Prompt emission mechanisms of GRBs

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Structure of the talk

- Main properties of the prompt emission
- Models for the GRB flow
  - Fireballs
  - Poynting-flux dominated flows
    - Reconnection model
- Dissipative mechanisms for the prompt emission
  - Internal shocks vs Magnetic reconnection
- Radiative mechanisms
  - Thomson thin vs photospheric emission
- Summary
The prompt emission spectrum

- The typical GRB spectrum has **non-thermal** appearance
  Band et al. 1993; Kaneko et al. 2006
  - Low energy power law slope $\alpha$
  - High energy power law slope $\beta$
  - Connected at ~a few hundred keV (spectral peak)

- Short bursts are harder, probably because of steeper low energy slope
  Paciesas et al. 2003; Ghirlanda et al. 2004
GRB Variability

- Variability detected to as short as sub-msec timescales
- Variable lightcurves composed by pulses Fenimore et al. 1995; Norris et al. 1996
- The typical pulse width is $\delta t \sim 1$ sec (~0.1 sec) for long (short) bursts
Summary for the prompt emission

- **Clues**
  - The prompt emission has
    - *non-thermal* spectral appearance Band et al. 1993; Preece et al. 1998
    - *Rapid* variability
  - The GRB-emitting flow is *ultrarelativistic* ($\gamma > 100$) e.g. Piran 1999

- **Big questions**
  - How is the flow accelerated?
  - What processes result in the observed spectral and temporal properties of GRBs?

- Can we learn something about the central engine?
General considerations: Acceleration

- Important quantities of the flow:
  - luminosity $L$
  - mass flux $\dot{M}$
  - Baryon loading: $\eta = \frac{L}{\dot{M}c^2} \gg 1$
  - Efficient acceleration can lead to $\gamma_{sr} \sim \eta$

- Depending on the energy extraction mechanism, the flow can be dominated by:
  - Thermal energy $\rightarrow$ thermal acceleration (*Fireball*
    Paczynski 1986; Goodman 1986; Sari & Piran 1991
  - Magnetic energy $\rightarrow$ magnetic acceleration (*Poynting-flux dominated flow*
    Usov 1992; Thompson 1994; Mészáros & Rees 1997; Drenkhahn & Spruit 2002; Lyutikon & Blandford 2003
Fireballs

- Parameters: \( L, \eta, \) initial radius \( r_0 \)

- Go through fast acceleration \( \gamma \propto r \)
  - Converting thermal energy into kinetic

- Saturation takes place when
  - \( \gamma_{\text{sr}} \eta \) \( \approx \) \( \gamma_{\text{sr}} \eta \)
  - at the photospheric crossing \( \gamma_{\text{sr}} < \eta \)

- Radiation and matter decouple when \( \tau \approx 1 \)
  - Photospheric emission takes place

[Notation: \( (L = L_{52}10^{52} \text{ erg/s}) \)]
Magnetic (Poynting) models

- The field can be
  - axisymmetric (DC flow)
    - Vlahakis & Königl 2003; Lyutikov & Blandford 2003; McKinney 2005; Uzdensky & MacFadyen 2006
  - highly asymmetric (AC flow)
    - Drenkhahn & Spruit 2002; Thompson 2006

- Acceleration is more gradual
  - Drenkhahn & Spruit 2002; Vlahakis & Königl 2003

- Here, I focus more on AC flow
The reconnection (AC) model

- Magnetic field changes polarity on small scales $\lambda = 2\pi c/\omega$

- Magnetic reconnection proceeds with a fraction $\varepsilon \sim 0.1$ of the Alfvén speed Lyubarsky 2005

- The dynamics of the flow have been worked out in detail Drenkhahn 2002 and Denkhahn & Spruit 2002; see also Lyubarsky & Kirk 2001 for pulsar winds

- Parameters: $L, \eta, (\varepsilon \omega)$

\[
\gamma = \gamma_{sr} \left( \frac{r}{r_{sr}} \right)^{1/3},
\]

\[
B' \propto r^{-4/3},
\]

\[
n' \propto r^{-7/3},
\]

\[
P'_{\text{diss}} = \frac{(B')^2}{8\pi t_{\text{diss}}} \propto r^{-3}
\]
These are all fine
Where are the $\gamma$-rays in this picture?

- Which processes power the prompt emission?

