Theory of the
Prompt and High Energy Emission of

Gamma-Ray Bursts

Peter Mészáros,
collabs: Kenji Toma, XueFeng Wu
Pennsylvania State University
**GRB 080319B**

*A prompt “naked eye” optical GRB*

Racusin et al, 08
Nature 455:183

γ, opt prompt l.c. appear similar → same emission region, e.g. “internal” shock; but rad. mechanism?

*Interpret prompt as:*

i) optical: synchrotron

ii) 0.1-1 MeV: IC (SSC) (and)

iii) predict 2nd order IC @ ~100 GeV

*there are also differing opinions*

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**Figure 1 | Prompt Emission Light Curve:** The Konus-Wind background-subtracted γ-ray lightcurve (black), shown relative to the Swift BAT trigger time. T<sub>γ</sub>. Optical data from “Pi of the Sky” (blue) and TORTORA (red) are superimposed for comparison. The optical emission begins within seconds of the onset of the burst. The TORTORA data have a gap during the slew of the RCM telescope to this field, but show 3 sub-peaks in the optical brightness, reaching a peak brightness of 5.3 magnitudes (white). The γ-ray light curve has multiple short peaks; these are not well correlated with the optical peaks in detail (cf. ref 25), but the optical pulses may be broader and peak somewhat later than the γ-ray pulses. If the optical is slightly below the synchrotron self-absorption frequency, which may account for the lack of detailed correlation. The optical flash, however, begins and ends at approximately the same times as the prompt γ-ray emission, providing strong evidence that both originate at the same site. See...
Figure 2 | Composite Light Curve. Broadband light curve of GRB 080318B, including radio, NIR, optical, UV, X-ray and γ-ray flux densities. The UV/optical/NIR data are normalized to the UVOT v-band in the interval between $T_0 = 500$ s and $T_0 = 500$ ks. The Swift-BAT data are extrapolated down into the XRT bandpass (0.3-10 keV) for direct comparison with the XRT data. The combined X-ray and BAT data are scaled up by a factor of 40, and the Konus-Wind data are scaled up by a factor of $10^4$ for comparison with the optical flux densities. This figure
Figure 4 | Schematic of Two-Component Jet Model. Summary diagram showing spectral and temporal elements of our two-component jet model. The prompt γ-ray emission is due to the internal shocks in the narrow jet, and the afterglow is a result of the forward and reverse shocks from both the narrow and wide jets. The reverse shock from the narrow jet is too faint to detect compared to the bright wide jet reverse shock and the prompt emission. If X-ray observations had begun earlier, we would have detected X-ray emission during the prompt
Supplementary Figure 7 | Two-Component Jet Model fit to X-ray Afterglow.

The X-ray afterglow is best described by the superposition of two broken power-laws, which is consistent with the narrow and wide jets of a two-component jet expanding into a stratified wind environment. The narrow jet dominates the first ~40 ks of the afterglow as indicated by the blue line, which shows the fit to the narrow jet component. After the narrow jet break decays, the wide jet dominates as indicated by the green line fit to late afterglow. The red line shows the superposition of both components and the overall fit to the X-ray light curve.
Supplementary Figure 6 | Three-Spectral Component Fit to the Decaying Optical Transient. Following the peak of the prompt optical flash, the optical transient light curve displays three distinct components that dominate in the intervals $t<50\text{s}$, $50\text{s}<t<800\text{s}$, and $t>800\text{s}$. The initial decay of the bright optical flash is a power-law with $\alpha_1=8.5\pm0.9$ (dotted line). This is superimposed on a power-law with decay index $\alpha_2=2.49\pm0.09$ (dashed line) that dominates in the middle time interval and a third power-law with $\alpha_3=1.25\pm0.02$ (dot-dashed line).
HE delayed onset in long and short GRBs

- The first LAT peak coincide with the second GBM peak
- Delay in HE onset: ~4-5 s

- The first few GBM peaks are missing in the LAT but later peaks coincide
- Delay in HE onset: 0.1-0.2 s
GRB 080916C

Spectrum : simple (~)

- “Band” fits (joint GBM/LAT) for all the different time intervals
- Soft-to-hard, to ”sort-of-soft-peak-but-hard-slope” afterglow
- No evidence for 2nd component
**BUT:** Extra power-law component

**GRB 090902B**

- Interval $b$ ($T_0 + 4.6 \text{ s} \text{ to } 9.6 \text{ s}$):
  $\Delta \text{ CSTAT} = 3165$, ($\geq 1000$ for GBM only)
- This is the first time a low-energy extension of the power-law component has been seen

