Implications of electron acceleration for high-energy radiation from gamma-ray bursts

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ABSTRACT

In recent work, we suggested that photons of energy > 100 MeV detected from gamma-ray bursts (GRBs) by the Fermi satellite are produced via synchrotron emission in the external forward shock with a weak magnetic field – consistent with shock-compressed upstream magnetic field of a few tens of μG. Here we investigate whether electrons can be accelerated to energies such that they radiate synchrotron photons with energy up to about 10 GeV in this particular scenario. We do this using two methods: (i) we check if these electrons can be confined to the shock front; and (ii) we calculate radiative losses while they are being accelerated. We find that these electrons remain confined to the shock front, as long as the upstream magnetic field is ≳ 10 μG, and do not suffer substantial radiative losses, the only condition required is that the external reverse shock emission be not too bright: peak flux less than 1 Jy in order to produce photons of 100 MeV and less than ~100 mJy for producing 1-GeV photons. We also find that the acceleration time for electrons radiating at 100 MeV is a few seconds (in observer frame) and the acceleration time is somewhat longer for electrons radiating at a few GeV. This could explain the lack of > 100 MeV photons for the first few seconds after the trigger time for long GRBs reported by the Fermi satellite and also the slight lag between photons of GeV and 100 MeV energies. We model the onset of the external forward shock light curve in this scenario and find it consistent with the sharp rise observed in the 100-MeV light curve of GRB 080916C and similar bursts.

Key words: radiation mechanisms: non-thermal – methods: analytical – gamma-ray burst: general.

1 INTRODUCTION

The Fermi satellite has detected 18 gamma-ray bursts (GRBs) at energies >100 MeV by the Large Area Telescope (LAT). This emission can be described as follows. The first 100-MeV photons arrive ~1 s (in the host galaxy frame) after the trigger time, for long GRBs; the trigger time is the time when low-energy photons (~1 MeV) are first detected by the Gamma-ray Burst Monitor (GBM) onboard Fermi. The 100-MeV light curve rises fast until it peaks and then it decays as a single power law for a long duration of time (of the order of 103 s) – much longer than the duration of the lower energy photons detected by the GBM – until it falls below the detector’s sensitivity. Radiation above 100 MeV from GRBs has been suggested to be produced via the synchrotron mechanism in the external forward shock (Kumar & Barniol Duran 2009, 2010); the external forward shock scenario was first proposed by Rees & Mészáros (1992), Mészáros & Rees (1993) and Paczyński & Rhoads (1993), and since then it has been widely used (see e.g. Mészáros & Rees 1997; Sari et al. 1998; Dermer & Mitman 1999; for a comprehensive review, see e.g. Piran 2004 and references therein). After our initial suggestion, many groups have also considered and provided evidence for this origin of the >100 MeV radiation (Gao et al. 2009; Corsi, Guetta & Piro 2010; De Pasquale et al. 2010; Ghirlanda, Ghisellini & Nava 2010; Ghisellini, Ghirlanda & Nava 2010). The magnetic field required for this model is consistent with being produced via shock-compressed seed magnetic field in the circumstellar medium (CSM) of strength of a few tens of μG. The peak of the 100-MeV light curve can be attributed to the deceleration time, which is the time it takes for the GRB jet to transfer about half of its energy to the external medium.