- Where (at which radii) is it produced?
General considerations:
energy source of the prompt emission

- The rapid GRB variability argues against the forward shock for the prompt emission
  e.g. Sari & Piran 1997; see however Dermer 2007 for a different point of view

  - Observationally: transition from the prompt to the early afterglow emission
    Zhang et al. 2006

  The prompt emission most likely comes from *internal* dissipation of energy in the fast flow

- This can take place by

  - Internal shocks Rees & Mészáros 1994; Sari & Piran 1997
  - Magnetic dissipation Thompson 1994; Denkhahn & Spruit 2002; Lyutikov & Blandford 2003
    - see Fan et al. 2004 for a combination of the two
Internal shocks vs Magnetic dissipation

- **Internal shocks**
  - Unsteady flow composed by many, fast shells
  - A fast shell with $\gamma_2 > \gamma_1$ collides with a slower one dissipating their relative kinetic energy through shock waves

- **Magnetic dissipation**
  - Magnetic fields carry most of the energy of the flow
  - The magnetic energy is dissipated internally through reconnection
  - Variability and dissipation are separate ingredients in magnetic dissipation models
Where is the prompt emission produced?

- anywhere between the Thomson photosphere $r_{ph}$ and the deceleration radius $r_d$

- Typically $r_{ph} \sim 10^{11} \text{cm}$ and $r_d \sim 10^{17} \text{cm}$; in this range of radii
  - density \sim 12 orders of magnitude
  - optical depth \sim 6 orders of magnitude

Different radiative mechanisms depending on the location of the energy dissipation

- **Case 1: Thomson thin dissipation**
- **Case 2: Photospheric dissipation**
Case 1
Internal shocks in the Thomson thin regime

- Internal shocks
  - The collision of the shells takes place at $r_{\text{col}} \sim \gamma^2 c t_v$
    - $t_v$ related to the central engine activity (not trivially! Janka et al. 2005; Aloy & Rezolla 2006)
    - Each collision results in an observed pulse of gamma-rays

- Shocks cross the shells

- In the shock front
  - Particle acceleration takes place
  - Magnetic field amplification due to plasma instabilities (see next talks!)

- Parameters: fractions $\epsilon_e, \zeta_e, \epsilon_B$, power-law $N(\gamma_e) \sim \gamma_e^{-p}$, $p \geq 2$

- Fast particles + magnetic fields Synchrotron self-Compton emission

- Thin synchrotron emission may explain the observed spectrum
Case 1
Can thin Synchrotron emission explain the spectra?

- **Pros**
  - For $t_v \sim 1$ s the characteristic pulse duration and separation can be reproduced
    Kobayashi et al. 1997; Daigne & Mochkovitch 1998; Nakar & Piran 2002
  - The peak of the synchrotron spectrum can be in the $\sim$ a few 100 keV range
  - Flat high-energy power law

- **Cons**
  - Low radiative efficiency (though uncertain)
    $\sim \epsilon_{\text{diss}} \epsilon_e \epsilon_{\text{Band}}$ at the $\sim \%$ level
  - Low-energy spectra often too steep for thin synchrotron
e.g. Preece et al. 1998; Ghirlanda et al. 2004
    - jitter radiation Medvedev 2000
  - The synchrotron spectrum gets distorted by Self Compton emission, pair creation for a large parameter space
    Kobayashi et al. 2002; Mészáros et al. 2002
Case 1
Magnetic dissipation in the Thomson thin regime

- In DC models, the magnetic energy can be dissipated because of MHD instabilities
  - e.g. current driven instabilities at \( \sim 10^{16} \) cm Luytikov & Blandford 2003; Lyutikov 2006
  - Fast proper plasma motions lead to the rapid observed variability

- AC model: dissipation near photosphere as well as outside
  - Significant amount of energy is dissipated in Thomson thin conditions DG & Spruit 2005

- Particle acceleration through electric fields in current sheets
  e.g. Craig & Litvinenko 2002; Zenitani & Hoshino 2004

- Thin synchrotron emission may be responsible for the GRB
  - The B-field is given directly by the model
  - At low densities particle distributions in reconnection uncertain
Case 2

Photospheric emission is radiation, advected with the flow, that is released when the flow becomes optically thin.
Photospheric emission