Plethora of Models

- Radiative $e^\pm$ ext. shock (Ghisellini et al)
- Unmag. adiab. ext. shock (Kumar & Barniol)
- Critique thereof (Piran & Nakar)
- Klein-Nishina IC ext. shock (Wang, He, ..)
- Structured adiab. ext. shock (Corsi et al)
- Cocoon int. shock upscattering (Toma et al)
- Photosp. int. shock upscattering (Toma et al)
- Critique phot & magn. outflow (Zhang, Pe’er)
- Hadronic models (Razzaque et al, Asano et al)
Radiative ext. shock model
Ghisellini et al, 0910.2459

- GeV light curves roughly $F_E \sim t^{-1.5}$ for most LAT obs.
- Spectrum roughly $F_E \sim E^{-1}$, not strongly evolving
- Argue it is external shock, with $L \sim t^{10/7}$ as expected for `radiative' f`balls $\Gamma \sim r^{-3} \sim t^{3/7}$
- To make `radiative', need `enrich' ISM with $e^\pm$
- Argue pair-dominated f`ball obtained from backscatt. of
  $E>0.5$ MeV photons by ext. medium, $\rightarrow$ cascade
- External shock (afterglow) delay: explain GeV from
  MeV delay (MeV prompt is something else (?))

- Problem: $r \gtrsim 10^{15}$ cm needed, where $n_{\pm} \approx n_p$ (e.g. '01, ApJ 554,660)
Adiabatic unmagn. ext. shock

Kumar & Barniol Duran, I, II : arXiv.0905.2417, 0910.5726

- Consider late (>4 s) afterglow at >100 MeV
- $E > E_c$, $E_m$ (sync.) $\Rightarrow$ spectrum indep. of $\Gamma$, $n$
- $F_E \sim t^{-1.2 \pm 0.2} \Rightarrow$ as adiabatic ext. shock
- At $t < 4s$ argue KN significant ($\gamma \approx 1$)
- Derive $\varepsilon_B$, $n$ from argument that ES at $t < 50$ s should not dominate spectrum at $<500$ keV (which is unspecified 'prompt' emiss.)
- $\rightarrow$ ES params. from $>0.1$ GeV predict XR, O $\checkmark$
- $\rightarrow B' \sim 0.1G \rightarrow B_{ext} \sim 10-70 \mu G$ shock comp. $\checkmark$
Adiab. Unmagn. ES (cont.)

- Smooth match of unspecified prompt and afterglow considered not implausible ('natural')
- $080916\mathrm{C}: \mathrm{XO} \rightarrow \rho \sim r^{-2} \text{ wind, }$
  $090902\mathrm{B}, 090510 \rightarrow n \sim 1 \times 10^{-3}, 10^{-1} - 10^{-5}$

- PROBLEMS:
  - Densities rather low
  - In SNR shocks have indications for $B >> B_{\text{compr.}}$
  - Adiabaticity reliant on low $n$ (param. fit assumptions)
• Confirm previous, expand a bit (but c.f. Piran-Nakar)
• Argue $B_{\text{ext}} \approx \text{few } 10 \, \mu \text{G}$ enough to accel. $e^{-}$ to $\gamma \approx 10^{8}$ in a few seconds, such that: $\nu_{\text{sy}}(\gamma) \approx 10 \text{ GeV}$, provided $\text{Rev.Sho. } F_{\text{pk}} \leq 1 \text{ Jy (for 10 GeV), or } \leq 0.1 \text{ Jy (for 1 GeV)}$
• For $\gamma \approx 10^{8}$ (10 GeV Sy photon) $\rightarrow$ need 4-5 s acc.time, and $\gamma \approx 10^{7}$ (1 GeV Sy photon) a bit earlier.
ES Sy shock model critique

Piran-Nakar, 1003.5919

• Late photons (E > 10 GeV, t > 100 s) cannot arise from ES Synchrotron (from general accel + sy constraints) → must be ≠ process

• few mJy IR flux from RS → quench GeV emiss. (by IC), unless B is amplified in shock

• If no amplification → need $B_{ext} \geq 100 \mu G$ (adiabatic; unless $n_{ext}$ very low, $n<10^{-6}$) - or B higher for radiative

• If ES Sy model is true,
  → no late >10 GeV phot (t>100 s), and
  → no simult.. < mJy IR flux should be observed

--- Other recent ES Sy critique: Zhuo Li, 1004.0791, argue need $5n_{0}^{5/8} mG < B_{u} < 10^{2} n_{0}^{3/8} mG$ → upstr. preamplification
KN adiabatic ES model