We investigate in this work whether electrons in the external forward shock can be accelerated to sufficiently high Lorentz factors (LFs), even for a small CSM magnetic field of a few tens of μG, so that the synchrotron radiation can extend to ~10 GeV as seen by the Fermi/LAT for a number of GRBs. We study the electron acceleration in the context of diffusive shock acceleration...
If the downstream magnetic field is simply the shock-compressed large-scale upstream field, then the field component perpendicular to the shock normal is amplified, while the parallel component is not. In this case, the downstream magnetic field will be mainly pointing to the direction perpendicular to the shock front normal; therefore, particles trying to cross the shock front from downstream to upstream will find it difficult to catch up with the shock front, which moves with a speed of \(\sim c/3\) with respect to the downstream medium (see e.g. Achterberg et al. 2001; Lemoine, Pelletier & Revenu 2006; Pelletier, Lemoine & Marcowith 2009). One way that the particles might return to the upstream is if there is efficient cross-field diffusion of particles, which might occur if turbulent magnetic field is produced downstream (Jokipii 1987; Achterberg & Ball 1994; Achterberg et al. 2001). In principle, the turbulent magnetic field could dominate the shock-compressed field throughout the downstream region. However, it seems that although some turbulence is present just downstream of the shock front, it does not persist across the entire downstream region [see recent simulations by Sironi & Spitkovsky (2010) that show that magnetic field is amplified only right behind the shock front and returns to the shock-compressed value far downstream]. In this case, much of the radiation is produced by particles swept downstream where the turbulence has died out and the magnetic field is consistent with the shock-compressed value. We also note that as long as the thickness of the turbulent magnetic field layer is smaller than the thickness of the shocked fluid divided by \((B_1/B_2)^2\), where \(B_1\) is the turbulent magnetic field strength and \(B_2\) is the shock-compressed magnetic field, the energy loss in the turbulent layer is small. Therefore, in this work, we neglect energy loss in the turbulent magnetic field layer, since it persists for a very short distance compared to the thickness of the shocked fluid (see e.g. Keshet et al. 2009 and references therein).

This work is organized as follows. In Section 2, we address the question of high-energy electron confinement upstream and downstream of the shock front and also radiative losses suffered by electrons in between acceleration. Also, in Section 2, we discuss the lag of the \(>100\) MeV light curves observed by the Fermi/LAT for several GRBs in light of our results on electron acceleration. In Section 3, we calculate the rise of the external forward shock light curve, taking into consideration the non-zero time to accelerate electrons to high enough energies so they can radiate at \(>100\) MeV. We present our conclusions in Section 4.

2 ELECTRON ACCELERATION FOR \(>100\) MEV EMISSION

2.1 Electron confinement

It is widely believed that electrons in non-relativistic shocks undergo diffusive shock acceleration (see e.g. Krymskii 1977; Axford et al. 1978; Bell 1978; Blandford & Ostriker 1978; Blandford & Eichler 1987). In the context of relativistic shocks, it has been shown that electrons gain energy, each time they cross the shock front, by a factor of \(\sim 2\), except on the first crossing when they gain energy by a factor of the LF of the shock front (Achterberg et al. 2001).

In order for electrons to turnaround while up/downstream and cross the shock front, their Larmor radius should be smaller than the size of the system, that is, electrons should be confined to the system in order to be accelerated. In this section, we explore the confinement of electrons in the external forward shock model when the magnetic field in the unshocked medium, upstream of the shock front, is a few tens of \(\mu G\) in strength and the magnetic field in the shocked medium, downstream of the shock front, is simply the shock-compressed upstream field.

The highest photon energy detected for Fermi GRBs is of the order of 10 GeV. We first calculate the random LF in the downstream comoving frame, \(\gamma_e\), of electrons radiating 10-GeV photons via synchrotron radiation, because these electrons have the largest Larmor radius and thus give us stricter confinement requirements. The synchrotron frequency in observer frame is

\[
\nu_{\text{syn}} = eB_2\gamma^2 \Gamma/2 \tau_{\text{mc}}(1 + z),
\]

where \(\Gamma\) is the bulk LF of the shocked fluid measured in the upstream rest frame (laboratory frame), \(B_2\) is the magnetic field downstream (measured in the local rest frame), \(z\) is the redshift, \(m_e\) and \(e\) are the electron’s mass and charge, respectively, and \(c\) is the speed of light (Rybicki & Lightman 1979).

