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

P. Kumar1* and R. Barniol Duran1,2*

1Department of Astronomy, University of Texas at Austin, Austin, TX 78712, USA
2Department 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: 8 keV to >300 GeV, 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 (>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 – gamma-rays: theory.

1 INTRODUCTION

The discovery of a bright gamma-ray burst (GRB), 080916C, by the recently launched Fermi satellite is an important advance towards our understanding of these spectacular explosions. The Large Area Telescope (LAT) onboard the Fermi satellite can detect photons in the energy range from 20 MeV to >300 GeV (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 >10^3 (Greiner et al. 2009).


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 (ES); lower energy photons (<1 MeV) had a different origin. In the next section, we provide a summary of the observed data for GRB 080916C. In Section 3, we describe the expected high-energy emission from the ES and compare that with the data for GRB 080916C, and in Section 4 we show that the entire optical and X-ray afterglow data for this burst is consistent with the ES model. Moreover, using the ES parameters determined from the late afterglow data alone (i > 1d) we show that the expected emission at >10^5 MeV during the prompt phase is entirely in agreement with the observed Fermi/LAT data (Section 4). The main conclusions are summarized in Section 5.
2 GRB 080916C: SUMMARY OF OBSERVATIONS

GRB 080916C was detected by Fermi (Abdo et al. 2009) in the energy band ~8 keV–13 GeV. The spectrum of GRB 080916C peaked at ~500 keV; the flux was independent of frequency below the peak, that is \( f_\nu \propto \nu^{-0.2 \pm 0.0} \), whereas above the peak a single power-law function, \( f_\nu \propto \nu^{-1.2 \pm 0.0} \), 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 (\( \beta \)) corresponding to this spectrum was 2.4. The LAT band photon flux rose as \( \nu^{0.04 \pm 0.5} \) during the first 4 s of observations (the time is measured starting from the first detection of photons in the 8 keV–10 MeV band), and declined as \( t^{-1.2 \pm 0.2} \) from 4 s to 1400 s. The light curve for lower energy photons on the other hand declined as \( \sim t^{-0.6} \) for the initial 55 s, and subsequently it underwent a steep decline of \( t^{-3.5} \) 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 4 s, 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 d after the trigger time. Optical observations allowed to determine a photometric redshift for this burst, \( z = 4.35 \pm 0.15 \) (Greiner et al. 2009). Using the usual convention, \( f_\nu(t) \propto \nu^{-\beta(t)} \), the X-ray data decayed as \( \alpha_X = 1.29 \pm 0.09 \) with \( \beta_X = 0.49 \pm 0.34 \), both values completely consistent with the shape of the optical light curve and its spectral energy distribution: \( \alpha_0 = 1.40 \pm 0.05 \) and \( \beta_0 = 0.38 \pm 0.20 \) (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 six-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 AND HIGH-ENERGY PHOTONS

The first evidence for two different sources of radiation – one dominating in the sub-MeV band and the other at \( \gtrsim 10^5 \) MeV – comes from the fact that the flux in the 50–300 keV band declined weakly with time (\( t^{-0.5} \)) during the initial 55 s and then underwent a steep decline (\( t^{-1.5} \)) with a distinct signature of a short-lived source of lifetime 55 s. This rapid decay in flux in the X-ray band has been observed in ~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 1400 s, 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 behaviour is seen: a longer lasting source for high-energy photons relative to sub-MeV photons (see, e.g. Cutini, Vasileiou & Chiang 2009; Ohno et al. 2009).

It is striking that the decay of the LAT light curve \( [f_\nu(t) \propto t^{-1.2 \pm 0.2}] \) is exactly what one expects for synchrotron radiation from the shock heated circum-stellar medium (CSM) by the relativistic jet of a GRB; 2 from here on we will refer to this as 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; Panaitescu & Kumar 2000). Photons of energy \( > 10^5 \) MeV safely satisfy this frequency criterion. The flux in this case can be shown to be equal to

\[
f_\nu = 0.2 \text{ mJy } E_{55}^{(p+2)/4} \epsilon_e^{p-1} \epsilon_B^{(p-2)/2} \nu_9^{(3p-2)/4} (1 + Y)^{-1} \times (1 + z)^{1/2} d_{28}^{1/2},
\]