• KN effects influence IC emission through Y parameter
• Calc. $Y(\gamma)$, where $\nu_{\gamma} = 0.1\text{GeV}$; also calc. $Y(\gamma_{c}), Y(\gamma_{m})$
• At $t \leq 10$ s, $Y(\gamma_{c}) \leq 1$ (SSC in KN) $\rightarrow 0.1$ GeV is SY (and strong)
• but $Y(\gamma_{c}, \gamma_{m}) \gg 1$ $\rightarrow$ this SSC is NOT in KN $\rightarrow$ X, O are low
• $Y(\gamma_{c})$ incr. in time (KN gets weaker) $\rightarrow$ SY GeV gets weaker
  $\rightarrow$ Light curve steeper than simple $t^{-1.2}$ adiab. decay
• Early steep LAT decay (SY modif. by SSC w. decr. KN), followed by flatter decay (SY w/o SSC)
• Argue Kumar’s late X not steep enough & early LAT too flat, while KN can make LC in LAT & X steeper, as seen

Wang, He et al, 0911.4189  (see poster)
ES shock model: 090510

Corsi, Guetta, Piro, arXiv:0911.4453

- ES: fit LAT, X, O, 
  $\Gamma_n \sim 10^4$, 
  $E_{iso,n} \sim 4 \times 10^{53}$, 
  $\varepsilon_e \sim 3 \times 10^{-3}$, 
  $p \sim 2.3$, $n \sim 10^{-6}$, 
  $\theta_{j,n} \sim 0.12^\circ$

- IS: fit GBM, BAT, 
  $\Gamma_w \sim 300$, 
  $E_{iso,w} \sim 1.7 \times 10^{53}$, 
  $\varepsilon_e \sim 3 \times 10^{-3}$, 
  $p \sim 2.7$, 
  $\theta_{j,w} \sim 0.64^\circ$

Or, another IS + ES model: De Pasquale et al '09, next slide
IS-ES shock model: 090510


- Early LAT and XRT could be due to IS and O rise could be due to onset of simple FS
- Or, FS may produce full spectrum from O thru GeV, but temporal behavior → structured jet
A Cocoon + IS Upscattering model of GRB lags, for GRB 080916C

- Assume jet emits synchrotron in optical, and 1st ord SSC is in MeV
- Cocoon emits soft XR, jet upscatters this to ~0.3 GeV; time lag ~3s
Property (ii): Delayed Onset of HE emission

We consider an external inverse Compton radiation as the HE component, i.e., up-scattering of delayed soft photons off the electrons accelerated in the jet which emits the MeV component.

Seed photons?
- Jet breakout X-rays? - No. This is prior to the MeV emission.
- Cocoon X-rays? - Yes! This is energetic and may be delayed.
- Supernova shock breakout? - This is behind the cocoon.

Hydrodynamical simulation by Morsony et al. 2007
Property (iii): High-energy lag within the 2nd pulse

Inverse Compton scattering of photons coming from the rear by electrons in the jet is stronger in the high latitude region for the observer.

The IC emissivity of the head-on collisions is much larger than that of the rear-end collisions in the jet rest frame. The IC emission is stronger from the high-latitude region in the observer frame.

The pulse peak of the EIC emission lags behind those of synchrotron and SSC emission, which are isotropic in the jet rest frame, on the angular spreading timescale $\sim r/(2c\Gamma^2)$ (cf. Aharonian & Atoyan 1981, Wang & Meszaros 2006, Fan et al. 2008).
Photon time lags

- photon arrival time in different energy bands
- GeV band: delayed 2-3 s, due to geometry (source photons come from high latitude cocoon)
Cocoon + jet IS

- $L_{55} = 1.1$
- $\Gamma_3 = 0.93$
- $\Delta t = 2.3$ s
- $\gamma_m = 400$
- $\gamma_c = 390$
- $\tau_T = 3.5 \times 10^{-4}$
- $\varepsilon_B = 10^{-5}$
- $\varepsilon_e = 0.4$

Data: courtesy of Fermi GBM/LAT coll.
Photosphere + IS model

Toma, Wu, Mészáros, arXiv:1002.2634

Photosphere and internal shock of the GRB jet

- Photosphere: prompt, variable MeV
- IS occur at $r \gtrsim 10^{15}$ cm (high $\Gamma$): $S_{y}=XR$, $IC(UP)=GeV$
**Phot-IS model, cont.**

**Temporal properties: a simple two-shell collision**

The electrons in the internal shock of two given shells can upscatter their own photospheric emission.

