On the generation of high energy photons detected by the Fermi Satellite from gamma-ray bursts

P. Kumar\(^1\)\(^\star\) and R. Barniol Duran\(^{1,2}\)\(^\star\)
\(^1\)Department of Astronomy, University of Texas at Austin, Austin, TX 78712, USA
\(^2\)Department of Physics, University of Texas at Austin, Austin, TX 78712, USA

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ABSTRACT

Observations of gamma-ray bursts by the Fermi satellite, capable of detecting photons in a very broad energy band: 8keV to >300GeV, have opened a new window for the study of these enigmatic explosions. It is widely assumed that photons of energy larger than 100 MeV are produced by the same source that generated lower energy photons – at least whenever the shape of the spectrum is a Band function. We report here a surprising result – the Fermi data for a bright burst, GRB 080916C, unambiguously shows that the high energy photons (\(\gtrsim 10^2\)MeV) were generated in the external shock via the synchrotron process, and the lower energy photons had a distinctly different source. The magnetic field in the region where high energy photons were produced (and also the late time afterglow emission region) is found to be consistent with shock compressed magnetic field of the circum-stellar medium. This result sheds light on the important question of the origin of magnetic fields required for gamma-ray burst afterglows. The external shock model for high energy radiation makes a firm prediction that can be tested with existing and future observations.

Key words: radiation mechanisms: non-thermal - methods: analytical - gamma-rays: bursts, theory

1 INTRODUCTION

The discovery of a bright gamma-ray burst (GRB), 080916C, by the recently launched Fermi satellite is an important advance toward our understanding of these spectacular explosions. The Large Area Telescope (LAT) onboard the Fermi satellite can detect photons in the energy range from 20MeV to >300GeV (hereafter we will call it the LAT band). LAT observed photons of energy up to 13 GeV from GRB 080916C where the flux was close to the threshold of its sensitivity (Abdo et al. 2009), and this detection suggests that the Lorentz factor of the outflow in this explosion was \(\gtrsim 10^3\) (Greiner et al. 2009).

A number of different proposals have been put forward for the generation of high energy photons in GRBs. For instance, one possible mechanism is the synchrotron process – either electron or proton synchrotron – e.g. Meszaros & Rees (1994), Totani (1998), Zhang & Meszaros (2001). Another possibility is inverse-Compton scattering of lower energy photons produced in the same region (such as the synchrotron-self-Compton process) or of an external origin e.g. Meszaros & Rees (1994), Pilla & Loeb (1998), Dermer et al. (2000), Sari & Esin (2001), Wang et al. (2001a, 2001b), Zhang & Meszaros (2001), Granot & Guetta (2003), Guetta & Granot (2003), Piran et al. (2004), Beloborodov (2005), Fan et al. (2005 & 2008), Fan & Piran (2006), Wang et al. (2006), Galli & Guetta (2008), Zou et al. (2009). Yet another class of high energy photon generation mechanism is hadronic collisions and photo-pion production e.g. Katz (1994), Derishev et al. (1999), Bahcall & Meszaros (2000), Dermer & Atoyan (2004), Razzaque & Meszaros (2006), Gupta & Zhang (2007), Fan & Piran (2008). Please see Fan & Piran (2008) for a review of the extensive literature on high energy photon generation processes.

In this Letter we provide multiple lines of evidence that show that high energy photons and late time X-ray and optical afterglow emissions from GRB 080916C were produced via the electron synchrotron process in the external shock; lower energy photons (\(\lesssim 1\)MeV) had a different origin. In the next section we provide a summary of the observed data for GRB 080916C. In §3 we describe the expected high energy emission from the external shock and compare that with the data for GRB 080916C, and in §4 we show that the entire optical and X-ray afterglow data for this burst is consistent with the external shock model. Moreover, using the external shock parameters determined from the late afterglow data alone (\(t \gtrsim 1\) day) we show that the expected emission at > 10^2 MeV during the prompt phase is entirely in agreement with the observed Fermi/LAT data (§4). The main conclusions are summarized in §5.
2 GRB 080916C: SUMMARY OF OBSERVATIONS