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 10 s), \( \nu_9 \) is photon energy in units of 100 MeV, \( E_{55} \equiv E/10^{55} \) erg is the scaled isotropic kinetic energy in the ES, \( Y \) is the Compton-Y parameter, \( z \) is the redshift and \( d_{28} \) is the luminosity distance to the burst. The second equality in equation (1) was obtained by taking \( p = 2.4, t = 4 \text{ s}, z = 4.3 \) and \( d_{28} = 12.3 \); \( Y \lesssim 1 \) 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 100 MeV is approximately proportional to \( \epsilon_e \), the energy in electrons; it is independent of the density of the CSM \( \rho \), and has an extremely weak dependence on \( \epsilon_B \) which for all practical purposes can be ignored. According to equation (1) the time dependence on the flux should be \( t^{-1.3} \) \( (p = 2.4 \text{ for GRB } 080916C) \) 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 8 s of the burst, and for the next 47 s the energy deposited in the external medium increased as \( t^{0.4} \) and thereafter no additional energy was added to the ES. Therefore, for \( 4 \text{ s} < t < 55 \text{ s} \) the light-curve decay should have been \( t^{-0.9} \) 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 \( t > 55 \text{ s} \) the decay attains the asymptotic slope of \( t^{-1.3} \). Before the deceleration time, \( t < 4 \text{ s} \), the ES light curve is expected to rise as \( t^{1/2} \) which is a very significant feature that could probably shed light on the onset of the

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 \( \sim 10^3 \text{ MeV} \) or \( \sim 10^3 \text{ GeV} \) 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.
ES and the particle acceleration mechanism. The observed 4 s 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 ES, that is the deceleration time (Sari & Piran 1999).

For a sample of 10 well-observed and studied GRB afterglows it is found that 0.2 < ε < 0.8 (Panaitec & Kumar 2001), and for GRB 080916C, ESS > 0.5 at t = 4 s. Therefore, from equation (1) we find that the flux at 100 MeV from shock heated external medium should be > 2.5 Jy, which is consistent with the observed value of 3 Jy. 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 > 10^2 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 the ES 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 the Band function by a dotted line (χ<sup>2</sup>/d.o.f. = 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 100 keV and 20 MeV (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 1.6 (ν<sup>1.6</sup>) below (above) the peak; the choice of the high-energy spectral index for this component is motivated by observations during the first 4 s 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, 100 keV and 70 MeV), the superposition would also give an acceptable Band function fit.

**Figure 1.** Band function fit to a superposition of 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-fitting Band function by a dotted line (χ<sup>2</sup>/d.o.f. = 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 100 keV and 20 MeV (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 1.6 (ν<sup>1.6</sup>) below (above) the peak; the choice of the high-energy spectral index for this component is motivated by observations during the first 4 s 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, 100 keV and 70 MeV), the superposition would also give an acceptable Band function fit.

We now determine the two uncertain parameters for the ES mentioned previously, ε<sub>b</sub> and n, by making use of the spectra during the initial 55 s of the burst. The ES emission should not dominate the observed flux in the 8–500 keV band since otherwise the spectrum in this hand would be ν<sup>1/3</sup> instead of the observed ν<sup>5</sup>; this means that the flux from ES at t = 4 s between 8 and 500 keV should be less than 1 mJy (the observed flux was 2 mJy). This condition provides an important constraint on ε<sub>b</sub> and n. The flux from ES at ν = 100 keV and t = 4 s is given by (Chevalier & Li 2000; Panaitec & Kumar 2000)

\[ f_\nu = 7 \text{ mJy} E_{SS}^{5/6} n^{1/3} B_{B}^{-1/3} E_{SS}^{-2/3}. \]

For ε<sub>b</sub> ~ 0.3, the requirement that f<sub>ν</sub> < 1 mJy yields: n < 10<sup>-2</sup> E<sub>SS</sub><sup>-2/3</sup> B<sub>B</sub><sup>-1/3</sup> E<sub>SS</sub><sup>-5/6</sup> cm<sup>-3</sup>.