We convert the synchrotron frequency to 10 GeV, that is, \(\nu_{10} = \nu_{\text{syn}}/1.6 \times 10^{-2}\) erg, where \(h\) is the Planck constant and 10 GeV corresponds to \(1.6 \times 10^{-2}\) erg. Using the convention \(Q_\gamma = Q/10^4\) and solving the last expression for \(\gamma_e\) yields

\[
\gamma_e = 1.5 \times 10^8 \nu_{10}^{1/2}(1 + z)^{1/2}\Gamma^{-1} B_5^{-1/2},
\]

where \(B_5\) is the magnetic field upstream, which is the magnetic field in the CSM. To obtain (1) we have assumed that the magnetic field in the downstream region is \(B_5 = 4\Gamma B_2\) (Gallant & Achterberg 1999; Achterberg et al. 2001; note that the shock front LF measured in the laboratory frame is \(\Gamma = \sqrt{2}\), Blandford & McKee 1976), that is, \(B_5\) is the shock-compressed magnetic field in the upstream (laboratory frame), which is what we have found for Fermi GRBs (Kumar & Barniol Duran 2009, 2010).

The electron’s LF in the rest frame of the upstream plasma is \(\Gamma \gamma_e\); therefore, the Larmor radius in the upstream is given by

\[
R_{\text{L,a}} = \frac{m_e c \gamma_{\text{e}} \Gamma}{e B_a} = (2.6 \times 10^{19} \text{ cm}) \nu_{10}^{1/2}(1 + z)^{1/2} B_5^{-3/2},
\]

where we made use of (1) to eliminate \(\gamma_e\). Comparing the Larmor radius with the size of the system upstream, \(R\), which is given by the blast wave radius in the host galaxy rest frame – \(R = 2c \Gamma^2 \tau (1 + z) \sim 10^{19}\) cm (where \(\tau\) a few seconds and \(\Gamma \sim 10^3\) is the blast wave LF, see e.g. Abdo et al. 2009a) – we find that \(R_{\text{L,a}} \gg R\). This might suggest that electrons of \(\gamma_e \sim 10^3\) are not confined to the system. However, an electron upstream of the shock front travels only a distance \(\sim R_{\text{L,a}}/\Gamma\) before returning to the downstream, because by the time the angle between the electron’s velocity vector and the normal to the shock front exceeds \(1/\Gamma\), the shock front catches up with the electron and sweeps it back downstream (Achterberg et al. 2001). Therefore, for electron confinement upstream, one should compare \(R_{\text{L,a}}/\Gamma\) with \(R:\)

\[
\frac{R_{\text{L,a}}}{\Gamma R} = 0.26 \frac{\nu_{10}^{1/2}(1 + z)^{1/2}}{\Gamma \Gamma B_5^{3/2}} = \frac{1.1 \nu_{10}^{1/2}(1 + z)^{3/8}}{B_5^{3/2}(E_{54}/n_2)^{3/8}},
\]

where \(E\) is the energy in the blast wave, \(t\) is the time since the burst trigger in the observer frame and \(n\) is the number density of particles in the CSM; in deriving the second equality, we made use
of the time dependence of $\Gamma$ and $R$ in the external forward shock scenario for a homogeneous CSM (Sari et al. 1998). For $R_{\text{sh}} \approx 4$ found for the Fermi bursts, $R_{\text{sh}}/\Gamma \lesssim 0.2$ and thus electrons radiating at 10 GeV cannot escape from the upstream side of the shock front; note that this conclusion holds for at least several hours in the observer frame.

One should also check for electron confinement downstream. Here, the Larmor radius is smaller than it is upstream, because the magnetic field is larger by at least a factor of 4$^{\Gamma}$ due to shock compression. Therefore, the requirement for the confinement of electrons downstream is automatically satisfied whenever it is satisfied upstream.

We conclude that there is no problem confining external forward shock electrons that radiate $\sim 10$ GeV synchrotron photons by the CSM magnetic field of strength $\geq 10 \mu$G.

### 2.2 Radiative losses during electron acceleration

Electrons suffer radiative losses while being accelerated that could prevent them from reaching LFs of $\sim 10^8$ that are needed for radiating photons of 10 GeV via the synchrotron process. In this section, we ascertain whether or not the radiative losses suffered by electrons – due to synchrotron and inverse-Compton (IC) processes – are small compared to the energy gain in each round of crossing the shock front. We do this by comparing the total radiative cooling time-scale, $t_{\text{cool}}$, which is the time-scale for electrons to lose half of their energy, with the acceleration time-scale.