\[ l_{ns} = c(1 - \beta_r) l_i = \frac{1 - \beta_r}{\beta_r - \beta_s} c t_r \approx \frac{\Gamma^2}{\Gamma_r^2} c t_r \ldots < W/2: \text{efficient scattering regime} \]

(The case of \( W \sim c t_r \) is included.)

\[ t_{\text{delay}} = (W + c t_r + l_{ns}) / c \sim W / c \ldots \text{(pulse duration of the photospheric emission)} \sim 0.01-0.1 \text{ s} \]

This kinematic delay could explain the observed high-energy delays of short GRBs. For long GRBs, we will propose alternative explanation.
Phot-IS model, cont.

Broadband spectrum for the high baryon load case

This figure does not take into account the secondary emission by the $e^+e^-$ pairs created by the high-energy absorption (and the cascade process), which could make the UP, synchrotron, and SSC emission appear as a broad component. To derive a more
A distinct, bright UP emission does not need a strong fine tuning of the physical parameters, but the appropriate parameter ranges are limited, which is consistent with the fact that not all the LAT GRBs have a distinct high-energy component.
Phot-IS model, cont.

A possible origin of the large high-energy delay of long GRBs

The parameters of the long GRB jet could evolve as shown by the thick arrow. The delay of the UP emission corresponds to the light crossing time of the high dissipation portion of jet, which may be $\ll 10^9$ cm/c $\sim 0.3$ s.

(i) initially have $r_a/\Gamma_a \sim 10^{10}$ cm, $r_{\text{coast}} > r_{\text{ph}}$, $\rightarrow$ Phot. dom, dim UP
(ii) later have $r_a/\Gamma_a \sim 10^7$ cm, $r_{\text{coast}} < r_{\text{ph}}$, $\rightarrow$ Phot. dom, UP dom

$\downarrow$ $\Rightarrow$ delay
Photosp. critique: mag. outflow?


- Argue (based on $r_a \sim c \tau_{\text{var}}$ and assuming 080916c Band is ES sy) that the photosphere radius $r_{ph}$ is too low (below $T_{\gamma\gamma} \sim 1$), and its $T_{ph}$ too low to be MeV; also object to phot. thermal spectrum

- Hence conclude outflow probably Poynting, or at least much more baryon-poor than usual baryonic fireball

- However, underestimated $r_{ph}$ and its $T_{ph}$; especially if include additional $e^\pm$ and use more recent numerical simulations of jet/phot/cocoon, e.g. Morsony 09.

- This is what is used in the Toma et al. phot+IS model, where $T_{ph} \sim$ MeV (i.e. GBM), without invoking Poynting, and IS-UP provides LAT, either as Band or Band+PL
Proton Sy model: 080916C

- GBM range: produced by primary $e^-$ sy (dark line, 1st pulse)
- LAT range: $p^+$ sy (2nd pulse, color curves), moving down in energy and up in flux with incr. time
- 2nd gen’tn $e^-$ sy comp. (from $\gamma\gamma$) appears in KeV to MeV range

Razzaque, Dermer, Finke, arXiv:0908.0513
GRB 090510

- Fermi LAT/GBM identified **SHORT** burst
- Shows (sim. to long bursts) time **LAG** between soft 1st pulse and hard 2nd pulse
  - **LIV** limit even more severe than in GRB 080916C - in fact, most severe limit to date!
- Shows an **EXTRA** spectral component, besides usual Band component (first clear!)
GRB 090510

Short burst
LAT/GBM, shows lags
Abdo, et al. 09
(LAT/GBM coll.)
Nature, 462:331

Spectrum:
clear 2nd comp (5σ)
Hadronic model of extra comp:

**GRB 090510**

Asano, Guierec, Mészáros, 09
ApJL, 705:L191

Secondaries from photomeson cascades ✔
(but: need $L_{\text{iso}} \sim 10^{55}$ erg/s !)