GRB 080916C was detected by Fermi (Abdo et al. 2009) in the energy band ∼ 8keV–13GeV. The spectrum of GRB 080916C peaked at ∼ 500 keV; the flux was independent of frequency below the peak, i.e., $f_\nu \propto \nu^{\beta \pm 0.03}$, whereas above the peak a single power-law function, $f_\nu \propto \nu^{-1.2 \pm 0.02}$, extending from ∼ 500 keV to 13 GeV provided a good fit to the data (time dependences of these quantities can be found in Fig. 3 of Abdo et al. 2009). The electron energy distribution index ($p$) corresponding to this spectrum was 2.4. The LAT band photon flux rose as $t^{\phi \pm 0.5}$ during the first 4s of observations (the time is measured starting from the first detection of photons in the 8keV–10MeV band), and declined as $t^{-1.2 \pm 0.2}$ from 4s to 1400s. The light curve for lower energy photons on the other hand declined as $\sim t^{-0.6}$ for the initial 55s, and subsequently it underwent a steep decline of $t^{-3.3}$ which is often seen in the sub-MeV band of GRBs (Tagliaferri et al. 2005, Nousek et al. 2006) and marks the end of the emission activity of the source. Thus, photons of energy $>10^3$MeV lagged lower energy photons by 4s, and that is an important discovery by Fermi. The other puzzling discovery is that radiation in the LAT band lasts for a much longer duration of time than lower energy emission.

X-ray and optical observations began about 1 day after the trigger time. Optical observations allowed to determine a photometric redshift of this burst, $z = 4.35 \pm 0.15$ (Greiner et al. 2009). Using the usual convention, $f_\nu(t) \propto \nu^{-\beta - t^{-\alpha}}$, the X-ray data decayed as $\alpha_X = 1.29 \pm 0.09$ with $\beta_X = 0.49 \pm 0.24$, both values completely consistent with the shape of the optical light curve and its spectral energy distribution: $\alpha_O = 1.40 \pm 0.05$ and $\beta_O = 0.38 \pm 0.20$ (see Fig. 2 of Greiner et al. 2009).

Since the spectrum from 8 keV to 13 GeV had the shape of a Band function (two power-law components smoothly joined) it has been suggested that the observed radiation over the entire 6-decades interval in frequency was produced by the same source (Abdo et al. 2009, Wang et al. 2009, Zhang & Pe’er 2009). However, a closer analysis of the Fermi data shows that this possibility can be ruled out.

3 EXTERNAL SHOCK & HIGH ENERGY PHOTONS

The first evidence for two different sources of radiation – one dominating in the sub-MeV band and the other at $\gtrsim 10^2$MeV – comes from the fact that the flux in the 50–300 keV band declined weakly with time ($t^{-0.6}$) during the initial 55s and then underwent a steep decline ($t^{-3.3}$) with a distinct signature of a short lived source of lifetime 55s$^{\text{I}}$. This rapid decay in flux in the X-ray band has been observed in $\sim 60\%$ of all bursts detected by the Swift satellite (Evans et al. 2009). In contrast, the source for high energy photons – declining as $\sim t^{-1.2}$ – was active for at least 1400s, when the flux fell below the Fermi/LAT sensitivity (see Fig. 4 of Abdo et al. 2009). Further evidence for two distinct sources is provided by the detection of several other bursts by the Fermi satellite for which the same behavior is seen: a longer lasting source for high energy photons relative to sub-MeV photons (see, e.g. Ohno et al. 2009, Cutini et al. 2009).

It is striking that the decay of the LAT light curve ($f_\nu(t) \propto t^{-\phi}$) is exactly what one expects for synchrotron radiation from the shock heated circum-stellar medium (CSM) by the relativistic jet of a GRB$^{\text{II}}$. From here on we will refer to this as external shock or ES. We show that it is not only the time dependence of the ES emission but also its magnitude that are the same as Fermi/LAT observations (with no dependence of the flux in the LAT band on unknown, and therefore adjustable, parameters).