For the case of ultrarelativistic shocks, when the downstream magnetic field is simply the shock-compressed upstream field, the upstream and downstream residency times for electrons are approximately equal, when particle diffusion is in the Balth field (Gallant & Achterberg 1999; Achterberg et al. 2001). Thus, the time it takes for electrons to make one complete cycle across the shock front is about twice the upstream residency time and the upstream residency time is of the order of the gyro-time in the shock front comoving frame (Baring 2004). In the laboratory frame, their upstream residency time is of the order of the time it takes them to travel a distance $\sim R_{\text{sh}}/\Gamma$. Since the Larmor radius ($R_{\text{sh}}$) increases with increasing electron energy, the last shock crossing dominates the total upstream residency time. Thus, the time, in the comoving frame of the blast wave, that electrons spend during the last cycle of crossing the shock front (upstream $\rightarrow$ downstream $\rightarrow$ upstream) before getting accelerated to LF $\gamma_e$ given by (1) is

$$t'_s \sim \frac{2R_{\text{sh}}}{cT_{\text{syn}}} = (1.7 \times 10^3 \text{s}) v_{\text{A}0}^{-1/2}(1+z)^{1/2}T_{\text{syn}}^{-1/2}B_{a,-5}^{-3/2}.$$  \hspace{1cm} (4)

Taking into account the energy loss that these electrons experience because of radiative cooling, the acceleration time-scale, in the blast wave comoving frame, is given by

$$t_{\text{acc}}(\gamma_e) \approx t_{\text{cool}}(\gamma_e) + t'_s(\gamma_e),$$  \hspace{1cm} (5)

where $t_{\text{cool}}(\gamma_e)$ is the elapsed time since the beginning of the explosion when $t'_s(\gamma_e) = t_{\text{cool}}(\gamma_e)/2$ (shock front crossing time should be equal to at least half of the radiative cooling time in order to reach a particular $\gamma_e$). At $t_{\text{cool}}$, the electron barely reaches $\gamma_e$; therefore, it needs an extra time of order $\sim t'_s$ to fully reach the desired $\gamma_e$. If $t'_s > t_{\text{cool}}/2$, then the radiative cooling is too strong and prevents the electron from reaching the desired $\gamma_e$. In the sections below, we discuss synchrotron and IC losses and calculate the radiative cooling time.

#### 2.2.1 Synchrotron losses

The synchrotron cooling time-scale (in the blast wave comoving frame) in the upstream of the shock front is $t'_{\text{syn,u}} = \frac{\sigma_T B_{\gamma w} \Gamma^2}{m_e c^3}$, where $\sigma_T$ is the Thomson scattering cross-section. We find that the synchrotron cooling time for an external forward shock electron with LF given by (1) is

$$t'_{\text{syn,u}} = (5.2 \times 10^5 \text{s}) v_{\text{A}0}^{-1/2}(1+z)^{-1/2}T_{\text{syn}}^{-1/2}B_{a,-5}^{-3/2}. \hspace{1cm} (6)$$

Since $t'_{\text{syn,u}} > t'_s$ by a factor of 30, synchrotron cooling in the upstream is unimportant for electrons radiating at 10 GeV.

Next, we calculate synchrotron losses in the downstream. Since $t_{\text{syn}} \propto B^{-2}$, the synchrotron loss rate is larger downstream because of the larger magnetic field. For shock-compressed magnetic field downstream, $B$ is larger than the upstream field by a factor of 4 (in the blast wave comoving frame) and therefore $t'_{\text{syn,d}} = t'_{\text{syn,u}}/16$. The effective synchrotron cooling time for electrons of LF given in (1) is $t_{\text{syn}} \approx [1/2 t'_{\text{syn,d}} + 1/2 t'_{\text{syn,u}}]^{-1}$, which gives

$$t'_{\text{syn}} = (6.1 \times 10^5 \text{s}) v_{\text{A}0}^{-1/2}(1+z)^{-1/2}T_{\text{syn}}^{-1/2}B_{a,-5}^{-3/2}. \hspace{1cm} (7)$$

We see from (4) that $t'_{\text{syn}} \sim 4t'_s$ for electrons that produce synchrotron photons of 10 GeV energy and therefore the maximum synchrotron photon energy – obtained by setting $t'_{\text{syn}} = t_{\text{max,syn}} \sim 40 \Gamma_s (1+z)^{-1}$ GeV (see e.g. Guilbert, Fabian & Rees 1983; Cheng & Wei 1996; de Jager et al. 1996).