Secondary photons ↑

Secondary neutrinos →

(not detectable, for this burst)
General issues about prompt & high energy

- GBM to LAT ratio implications
- Radiation mechanism issues: turbulence? Poynting? ...
LF of GBM/LAT GRB

Guetta, Pian, Waxman, arXiv:1003.0566

- LF (GBM) ~ LF(Swift, BATSE)
- LAT non-det. \( \Rightarrow \) ratio \( R = \frac{F(100\text{MeV})}{F(1\text{MeV})} \) is \( \leq 0.1, 0.3, 1.0 \) for 5%, 30%, 60% of bursts, and for most bursts: \( R \leq 1 \)
- Models where 1MeV is IC of Opt. \( \rightarrow R > 1 \) \( \rightarrow \) ruled out
- If ~1 MeV is fast cool’g \( (F_\gamma \sim E^{-p/2}) \) then either
  i) \( N(\gamma) \) not PL, or
  ii) high pair opacity, \( \rightarrow \Gamma \leq 300(L_{52} t_{-2})^{1/6} \)
- ( BUT most estimates: \( \Gamma \geq 1000 \) )
Relativistic turbulent model

• Objections to IS model (unchanged since ~1999):
  i) fast cool → spectrum $F_\nu \sim \nu^{-1/2}$;
   ii) Acell. all e- → $\nu_{pk}$ below MeV;
   iii) Low rad. efficiency;

• Propose: relativistic eddys of $\gamma_t$ in frame of bulk $\Gamma$

• Shock radius $R$, shell size $r \sim R/\Gamma$ in shell frame

• Max. size of eddy in eddy frame: $r_e \sim r/\gamma_t, \sim R/\Gamma \gamma_t$

• Expect eddys to move ballistically for $r_e$, collide w. another eddy and change directions, etc., $\gamma_t$ times

Relat. Turb., cont.

- Eddy changes directions $\gamma_t$ times, cum. change $\sim$radian over its lifetime
- Eddy visible when its light cone intersects observer LOS
- Calculate no. of eddies, conclude have:
  $t_{\text{burst}} \sim R/\Gamma^2c$,  
  $t_{\text{var}} \sim R/\Gamma^2\gamma_t^2c$,  
  and  $n_{\text{pulse}} \sim \gamma_t^2$,  

Possible problem: after each “causal time” (change direction) 
→ would also shock → thermalize, $\gamma_t \rightarrow$ unity, 
after only a few changes of direction (instead of $\gamma_t$ changes); 
Can isotropic turbulence survive as relativistic for any time?
ICMART model
(IC MAgnetic Reconnection Transient) - Zhang, Yan, ’10

- Int. coll. w. $1 \leq \sigma \leq 100$, where $\sigma = \frac{B'^2}{4\pi \rho' c^2}$ (MHD)
- Magn. reconn. in intern. shock (aided by turbulence)
- Accel e⁻: direct (recon.) or stochast. (turb.) $\rightarrow$ rad: SY
- Need reconn. over $\lambda_{\text{par}} \leq 10^4$ cm lengths, envisage blobs w. same directions spiral but staggered, have $\downarrow \uparrow$ regions of $B_{\text{perp}}$ $\rightarrow$ turb. resist. $\rightarrow$ reconn. (early colls. distort $B$, at large r much distort., recon)
ICMART model, cont.

(a) Initial collisions only distort magnetic fields

(b) Finally a collision results in an ICMART event
ICMART model, cont.

- Reconnect at \( r \gtrapprox 10^{15} \) cm, there \( \sigma_f \approx 1, Y \approx 1 \), no IC
- \( n_{e,p} \sim 1/(1+\sigma_i) \ll n_e \) (bar. models) \( \rightarrow \) weak photo.
- \( n_p \) also \( \ll \) than baryon model, \( \rightarrow \) no hadr. comp.
- \( E_{pk} \) drops during pulse, hard to soft evol.
- Reverse shock possible, at late stage \( \sigma_f \sim 1 \).
- Solve: i) low effic.; ii) fast coolg sp.; iii) electron excess; iv) no bright photosph. (need \( \sigma < 3 \times 10^3 \))

(Other recent MHD model: Granot et al arXiv:1004.0959 - dynamics mainly)
Other recent theoretical papers
(won’t have time to discuss, sorry)

- Acceleration of high-σ relativistic flow: Granot et al, arXiv:1004.0959
- Dynamics of strongly magn. ejecta in GRB: Lyutikov, arXiv:1004.2429
- Accel. of UHECR in blazars & GRB: Dermer, Razzaque, preprint
- Leptonic & hadronic model GRB 090510, Razzaque et al, preprint
Prospects & Perspectives

- Swift and Fermi have greatly expanded and deepened our probing into the GRB physics.

- Jet structure is essential, and being probed; also the role and existence/absence of reverse shocks.

- Prompt emission mechanisms are being challenged: new factors may play role - pairs, hadrons, magnetic fields, photospheres, turbulence, reconnection, ...

- Debated whether magnetic fields play larger role than previously assumed - quantitative magnetic models remain sketchy; so do turbulent/reconnection models. They warrant continued attention, together with pair, photosphere, cocoon, leptonic and hadronic models.