A number of uncertainties plague the emission calculation from a shock-heated gas. The largest of these are the unknown strength of the magnetic field, and the density of the circum-stellar medium. Fortunately, it turns out that the observed flux at a frequency $\nu$ that is larger than all characteristic frequencies for the shocked gas, namely the synchrotron peak and cooling frequencies, is independent of these two highly uncertain parameters (Kumar 2000, Panaitecu & Kumar 2000). Photons of energy $>10^3$MeV safely satisfy this frequency criterion. The flux in this case can be shown to be equal to

$$f_\nu = \frac{0.2 \text{mJy} \ E_{55}^{\frac{4}{3}} \ e^{-\epsilon_{\nu} \ \epsilon_{B, -2.4} \ \frac{n_{p} \ m_{e}}{e_{c}^{3}} \ 8 \ (1 + Y)^{-1}}}{(1 + z)^{\frac{2}{3}} \ d_{L28}^{2}}$$

where $\epsilon_e$ and $\epsilon_B$ are the fractions of energy of the shocked gas in electrons and magnetic fields respectively, $t_1 = t/10$s is the time since the beginning of the explosion in the observer frame (in units of 10s), $\nu_0$ is photon energy in units of 100MeV, $E_{55} = E/10^{55}$erg is the scaled isotropic kinetic energy in the ES, $Y$ is the Compton-Y parameter, $z$ is the redshift and $d_L$ is the luminosity distance to the burst. The second equality in equation (1) was obtained by taking $p = 2.4$, $t = 4s$, $z = 4.3$ and $d_{L28} = 12.3$; $Y \lesssim 1$ because of Klein-Nishina effects even though $\epsilon_E/\epsilon_B \gg 1$, and furthermore, cooling of ES electrons by Inverse Compton scattering of prompt $\gamma$-ray photons can be shown to be weaker than synchrotron cooling. Note that the flux at 100MeV is approximately proportional to $E_{55}$, the energy in electrons; it is independent of the density of the circum-stellar medium ($n_p$), and has an extremely weak dependence on $\epsilon_B$ which for all practical purposes can be ignored. According to equation (1) the time dependence of the flux should be $t^{-1.3}$ ($p = 2.4$ for GRB 080916C) which is in excellent agreement with the observed flux decay of $t^{-1.2 \pm 0.2}$ in the LAT band. We note that a good fraction of the energy of the explosion was released during the initial 8s of the burst, and for the next 47s the energy deposited in the external medium increased as $\sim t^{0.4}$, and thereafter no additional energy was added to the ES. Therefore, for $4s < t < 55$s the light curve decay should have been $t^{-1.0} \pm 0.9$ due to energy injection in ES (a slightly steeper decay – $t^{-1.1}$ – will in fact occur during this time interval due to radiative loss of ES energy), and for $t > 55$s the decay attains the asymptotic slope of $t^{-1.3}$. Before the deceleration time, i.e., $t < 4$s, the ES light curve is expected to rise as $\sim t^t$ which is significantly shallower than the observed rise of $\sim t^6$. This is a very puzzling feature that could probably shed light on the onset of the ES and the particle acceleration mechanism. The

$^{1}$ The light curve of a relativistic source decays as $t^{-2-\beta}$ when the source is suddenly turned off (Kumar & Panaitecu 2000); where $\beta$ is the spectral index which for GRB 080916C was $\sim 1$ in the 50–300 keV energy band for $t \gtrsim 55$s.

