Photospheric emission in GRBs

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Jet energy per photon $\bar{E} \approx 4 r_{0.7}^{-1/2} L_{52}^{1/4}$ MeV

Photospheric radius: $R_* \approx 10^{10} L_{52} \Gamma^{-3}_3$ cm

($r_0$ – base of the jet,
$L$ – isotropic equivalent of kinetic luminosity)

Photospheric radiation:
-- strong in jets with $\Gamma > 500$
-- peaks at $\sim$ MeV
-- released at radii $\sim 10^{11}$ cm (explains ms variability)
Emission from a passively cooling fireball
$Y_e = \frac{n_p}{n_p + n_n}$ - proton fraction (charged nucleons)
Nuclear composition of GRB jets

<table>
<thead>
<tr>
<th>Nucleosynthesis</th>
<th>Big bang</th>
<th>GRB</th>
</tr>
</thead>
<tbody>
<tr>
<td>$kT$</td>
<td>80 keV</td>
<td>140 keV</td>
</tr>
<tr>
<td>expansion timescale</td>
<td>$10^2$ s</td>
<td>$10^{-5}$ s</td>
</tr>
<tr>
<td>$\frac{n_X}{n_b}$</td>
<td>$10^{10}$</td>
<td>$10^5$</td>
</tr>
<tr>
<td>reaction rate expansion rate</td>
<td>10</td>
<td>$\sim 1$</td>
</tr>
<tr>
<td>$\frac{n_n}{n_p}$</td>
<td>$\frac{1}{7}$</td>
<td>$&gt; 1$</td>
</tr>
</tbody>
</table>

![Graph showing mass fraction vs. kT, MeV with curves for BB, GRB, d, and α particles.](image-url)
1. Jets with $\Gamma \sim 1000$ contain neutrons with $\Gamma \sim 100$.
   (Derishev et al. 1999; Bahcall, Meszaros 2000)

2. Neutrons migrate in variable jets (Meszaros, Rees 2000)

Compound flows ($\Gamma \gg \Gamma_n$) form at radius where $t_{\text{coll}} = t_{\text{exp}}$:

$$R_n = 5 \times 10^{10} \left( \frac{L_n}{10^{51} \text{erg/s}} \right) \left( \frac{\Gamma_n}{100} \right)^{-3} \text{ cm}$$
GRB jets contain a neutron component

\[ \Gamma_n < \Gamma \quad \text{at radii} \quad r > R_n = 5 \times 10^{10} \left( \frac{L_n}{10^{51} \, \text{erg/s}} \right) \left( \frac{\Gamma_n}{100} \right)^{-3} \, \text{cm} \]

Jets with \( \Gamma \sim 1000 \) contain neutrons with \( \Gamma \sim 100 \).

(Derishev et al. 1999; Bahcall, Meszaros 2000)

Neutrons migrate in the jet \quad (Meszaros, Rees 2000)
Collisional dissipation in jets with $\Gamma_n < \Gamma$

Each n-p collision dissipates energy $\Gamma \Gamma_{\text{rel}} m_p c^2$ where $\Gamma_{\text{rel}} \approx \Gamma / 2 \Gamma_n$.

Collisions produce $\pi^\pm$ and $\pi^0$.

\[
\pi^+ \rightarrow \mu^+ + \nu_\mu, \quad \pi^- \rightarrow \mu^- + \bar{\nu}_\mu, \quad \pi^0 \rightarrow 2\gamma \\
\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu, \quad \mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu
\]
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$$

$\Rightarrow$ Injection of $e^\pm$ with energy $\sim m_\pi c^2 \approx 140$ MeV

$\Rightarrow$ $e^\pm$ cascade radiating almost all $e^\pm$ energy

(Svensson 1987)
$e^+$ creation regulates the position of photosphere:

$$R_* \approx 20R_n$$
Collisional heating

\[ \frac{1}{n m_p c^2} \frac{dQ_{cp}}{d \ln r} \approx 0.02 \frac{\tau}{r} \]

\[ \approx 0.4 \frac{R_n}{r} \]

\[ \frac{1}{n m_p c^2} \frac{dQ_{nth}}{d \ln r} \approx \frac{1}{16} \frac{\Gamma}{\Gamma_n} \frac{R_n}{r} \]
Thermalized e+- population

Density:

\[ \frac{\Gamma c}{r^2} \frac{d}{dr} (r^2 n_\pm) = \dot{n}_\pm - \dot{n}_{\text{ann}} \]

⇒ Optical depth of the jet:

\[ \tau_T = \tau_0 \frac{R_n}{r}, \quad \tau_0 \approx 20 \]

\[ R_* \approx 20R_n \]

Temperature: regulated by balance between Coulomb heating and Compton cooling

\[ \frac{3}{2} \ln \Lambda \frac{\sigma_T n_\pm}{\beta_p} m_e c^3 n = 2n_\pm kT_e \frac{U_{\text{rad}} \sigma_T}{m_e c} \]

⇒ \[ kT_e \sim 10 \text{ keV}, \quad y = 4 \frac{kT_e}{m_e c^2} \tau_T \sim 1 \]
Photospheric radiation from collisionally heated jets

Jet radiates \(~50\% \) of its energy
Spectrum of GRB 080916C

(Abdo et al. 2009)
\[ \frac{dN}{d\ln E} = L_E \]

\[ \alpha = 0.4 \]

\[ \beta = 1.8 \]

\[ \Gamma = 300 \]

\[ \Gamma_n = 50 \]
Multi-GeV emission
(multi-MeV in jet frame)

-- suppressed in photospheric spectrum by $\gamma-\gamma$ absorption

-- observed as a separate component that is delayed by a few seconds and lasts longer than the main MeV emission

$\Rightarrow$ produced at large radii $r > 10^{15}$ cm.

[ Prompt optical radiation is produced at similar large radii (not self-absorbed). It is also observed with ~ second delay (Beskin et al. 2009). ]

Shocks?
Magnetic dissipation?
Neutron decay?
Neutron decay in GRB jets

-- source of huge heat ~ total energy of the jet

-- creates a perfect maser in the jet (cf. comets) and generates turbulence that may accelerate electrons.

\[ R_\beta = c \Gamma_n \tau_\beta \approx 3 \times 10^{15} \left( \frac{\Gamma_n}{100} \right) \text{ cm} \]

Strong dissipation begins at \( R_1 \sim \frac{\Gamma_n}{\Gamma} R_\beta \)

Delay of neutron-decay emission with respect to photospheric emission:

\[ \Delta t_{\text{obs}} = (1 + z) \frac{r}{2 \Gamma_n^2 c} \approx \frac{1 + z}{2} \left( \frac{\Gamma}{900} \right)^{-1} \left( \frac{r}{R_1} \right) \text{ sec} \]
Robust collisional heating operates in the jet below photosphere and converts > 30% of total energy to escaping radiation.

The resulting photospheric spectrum (released at r ~ 10^{12} cm) has the observed Band shape.
Summary

1. Baryonic jets contain neutrons and form compound flows $\Gamma \gg \Gamma_n$

2. Robust collisional heating operates in the jet below photosphere and converts > 30% of total energy to escaping radiation. The resulting photospheric spectrum (released at $r \sim 10^{12}$ cm) has the observed Band shape if $\Gamma > 500$.

3. Multi-GeV component:
   Produced at $r > 10^{15}$ cm by some form of collisionless dissipation. May be generated by neutron decay in the jet.