- In the fireball the photospheric luminosity is e.g. Mészáros & Rees 2000
  \[ \frac{L_{\text{ph}}}{L} \approx 0.05 \frac{\eta_{2.5}^8}{2.3} \frac{r_{0.7}^5}{L_{2.3}^2}, \quad \eta < 1000 \left( \frac{L_{52}}{r_{0.7}} \right)^{1/4} \]

  - Spectrum quasi thermal Goodman 1986
  - Energy dissipation at \( \tau \geq 1 \) distorts the spectra
    Mészáros & Rees 2005; Pe’er et al. 2006

- In the AC model DG 2006; DG & Spruit 2007
  \[ \frac{L_{\text{ph}}}{L} \approx 0.16 \frac{L_{52}^{1/5} (\varepsilon \omega)^{1/5}}{\eta_{2.5}}, \quad \eta \geq 150L_{52}^{1/5} (\varepsilon \omega)^{1/5} \]

- For this range of \( \eta \), the model predicts a dissipative photosphere
Dissipative Photosphere in a fireball

- Internal shocks take place below the photosphere for $t_v << 1$ s
- Pe’er et al. (2006) - energy release close to the fireball’s photosphere – Thompson et al. 2007
  - Injecting fast electrons
  - Slow heating Ghisellini & Celotti 1999
- Studied the radiative transfer for various values of $\epsilon_{\text{diss}}, \epsilon_B, \epsilon_e, \tau$
- Big variety of spectra depending on $\tau$
- Dominant process: Compton scattering of photons advected with the flow
Our suggestion: photospheric emission from the AC model

Main features

- **AC model**: gradual dissipation through the photosphere.
- **If** the fraction $f_e \sim$ fraction of energy goes to the electrons then:
  - Hot photosphere
  - Soft photon upscattering
- ** Unsaturated Comptonization spectrum with** $DG\ 2006;\ DG\ & Spruit\ 2007$
  - Peak in the sub-$\text{MeV}$ range
  - Flat high-energy emission
  - Steep low-energy slopes
- **Rather high efficiency** $L_{ph} \sim 0.03 \ldots 0.3L$, for $100 \leq \eta \leq 1500$
Radiative transfer: analytical estimates + Monte Carlo Comptonization

- Deep in the flow, radiation & particles are in thermal equilibrium

- At $r_{eq} \sim r_{ph}/10$, radiation and electrons drop out of equilibrium
  - $T_{eq} \sim 1$ keV; $T_{obs} = \gamma_{eq} T_{eq} \sim 100$ keV

- For $r > r_{eq}$ balance in heating and cooling determined $T_e$
  - Mildly relativistic temperatures at $\tau \sim 1$
  - Soft photon up scattering
Photospheric spectra

- *Characteristic* peak at ~1 MeV *(in the central engine frame)*

- *Flat* power law high energy tails *(unsaturated Comptonization)*

- Quasi-thermal spectrum for high baryon loadings the spectrum
  - May be relevant for a sub-group of bursts Ryde 2004; 2005

- Analytical fitting formulas give the spectra as a function of the characteristics of the flow
  DG & Spruit 2007
Inferences for the central engine: the stronger the cleaner?

- The Amati relation explained if $\eta \propto L^{0.6}$ in different bursts

- Variability in prompt emission
  - Reflects changes in $L$, $\eta$

- Assumption: $\eta \propto L^{0.6}$ relation holds during the GRB
  - the model predicts the observed narrowing of pulses with increasing energy

Fenimore et al. 1995
Summary

- Spectral and temporal properties of GRBs are very intriguing

- The prompt emission most likely comes from *internal* dissipation of energy in the fast flow
  - Internal shocks or Magnetic dissipation

- Dissipation can take place in Thompson *thin* or *thick* conditions
  - Thin case: particle acceleration uncertainties $\epsilon_e, \zeta_e, p, \epsilon_B$

- Gradual dissipation throughout the photosphere has very promising properties
  - The reconnection model has them
The peak energy and the energetics
Comment

The temperature of the flow at the $r_{\text{eq}}$ in the observer frame is

$$T_{\text{eq}}^{\text{obs}} \approx \frac{\gamma (r_{\text{eq}}) T_{\text{eq}}}{1 + z} \approx 100 \frac{f_{e,1} L_{52}^{1/9} (\varepsilon \omega)^{1/3}}{1 + z} \frac{\eta_{2.5}^{2/9}}{\text{keV}}$$

The $E \cdot f(E)$ spectrum of this component peaks at $\sim 4$ times this energy.