$^{2}$ The shocked CSM moves with a Lorentz factor approximately equal to that of the GRB jet Lorentz factor. Electrons are accelerated by the Fermi process (Blandford & Eichler 1987) to a power-law distribution with index $p$ such that $n(\epsilon) \propto \epsilon^{-p}$. As a result of radiative losses the maximum electron energy is such that the synchrotron frequency in the shocked fluid rest frame is $\sim 10^3$MeV or $\sim 10^2$GeV in the lab frame (see e.g. Cheng & Wei 1996, Fan & Piran 2008). However, this limiting synchrotron frequency depends on the details of the electron scattering process, and it is likely to be higher for highly relativistic shocks.
observed 4s lag for the high energy photons at the beginning of the burst is due to the time it takes for energy transfer from GRB jet to the external shock i.e., the deceleration time (Sari & Piran 1999). For a sample of 10 well observed and studied GRB afterglows it is found that $0.2 < \epsilon_e < 0.8$ (Panaitescu & Kumar 2001), and for GRB 080916C, $E_{55} \geq 0.5$ at $t = 4s$. Therefore, from equation (1) we find that the flux at 100 MeV from shock heated external medium should be $\geq 2.5 \mu Jy$, which is consistent with the observed value of 3Jy. It should be emphasized that this emission from the shocked external medium cannot be avoided. It must be present at approximately the observed flux value as long as electrons carry some reasonable fraction of the shocked gas energy (which we know is the case for GRB afterglows), and the cooling frequency is $\leq 10^9$MeV.

Does it require a coincidence for the superposition of two different spectra, that originated in two separate sources, to have the shape of a Band function? It turns out that no fine tuning or coincidence is needed because the spectral peaks, and the flux at the peak, for ES radiation is closely tied to the GRB jet luminosity which also regulates the sub-MeV emission; for a very broad range of values for $\epsilon_B$ and $n$ the peak of $\nu f_\nu$, for the external shock emission, at the deceleration time of 4s, lies between $\sim 1$ MeV and $10^9$MeV. Figure 1 shows an example of a superposition of external shock spectrum and the sub-MeV source, and the result of a Band function fit to it.

We now determine the two uncertain parameters for the external shock mentioned previously, $\epsilon_B$ and $n$, by making use of the spectra during the initial 55s of the burst. The external shock emission should not dominate the observed flux in the 8–500 keV band since otherwise the spectrum in this band would be $\nu^{1/3}$ instead of the observed $\nu^0$; this means that the flux from ES at $t = 4s$ between 8 keV and 500 keV should be less than 1 mJy (the observed flux was 2 mJy). This condition provides an important constraint on $\epsilon_B$ and $n$. The flux from external shock at $\nu = 100$ keV and $t = 4s$ is given by (Panaitescu & Kumar 2000, Chevalier & Li 2000)

$$f_\nu = 7 \text{ mJy } E_{55}^{5/6} n^{1/2} \epsilon_B^{-3/2} \epsilon_e^{2/3},$$

(2)

For $\epsilon_e \sim 0.3$, the requirement that $f_\nu < 1$ mJy yields:

$$n \leq 10^{-2} \epsilon_B^{-2/3} E_{55}^{5/3} \text{ cm}^{-3}.$$.

There is one other constraint that the external shock emission should satisfy, and it is that the ES flux at 55s for 50 & 300 keV should be smaller than the observed value by at least a factor 10 (so that the 50–300 keV light curve can decline steeply for $t > 55s$, as observed, when the sub-MeV source turns off). We numerically solve for the allowed values of $\epsilon_B$ and $n$ that satisfy these two constraints, and we keep track of various possible ordering of characteristic frequencies. The results are shown in Figure 2; the numerical results are consistent with the analytical estimate provided above. Note that there is a very wide range of $\epsilon_B$ and $n$ allowed by the prompt data. Although we did not impose any constraint on $\Gamma$, its value turns out to be $\geq 2 \times 10^3$ – consistent with $\epsilon_e^{\Gamma}$ pair opacity argument (Abdo et al. 2009, Greiner et al. 2009). Moreover, Compton-Y-parameter at 4s is $\leq 1$, even though $\epsilon_e/\epsilon_B \gg 1$, because of Klein-Nishina reduction to electron–photon scattering cross-section; this effect also makes the self-Inverse Compton scattering of ES photons undetectable by Fermi. Another interesting point to note is that the entire broad range for $\epsilon_B$ allowed by the prompt emission data corresponds to a comoving-shock-frame magnetic field of $\sim 100$ milli-Gauss, and that is of order what we expect from shock compression of a seed magnetic field in the circum-stellar medium of $\sim 20\mu$ Gauss (pl. see Fig. 2), i.e. no magnetic dynamo amplification of field is needed behind the shock front for this burst.