There is one other constraint that the ES emission should satisfy, and it is that the ES flux at 55 s between 50 and 300 keV should be smaller than the observed value by at least a factor of 10 (so that the 50–300 keV light curve can decline steeply for t > 55 s, as observed, when the sub-MeV source turns off). We numerically solve for the allowed values of ε<sub>b</sub> and n that satisfy these two constraints, and we keep track of various possible ordering of characteristic frequencies. The results are shown in Fig. 2; the numerical results are consistent with the analytical estimate provided above. Note that there is a very wide range of ε<sub>b</sub> and n allowed by the prompt data. Although we did not impose any constraint on Γ, its value turns out to be ≳ 2 × 10<sup>3</sup> – consistent with ε<sup>5</sup> pair opacity argument (Abdo et al. 2009; Greiner et al. 2009). Moreover, Compton-Y-parameter at 4 s is ≲ 1, even though ε<sub>b</sub>/ε<sub>b</sub> ≫ 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 ε<sub>b</sub> allowed by the prompt emission data corresponds to a comoving-shock-frame magnetic field of ∼ 100 milli-Gauss, and that is of order what we expect from shock compression of a seed magnetic field in the CSM of ∼ 20 µ Gauss (see Fig. 2), i.e. no magnetic dynamo amplification of field is needed behind the shock front for this burst.

**4 LATE-TIME (T ∼ 1 D) OPTICAL AND X-RAY DATA**

The ES that gave rise to the high-energy emission (∼ 10<sup>2</sup> MeV) at early times will radiate at X-ray and optical bands at late times. For the region of (ε<sub>b</sub>, n) parameter space allowed by the early time data (t ≲ 55 s) we calculate the X-ray and optical flux at ≥ 1 d after the burst, and find that these fluxes are in good agreement with the observed values for the entire allowed parameter space shown in Fig. 2. Furthermore, the observed spectra and light curves in these bands, f<sub>ν</sub>(t) ∝ ν<sup>-0.5 ± 0.1</sup>y<sup>-1.3 ± 0.1</sup> (Greiner et al. 2009), are also in excellent agreement with theoretical expectations (the theoretically calculated values for the synchrotron peak and cooling frequencies at ≥ 1 d are < 1 eV and > 1 keV, respectively, for the entire parameter space allowed by the high-energy data – shown in the top panels of Fig. 2). Therefore we expect the spectra in the optical band to be dominated by the ES emission at late times.

The observed optical and X-ray flux at 1 d are larger than the expected value by a factor of ∼ 3 for a uniform density circum-stellar medium, and these fluxes are smaller by about a factor of ∼ 2 when the CSM density decreases as R<sup>−2</sup>. Our calculations include the effect of energy added to the ES for the initial 55 s as well as the radiative loss of energy. The late-time afterglow data are best modelled by a non-uniform CSM where the density falls off a little bit more slowly than R<sup>−2</sup>.
and the X-ray bands to be $\propto \nu^{-(\nu-1)/2} \propto \nu^{0.7}$. The fact that the ES parameters determined from the early time $10^2$ 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 $t < 1$ d) 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. Using the ES parameters determined from the optical and X-ray data for $t \gtrsim 1$ d we can calculate the flux at $10^3$ MeV at 150 s (Fig. 3, right-hand panel), and find that to be in agreement with the observed data provided that (i) the Lorentz Factor of the ejecta at 1 d should be $\gtrsim 60$, so that the initial jet Lorentz Factor is $\gtrsim 10^3$ and (iv) the ES flux at 1 d should match the observed X-ray and optical fluxes at this time, (ii) the Lorentz Factor of the ejecta at 1 d should be $\gtrsim 60$, so that the initial jet Lorentz Factor is $\gtrsim 10^3$ and (iv) the ES flux at 150 s between 50 and 300 keV should be smaller than the observed value by at least a factor of 10 (see Section 3).

It is no small feat that the ES model fits the data over 10 decades in frequency and three decades in time, and provides a natural explanation for a number of puzzling features observed by Fermi during the first $10^3$ s of the burst.