#### 2.2.2 Inverse-Compton losses

In this section, we calculate the IC cooling time-scale for electrons. The IC cooling time depends on the energy density of photons and on the electron LF. Electrons in the external forward shock region are exposed to photons from three different sources of radiation: (i) prompt $\sim$MeV gamma-ray radiation, which carries most of the energy release in GRBs; (ii) synchrotron radiation produced in the external forward-shock-heated CSM; and (iii) radiation produced in the external reverse-shock-heated GRB jet. We will consider all of these sources in our estimate for the IC cooling time. All calculations will be carried out in the rest frame of the shocked CSM.

The IC cooling time is given by

$$t'_{\text{IC}} = \frac{3m_e c^2}{4 \pi \int d\nu F(\nu) \gamma_e^2}, \hspace{1cm} (8)$$

where $F(\nu)$ is the energy flux in radiation per unit frequency in the comoving frame of the shocked CSM, $\nu$ is photon frequency in the observer frame and $\sigma$ is the cross-section for interaction between electrons and photons; $\sigma \approx \sigma_T$ (Thomson cross-section) when $\nu < \Gamma m_e c^2/[(1+z) \gamma_e] \equiv \nu_{\text{kne}}$, where $\nu_{\text{kne}}$ is the Klein–Nishina frequency in the observer frame, and for $\nu \gg \nu_{\text{kne}}$, $\sigma \approx \sigma_T (\nu/\nu_{\text{kne}})^{-1}$. Thus, an approximate equation for the IC cooling time is

$$t'_{\text{IC}} \approx \frac{3m_e c^2}{4 \pi \sigma_T \gamma_e^2} \left[ F(< \nu_{\text{kne}}) + \frac{\nu_{\text{kne}}}{\nu_{\text{p}}} F(> \nu_{\text{kne}}) \right]^{-1}, \hspace{1cm} (9)$$

where $F(< \nu_{\text{kne}})$ is photon energy flux in the shock comoving frame below the frequency $\nu_{\text{kne}}$ and $F(> \nu_{\text{kne}})$ is the flux above $\nu_{\text{kne}}$. The frequency at the peak of the $F(\nu)$ spectrum is $\nu_{\text{p}}$ (in the observer frame, that is, comoving synchrotron peak frequency boosted by a factor of $\Gamma$ and redshift corrected) and $\nu_{\text{kne}}$ for an electron of LF $\gamma_e$, is $h \nu_{\text{kne}} \approx (5 \text{ eV}) \Gamma_s \gamma_e^{-1} (1+z)^{-1}$. We note that for $\nu_{\text{kne}} \gg \nu_{\text{p}}$, only the first term in (9) should be kept.
The comoving energy flux in radiation is related to the observed bolometric luminosity by

\[
F'(\nu, \nu_p) \sim \frac{L_{\text{obs}}}{4\pi R^2 \Gamma^2}.
\]

Combining (9) and (10), we find

\[
t'_{\text{IC}, a} = \left(2.2 \times 10^3 \text{ s}\right) R_4^{-1} \Gamma_{3,5} \nu_{p,0} \left(1 + \frac{\nu_{p,0}}{\nu_{p,5}}\right) \frac{\left(1 + \frac{\nu_{p,0}}{\nu_{p,5}}\right)^{\alpha - 1}}{L_{\text{obs}, 51}^{-1}}.
\]

