 1, for the magnetized internal shock model, a high linear polarization level should be typical, while for the 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 behaviour, if detected, labels its physical origin.

Indeed there were some claims of the detection of a 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 are 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, the Advanced Compton Telescope Mission (Boggis et al. 2006), 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 the gamma-ray band may be realized and we can impose tight constraints on the models. At present, the most reliable polarimetry is in the UV/optical band (e.g. Covino et al. 1999; Wieters et al. 1999). The optical polarization of the prompt emission and the reverse shock emission require a quick response of the telescope to the GRB alert. This is very challenging. Mundell et al. (2007) reported the optical polarization of the afterglow, at 203 s after the initial burst of gamma-rays from GRB 060418, using a ring polarimeter on the robotic Liverpool Telescope. Their robust (90 per cent confidence level) upper limit on the percentage of polarization, less than 8 per cent, coincides with the fireball deceleration time at the onset of the afterglow. Such a null detection is, however, not a surprise because for this particular burst the reverse shock emission is too weak to outshine the unpolarized forward shock emission (Jin & Fan 2007). Quite recently, the robotic Liverpool Telescope performed polarimetry measurements of the reverse shock emission of GRB 090102 (Kobayashi, private communication). Following Fan et al. (2002), Kumar & Panaitescu (2003) and Zhang, Kobayashi & Mészáros (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 favoured.

### Table 1. Differences between the models with the polarimetry data.

<table>
<thead>
<tr>
<th>Model</th>
<th>Unique polarization property</th>
<th>$R_{\text{pol}}$ (per cent)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standard internal shocks</td>
<td></td>
<td>$\lesssim 10$</td>
</tr>
<tr>
<td>Photosphere internal shocks$^a$</td>
<td>Strongly frequency dependent$^b$</td>
<td>$\lesssim 10$</td>
</tr>
<tr>
<td>Magnetized internal shocks</td>
<td></td>
<td>$\sim 100$</td>
</tr>
</tbody>
</table>

$^a$In the photosphere gradual magnetic dissipation model, very similar polarization properties are expected.

$^b$As shown in Fig. 6, the polarization degree is anticorrelated with the weight of the photosphere/thermal component.

### 4 IMPLICATIONS FOR THE DETECTION PROSPECTS OF PeV NEUTRINO EMISSION

The site of the prompt gamma-ray emission may be an ideal place for accelerating protons to ultrahigh 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 $E_{\nu,\text{obs}} \approx 5 \times 10^{14} eV F_\gamma^2 (1+z)^2 E_{\gamma,\text{obs}}/1\text{MeV})^{-1}$. Significant detections are expected if GRBs are the main source of ultrahigh-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 observational evidence for such a flat particle spectrum. Below we discuss the detection prospects of PeV neutrinos implicated by the non-detection of high-energy emission from most GRBs. In the magnetized outflow model, the acceleration of a significant part of the protons to energies $\geq 10^{19} eV$ is highly questionable because...
of the resulting soft proton spectrum. In the photosphere internal shock model, $y_{e,m} \sim 1$ 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 $\Gamma_{sh} - 1 \sim 0.04 (y_{e,m}^{2}/5)(\epsilon_{V}/0.2)^{-2} [3(p - 2)/ (p - 1)]^{-1}$, 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 ultrahigh energy is less efficient than the standard internal shocks. This is particularly the case if the acceleration is mainly via the 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 $dN/dE \propto E^{-2}$. Such a flat spectrum is predicted for Newtonian shocks and has been confirmed by supernova remnant observations. However, the typical MeV spectrum $F_{\nu} \propto \nu^{-1.25}$ (Preece et al. 2000) of GRBs suggests $dN/dE \propto E^{-2.5}$, supposing the accelerated protons and electrons have the same spectrum. The non-detection of $>100$ MeV photon emission from most GRBs implies soft electron (possibly) and proton spectra. Given a proton spectrum $dN/dE \propto E^{-2.2}$ 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 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 references therein). In other words, the GRB efficiency should be as low as $\sim 1$ per cent. If correct, the number of protons at $E \sim 10^{16}$eV will be quite a few times what was assumed in Guetta et al. (2004). Correspondingly the PeV neutrino flux will be higher. However, the current afterglow modelling usually yields a typical GRB efficiency $\sim 10$ per cent (e.g. Fan & Piran 2006; Zhang et al. 2007) or larger (e.g. Panaitescu & Kumar 2002; Granot, Königl & Piran 2006). Below we discuss a new possibility – the proton spectrum is curved. In the ‘low-energy’ part, the spectrum may be steepened significantly by the leakage of the very-high-energy cosmic rays from the ejecta (see Hillas 2005, 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, Pühlhofer & Vöölk 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 $s_{n} dN/d\epsilon_{n} \propto \epsilon_{n}^{3}$ and $s_{e}^{n} dN/d\epsilon_{e} \propto \epsilon_{e}^{-2}$ in their fig. 3 will be hardened by a factor of $\epsilon_{e}^{-0.5}$. However, the total flux may be just $\sim 10$ per cent that predicted in Guetta et al. (2004) because in this scenario the protons are not as many as 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 prospects a little bit. After the protons (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 $\epsilon_{p} \sim (10^{21}/1 + z)^{1/2} \epsilon_{B}^{1/2} L_{p}^{1/2} \delta n_{e} \sim 10^{20}$eV, the slope of the corresponding neutrino spectrum steepens by 2, where $L_{p}$ is the luminosity of the gamma-ray emission (Guetta et al. 2004). However, we do not suggest a smooth spectral transition around $\epsilon_{p}$ or $\epsilon_{\mu}$ because the cooling of pions (muons) will cause a pile of particles at these energies (see also Murase & Nagataki 2006). A simple estimate suggests that the number of neutrinos in the energy range $(0.5, 1)\epsilon_{p}$ 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. 7.