![Figure 1. Band function fit to a superposition of external shock (ES) spectrum (shown as a dot-dash line) and the sub-MeV source spectrum (dashed line). The superposed spectrum is shown by a solid line, and the best fit Band function by a dotted line (χ²/dof for the Band function fit is 1.2); errors in the Count Rate are taken from Abdo et al. (2009), and these are equal to the size of filled circles. The ES spectrum is a synchrotron spectrum in the slow cooling regime with break frequencies 100keV and 20MeV (values taken from the ES calculation shown in Fig. 2). The Sub-MeV spectrum (dashed line) peaks at 400 keV and has a slope of $\nu^0 (\nu^{-1.6})$ below (above) the peak; the choice of the high energy spectral index for this component is motivated by observations during the first 4s of the burst, when the emission is dominated by the sub-MeV component. If one were to use different break frequencies for the ES spectrum (for instance, 100keV and 70MeV), the superposition would also give an acceptable Band function fit.](image-url)
be \( \propto \nu^{-(p-1)/2} \propto \nu^{-0.7} \). The fact that the ES parameters determined from the early time \( 10^5 \) MeV data provide good fit to the late time X-ray and optical emissions (which are well known to be from ES) lends strong support to the interpretation that the radiation observed by Fermi/LAT originated in the ES.

One could argue that the observed X-ray and optical light curves (at \( t < 1 \text{ day} \)) could have been more complex - than a single power-law - making it difficult to predict the late time X-ray and optical fluxes using the ES model. However, optical light curves are often single power-law functions and very rarely show a plateau (Oates et al. 2009). Moreover, a fraction of GRBs show a single power-law decline in their X-ray light curve and GRB 080916c could belong to this class of bursts (Liang et al. 2009); we note that very bright GRBs are less likely to contain a plateau in their X-ray light curve (Kumar, Narayan, Johnson 2008) and so there is a good chance that GRB 080916c - the brightest burst ever detected - had a simple light curve. These arguments allow us to use the simple ES model to predict the X-ray and optical flux at late time and compare it with the observations.

It is interesting to note that this exercise works in the reverse direction as well, i.e. using the external shock parameters determined from the optical and X-ray data for \( t \geq 1 \text{ day} \) we calculate the flux at \( 10^2 \) MeV at 150s (Fig. 3; right hand panel), and find that to be in agreement with the observed data provided that we restrict \( E_{55} \epsilon_c \geq 0.1 \) (\( \epsilon_B \) & \( n \) can take whatever value that is allowed by the late time afterglow). It is also interesting to point out that although the \( \epsilon_B-n \) parameter space allowed by the late time optical and X-ray data for GRB 080916c is very large (pl. see Fig. 3; left panel), the entire allowed range for \( \epsilon_B \) by the late time data (without making use of the early time LAT data) is consistent with a shock compressed circum-stellar medium magnetic field of strength \( 30 \mu\text{Gauss} \) or less. The constraints we use to obtain the ES parameters in this reverse direction exercise are the following:

(i) At 1 day the optical and X-ray frequencies should lie between the synchrotron peak and cooling frequencies, (ii) the ES flux at 1 day should match the observed X-ray and optical fluxes at this time, (iii) the Lorentz Factor of the ejecta at 1 day should be \( \geq 60 \), so that the initial jet Lorentz Factor is \( \geq 10^3 \), and (iv) the ES flux at 150s between 50 & 300 keV should be smaller than the observed value by at least a factor 10 (see §3).