Case (b): The external forward shock synchrotron spectrum peaks at \(\sim 100\text{keV}\) (before the deceleration time) and the spectral index between \(\nu_{p,0}\) and \(\nu_{p,5}\) is \(\alpha \sim 1/3\). The luminosity from the external forward shock is \(L_{\text{obs}, 52} \sim 0.1\) at the deceleration radius \(R_0\) and at a smaller radius, it decreases as \(\sim R^3\). Therefore, we find from (11) that, for \(R \leq R_0\),

\[
t'_{\text{IC}, b} = \left(2.2 \times 10^3 \text{ s}\right) R_4^{-1} \Gamma_{3,5} \nu_{p,0} \nu_{p,5} \left(1 + \frac{\nu_{p,0}}{\nu_{p,5}}\right) \left(1 + \frac{\nu_{p,0}}{\nu_{p,5}}\right) \frac{\left(1 + \frac{\nu_{p,0}}{\nu_{p,5}}\right)^{\alpha - 1}}{L_{\text{obs}, 51}^{-1}}.
\]

Case (c): If the GRB jet is composed of protons and electrons, then the interaction of the jet with the CSM will heat up these particles by the reverse shock propagating into the cold jet, and the synchrotron radiation produced would be very effective at cooling electrons in the external forward shock region. This is because the peak of the reverse shock emission at the deceleration time is typically at a few eV (Sari & Piran 1999a), which is of the order of \(\nu_{p,0}\) for electrons of \(\nu_{p,5} \sim 10^5\). Since \(\nu_{p,0} \sim \nu_{p,5}\), we can keep only the first term in (9) and (10) for flux in the calculation of the cooling time. The observed luminosity (at the deceleration time) is given by \(L_{\text{obs}, 52} = 4\pi R_4^2 \nu_{p,0} \nu_{p,5} \Gamma_{3,5} \nu_{p,0} \nu_{p,5} \left(1 + \frac{\nu_{p,0}}{\nu_{p,5}}\right) \left(1 + \frac{\nu_{p,0}}{\nu_{p,5}}\right) \frac{\left(1 + \frac{\nu_{p,0}}{\nu_{p,5}}\right)^{\alpha - 1}}{L_{\text{obs}, 51}^{-1}}\),

\[
\text{where } \Gamma_d \text{ is the LF of the GRB jet at the deceleration time, } F_{p,5} \text{ is in Jy and } \nu_{p,5} \text{ in eV; the reverse peak flux can be } \sim 1\text{ Jy for very bright bursts, such as GRB 990123 (Sari & Piran 1999b).}
\]

The total IC cooling time is

\[
t'_{\text{IC}} = \left(\frac{1}{t'_{\text{IC}, a}} + \frac{1}{t'_{\text{IC}, b}} + \frac{1}{t'_{\text{IC}, c}}\right)^{-1}.
\]

and, finally, the total radiative cooling time, \(t'_{\text{cool}}\), is given by

\[
t'_{\text{cool}} = \left(\frac{1}{t'_{\text{IC}}} + \frac{1}{t'_{\text{syn}}}\right)^{-1}.
\]
difficult to estimate with any confidence. We calculate \( t_{\text{cool}} \) by neglecting the contribution of reverse shock emission to IC cooling of electrons \( (t_{\text{cool}}^*) \) and this provides a lower bound to \( t_{\text{cool}} \), which is reported in Table 2 as a fraction of the deceleration time, \( t_d = (1.7 \times 10^3 \text{ s}) R_d (t_d / t_d^*)^{-1} \), for several Fermi bursts. We also provide in Table 2 an upper limit for the external reverse shock peak flux that is obtained by the condition that \( t_{\text{cool}} = t_d \), at the deceleration time, when the contribution of the external reverse shock emission is included in the calculation of \( t_{\text{cool}}^* \).

**GRB 080916C.** The first \( > 100 \text{ MeV} \) photons arrived \( \sim 3 \text{ s} \) after the trigger time and then the \( 100-\text{MeV} \) light curve rose rapidly, as \( \sim \mathcal{F}_p \), and peaked at \( \sim 5 \text{ s} \) (Abdo et al. 2009a). After the peak, which we identify as the deceleration time, \( t_d \), the flux decayed as a single power law (this power law is consistent with the expectation of the external forward shock model). So the first \( > 100 \text{ MeV} \) photons arrived at \( t/t_d \sim 0.6 \) and photons of energies \( > \text{GeV} \) were detected at \( \sim 7 \text{ s} \) \( (t/t_d \sim 1.4) \). The highest energy photon, \( \sim 13 \text{ GeV} \), was detected \( \sim 16 \text{ s} \) after the trigger time \( (t/t_d \sim 3) \).