5 CONCLUSION

In the pre-Fermi era, it was widely expected that significant GeV emission would be detected in a good fraction of bright GRBs if they are powered by unmagnetized internal shocks (e.g. Pilia & Loeb 1998; Pe’er & Waxman 2004; Gupta & Zhang 2007; Fan & Piran 2008). The detection of a distinct excess at GeV–TeV energies, the SSC radiation component of such shocks, will be 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 $h_{\nu_{e,\nu_{\mu}}}$ $\sim$ TeV and a relative low $h_{\nu_{e,\nu_{\mu}}}$ $\sim$ 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 agreement with the data, too (see Table 2 for a summary). We attribute the delay in the onset of LAT detection in quite a few Fermi bursts to the unfavourable conditions for GeV emission of the early outflow (see Section 2.2 for details).

With polarimetry of GRBs people can potentially distinguish between some prompt emission models (see Table 1 for a summary; see also Toma et al. 2009). We show in Section 3.1 that in the photosphere internal shock model the linear polarization degree is roughly anticorrelated with the weight of the thermal component and will be highly frequency-dependent. Such a unique behaviour, if detected, labels its physical origin. However, a moderate/high linear polarization level is expected only when the line of sight is outside the cone of the ejecta (i.e. $\theta_{v} > \theta_{\nu}$). In addition,

![Figure 7](https://example.com/figure7.png)

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

<table>
<thead>
<tr>
<th>Model</th>
<th>The physical reason</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Standard internal shocks</strong></td>
<td>$h_{\nu_{e,\nu_{\mu}}, v_{\text{out}}} \sim (\text{TeV}, \text{GeV})$</td>
</tr>
<tr>
<td><strong>Photosphere internal shocks</strong></td>
<td>Very small $y_{e,m}$ and $y_{\mu,c}$</td>
</tr>
<tr>
<td><strong>Magnetized internal shocks</strong></td>
<td>Soft synchrotron spectrum and weak SSC</td>
</tr>
<tr>
<td><strong>Photosphere gradual magnetic dissipation</strong></td>
<td>Very small $y_{e,m}$ and $y_{\mu,c}$</td>
</tr>
</tbody>
</table>
\( \theta_c - \theta \lesssim 1 / \theta_c \) is needed otherwise the burst will be too weak to perform gamma-ray polarimetry. Consequently the detection prospects are not very promising.

In this work we have also briefly discussed the detection prospects of prompt PeV neutrinos from GRBs. The roles of the intrinsic spectrum of the protons and the cooling of pions (muons) have been outlined. The latter always increases the neutrino numbers at the energies \( E_{\nu} \) or \( E_{\bar{\nu}} \) by a factor of 3. The former, however, is uncertain. If the protons have an intrinsic spectrum \( dN / dE \propto E^{-2.2} \) and have a total energy about 10 times that emitted in gamma-rays, the detection prospects would be as good, or even better than, those 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 prospects would be discouraging.

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