Figure 2. The fraction of energy of the shocked medium in the magnetic field, $e_B$ (top left) at 4 s (observer frame) and Compton-$Y$-parameter (top right) at 4, 15, 50, 150, 1500 s, 1 d (red, blue, green, black, yellow and cyan, respectively) as a function of the distance from the centre of the explosion to the ES front, $R$; note that for most of the parameter space $Y \lesssim 1$. The parameters for the allowed solution space shown in these figures are obtained by applying the constraints described in the text. For the allowed parameter space shown in the upper panels we calculate the expected late-time afterglow flux in the optical and X-ray bands as a function of observer time (bottom left). The upper and lower limits for these theoretically calculated ES fluxes are shown as a pair of solid lines in the bottom left-hand panel together with the observed flux. The optical (Greiner et al. 2009) and X-ray (Evans et al. 2007) fluxes (squares and circles, respectively) are consistent with the theoretical expectation of the ES model (triangles are optical upper limits) when $n$ falls off with radius approximately as $R^{-2}$; energy added to the ES during the initial 55 s, and the radiative loss of energy, was included in the calculation of late-time ES flux. $e_B$ versus $n$ for the parameter space allowed by the prompt data (top panels) is displayed in the (bottom right) panel at 4 s, and also shown is the expected $e_B$ for shock compression of magnetic field in the CSM (for CSM magnetic fields of 10 and $70 \mu$-Gauss – green and blue lines, respectively); almost the entire allowed range for $e_B$ parameter space allowed by the prompt $\gamma$-ray data is consistent with the shock compressed CSM magnetic field of $\lesssim 70 \mu$G.

Figure 3. ES parameters derived using the late ($t \gtrsim 1$ d) optical and X-ray afterglow data only. $e_B$ as a function of $n$ (left-hand panel) at 150 s (observer time) and the expected $e_B$ for shock compression of magnetic field in CSM (for CSM magnetic fields of 1 and $30 \mu$-Gauss – green and blue lines, respectively). We note that the $(e_B, n)$ space determined using only the late ($t \gtrsim 1$ d) optical and X-ray afterglow data is found to be very similar to the $(e_B, n)$ space determined using only the 100 MeV early data, and that shock compressed CSM field is all that is needed for the ES synchrotron emission for GRB 080916C. The predicted flux at 100 MeV at 150 s as a function of $e_B$ $E_{100}$ using only the late ($t \gtrsim 1$ d) afterglow data (right-hand panel). The horizontal dashed line indicates the observed flux by the Fermi Satellite, which was $\sim 30$ nJy.
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 $t_\text{d}^{-3p-2/4} \propto \Gamma^{-p-2}$. Short duration GRBs should also satisfy the same scaling relation since the flux is independent of CSM density.

5 CONCLUSIONS

We summarize the four main reasons that $\gtrsim 10^{52}$ MeV photons observed by Fermi/LAT were produced in the ES. (1) The expected flux from ES at 100 MeV, at $t = 4$ s, 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 (1400 s) much longer than the burst duration of 55 s. (3) Furthermore, the light-curve decay in the LAT band, $r^{-1.2}$, is what is expected for the external-shock emission. So is the 4 s lag for the $\gtrsim 10^{2}$ MeV photons. (4) The ES parameters calculated using the initial 55 s of data alone (Fig. 2), are able to explain the late-time ($t \gtrsim 1$ d) X-ray and optical afterglow data which are 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 150 s (and also to 4 s) matches the observed flux at $\gtrsim 10^{2}$ MeV.

The fact that the $\gtrsim 10^{52}$ MeV light curve rises as $\sim t^6 (t < 4$ s) 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 (Rykov 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 ESs. Magnetic fields in the source inferred from the early LAT and GBM data ($t \lesssim 55$ s) – and independently calculated from the late afterglow data ($t \gtrsim 1$ d) by itself – are entirely consistent with a $\sim 20$ $\mu$-Gauss circumstellar field compressed by the ES, 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 ES 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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REFERENCES

Abdo A. et al., 2009, Sci, 323, 1688
Cheng K. S., Wei D. M., 1996, MNARS, 283, L133
Cutini S., Vasileiou V., Chiang J., 2009, GCN Circ., 9077
Evans P. A. et al., 2009, MNARS, 397, 1177
Fan Y. Z., Piran T., 2006, MNARS, 370, 24
Gupta N., Zhang B., 2007, MNARS, 380, 78
Kumar P., Narayan R., Johnson J. L., 2008, MNARS, 388, 1729
Meszaros P., Rees M. J., 1994, MNARS, 269, 41
Oates S. R. et al., 2009, MNARS, 395, 490
Ohno M., Cutini S., McEnery J., Chiang J., Koerding E., 2009, GCN Circ., 9021
Tagliaferri G. et al., 2005, Nat, 436, 985
Zou Y. C., Fan Y. Z., Piran T., 2009, MNARS, 396, 1163

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