For electrons to produce \( 100-\text{MeV} \) photons, their LF should be \( \sim 10^2 \) for this burst and for \( 1-\text{GeV} \) photons, the required \( \gamma \) exceeds \( \sim 3 \times 10^2 \); we used \( B_{\nu,5} \sim 4 \) as suggested by the data for this burst (Kumar & Barniol Duran 2009) – see Table 1. The acceleration time for electrons to attain these LFs is calculated using (5); note that our theoretical estimates are roughly consistent with the observed time-scales for GRB 080916C to within a factor of \( \sim 2 \) uncertainty of our estimates (Table 2).

**GRB090510.** For GRB090510 (Abdo et al. 2009b), there was a short delay in the detection of \( > 100 \text{ MeV} \) photons by \( \sim 0.1 \text{ s} \) (we take the trigger time to be \( \sim 0.5 \text{ s} \) after the GBM trigger, because of the presence of a precursor). The \( 100-\text{MeV} \) light curve peaked at \( \sim 0.2 \text{ s} \) (which we associate with the deceleration time) and so the arrival of the first \( > 100 \text{ MeV} \) photons was at \( t/t_d \sim 0.5 \). Higher energy photons arrived later: \( > 1 \text{ GeV} \) photons started arriving at \( t \sim 30 \text{ s} \) and \( \sim 10 \text{ GeV} \) photons arrived slightly after \( t_d \). As shown in Table 2, these results are roughly consistent with our estimates within a factor of 2.

**GRB 090902B.** The \( 100-\text{MeV} \) light curve for this burst peaked at \( \sim 10 \text{ s} \), which we identify as \( t_d \), and the first \( > 100 \text{ MeV} \) photons were detected at \( \sim 3 \text{ s} \) after the trigger time (Abdo et al. 2009c), that is, \( t/t_d \sim 0.3 \). Most of the GeV photons arrived at \( t \sim 3 \text{ s} \). The first \( 10-\text{GeV} \) photon is detected at \( \sim 12 \text{ s} \). The highest energy photon detected was \( \sim 30 \text{ GeV} \) at \( 80 \text{ s} \), that is, at \( \sim 8 t_d \). The arrival time for the first \( > 100 \text{ MeV} \) photons from this burst agrees with the electron acceleration time (Table 2).

To summarize the main results of this section, it takes a few seconds for electrons in the external forward shock to be accelerated to a LF so that they can produce \( 100-\text{MeV} \) photons and it takes a bit longer time for them to produce GeV photons. For this reason, GeV photons lag the \( 100-\text{MeV} \) radiation. If the external reverse shock flux is high (\( \sim 1 \text{ Jy} \)), then the first \( 100-\text{MeV} \) photons will be detected after the deceleration time and \( 10-\text{GeV} \) photons will be detected much later (\( \sim 10 t_d \)), when the reverse shock flux has decreased substantially. If the external reverse shock flux is small (\( \sim 10 \text{ mJy} \)), then the first \( 100-\text{MeV} \) photons will arrive at about a third of the deceleration time and GeV photons will be detected starting from close to the deceleration time.

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1. At this time, the LF has dropped by a factor of \( 8^{3/8} \sim 2 \) and at \( \xi = 1.8 \), \( v_{\text{max, syn}} \sim 10 \text{ GeV} \), a factor of \( \sim 4 \) smaller than the observed value. It can be shown that inhomogeneous magnetic fields lead to an increase in \( v_{\text{max, syn}} \) by about an order of magnitude.
4 CONCLUSIONS

In this paper, we have investigated the acceleration of electrons via diffusion shock acceleration in the external forward shock of GRBs and its implications for the high-energy photon detection by the Fermi satellite. The external shock model, with a weak magnetic field, has been proposed as the origin of the observed >100 MeV emission detected by the Fermi satellite from a number of GRBs (Kumar & Barniol Duran 2009, 2010). We find that high-energy electrons of $F \sim 10^3$, required for producing $\sim 10$ GeV photons via the synchrotron process, can indeed be accelerated in an external shock that is moving through a CSM with a magnetic field of strength a few tens of $\mu$G; they remain confined to the shock front as long as the upstream magnetic field is $\gtrsim 10 \mu$G.