It is a small feat that the external shock model fits the data over 10-decades in frequency and 3-decades in time, and provides a natural explanation for a number of puzzling features observed by Fermi during the first 10’s of the burst.

Fermi has detected a few other bursts in the high energy band. They all seem to share similar features – high energy photons lag lower energy photons initially but last for a longer duration of time (Omodei et al. 2009). The external shock model provides a straightforward explanation for these “generic” features.

The external shock model also makes a prediction that the fluence for \( \nu > 10^{17}\text{MeV} \) should be proportional to \( (E\epsilon_c)^{(p+2)/4}(\epsilon_c/k_d)^{(p-2)/4} \) whenever the synchrotron cooling
frequency is below 100 MeV – a condition that is easy to check from the spectrum in the LAT band (this relation follows from eq. 1, which provides dependence on $\gamma$): $t_d \propto \Gamma^{-4}$ is the deceleration time of a GRB jet – propagating into a wind like density stratified medium – which can be taken to be the observed lag time for high energy photons. This prediction can be used to confirm or disprove this model. If detectors are activated by flux level, rather than fluence, then they will only observe bursts with the highest $\Gamma$ since the flux scales as $t_d \sim (3p-2)^{1/2} \propto \Gamma^{3p-2}$. Short duration GRBs should also satisfy the same scaling relation since the flux is independent of circum-stellar medium density.

5 CONCLUSIONS

We summarize the 4 main reasons that $\gtrsim 10^8$ MeV photons observed by Fermi/LAT were produced in the external shock. (1) The expected flux from external shock at 100 MeV, at $t = 4s$, is $\gtrsim 2.5 \mu$Jy (independent of $n$ and $\epsilon_B$) and that is in good agreement with the observed flux of 3 $\mu$Jy. (2) The radiation observed by LAT lasted for a time ($1400s$) much longer than the burst duration of $55s$. (3) Furthermore, the light curve decay in the LAT band, $t^{-1.2}$, is what is expected for the external-shock emission. And so is the 4s lag for the $> 10^8$ MeV photons. (4) The external shock parameters calculated using the initial 55s of data alone (Fig. 2), are able to explain the late time ($t \gtrsim 1day$) X-ray and optical afterglow data which is widely believed to be ES emission; as pointed out in footnote 3 the flux at late times depends on the density stratification of the circum-stellar medium, and for a wide range of possible density stratification the theoretically calculated flux lies within a factor of a few of the observed value. Moreover, the converse is also true i.e., late time afterglow data extrapolated back to 150s (and also to 4s) matches the observed flux at $\gtrsim 10^8$ MeV.

The fact that the $\gtrsim 10^8$ MeV light curve rises as $\sim t^6$ ($t < 4s$) is puzzling, as mentioned before. There is another burst (GRB 061007) that also displays an extremely rapid rise of its optical light curve at early times (Rykoff et al. 2009) and its isotropic equivalent energy release is also very high (one of the highest ever recorded so far). This suggests that the fast rise might be related to the particle acceleration mechanism at the onset of the ES, but more theoretical work is needed to determine the cause of this rapid rise.

The Fermi burst (GRB 080916C) sheds a surprising light on the question of the origin of magnetic fields in external shocks. Magnetic fields in the source inferred from the early LAT and GBM data ($t \leq 55s$) – and independently calculated from the late afterglow data ($t \geq 1day$) by itself – are entirely consistent with a $\sim 20\mu$-Gauss circum-stellar field compressed by the external shock, i.e. no extra field amplification is needed for the observed radiation (this possibility was investigated in Granot \& Königl 2003). GRB 080916C was the brightest burst to date, and if no magnetic dynamo is needed for the external shock synchrotron emission for this burst then we suspect that this result is likely to be applicable to other GRB afterglows as well.

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