We have also calculated the time it takes for electrons to be accelerated to a LF $\sim 10^7$ so that they can radiate synchrotron photons at $\sim 100$ MeV. We find this acceleration time to be a few seconds in the observer frame; this calculation took into account radiation losses suffered during the acceleration process. This result offers a straightforward explanation as to why, for most Fermi GRBs, 100-MeV photons are not observed right at the trigger time, but a little later. This also explains why 100-MeV photons are observed before GeV radiation: it takes electrons radiating at GeV energies even longer time to accelerate. Taking this acceleration time into consideration while calculating high-energy light curves, we find that the light curve rises very rapidly – much faster than it does for the external forward shock model with instantaneous electron acceleration for which the flux rises as $t^3$ when the CSM has uniform density (the $t^3$ rise reflects the increasing number of swept-up electrons before the blast wave decelerates).

The detection of the first 100-MeV photons at some fraction of the deceleration time, the longer delays in the detection of higher energy photons$^2$ and the fast rise of the 100-MeV light curve follow the expectation of the external forward shock model when the finite time for electron acceleration is taken into account. Detection of synchrotron photons of different energies provides an upper limit for the radiation flux produced in the reverse-shock-heated GRB jet. For instance, the peak flux for the external reverse shock emission – if the peak of the spectrum is at a few eV – could not have been larger than about 300 mJy close to the deceleration time, for GRB 080916C; otherwise, it would prevent electrons from accelerating to a LF of $\sim 10^7$ so that they can produce synchrotron photons of 100 MeV energy at early times (see Table 2). Similarly, the reverse-shock flux should be $\lesssim 20$ mJy for GRB 080916C in order that electrons in the forward shock are accelerated to a LF so that they produce 1-GeV photons.

We speculate that the lack of >100 MeV emission during the prompt phase of GRBs might be due to the presence of a bright optical source with observed flux larger than about 100 mJy, which would prevent electrons from reaching high LFs. This, coupled with the fact that GRBs with the largest LFs, which have small deceleration time, are the most likely bursts to be detected by Fermi (Kumar & Barniol Duran 2009), might explain the detection/non-detection of >100 MeV radiation from GRBs.

We note that the shock-compressed magnetic field scenario requires some cross-field diffusion of particles – presumably generated by turbulence – to allow them to travel back to the upstream (e.g. Achterberg et al. 2001; Lemoine et al. 2006). This turbulent layer probably occupies a small fraction of the downstream region as suggested by recent simulations by Sironi & Spitkovsky (2010). Therefore, the picture that seems to emerge from numerical simulations and Fermi observations is that there might be a small region of turbulence behind the shock front that aids in the acceleration of particles across the shock, but that the radiation is mainly produced by particles that are swept downstream where the value of the downstream field is consistent with simple shock compression of upstream field.

There also exists the possibility that the CSM seed field is actually a few $\mu$G and some instability produced ahead of the shock amplifies it to the value of a few tens of $\mu$G we infer by our modelling of Fermi GRBs (Kumar & Barniol Duran 2009, 2010). These instabilities have been studied by, for example, Milosavljević & Nakar (2006), Sironi & Goodman (2007), Goodman & MacFadyen (2008) and Couch et al. (2008). However, this possible amplification of a factor of $\sim 10$ is much smaller than the amplification customarily invoked to explain afterglow observations.

We received a preprint from Piran & Nakar (2010) soon after this paper was completed. They have also considered the acceleration of electrons in the external shock.

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$^2$Note that this possible trend in the data goes in the opposite direction to that in the prompt $\sim 1$ MeV emission, where higher energy photons arrive earlier than lower energy photons in long GRBs and there is no lag detected for short GRBs (Norris et al. 1986; Norris & Bonnell 2006).