Multiple components in GRRB prompt emission and evidences for the IGC scenario

Luca Izzo

on behalf of a very large collaboration

Sapienza University of Rome and ICRANet Pescara

XIV Italian-Korean meeting - Pescara
**General introduction**

**Gamma ray bursts (GRBs)** are rapid flashes of soft gamma-rays → tens of keV up to tens of MeV photons

- connected to SNe
- extragalactic probes
- cosmological ruler (?)
- nucleosynthesis in the universe
- sources of GWs (?) and neutrinos
- QG with GRBs

GRBs are also multiwavelength sources (not only gamma-rays) → from radio to GeV frequencies (or energies...remember Planck)
Why GRBs are so interesting?

Three main arguments

1) The energy emitted isotropically in a GRB event can reach the value of $10^{54}$ erg, i.e. the equivalent of a solar mass but emitted in e.m. energy !!!

2) Their progenitors and mainly the emission mechanisms at the base of a GRB emission is still a mistery, even after more than 40 years after their discovery

3) The evidence that they are observed up to very high redshifts represents an important tool to study with more details the far universe and, at the same time, to understand a possible role of GRBs in the evolution of the universe
The discovery of GRBs

Vela satellites
Satellite-borne system for the detection of nuclear devices detonated in space

→ the major fraction of energy emitted by a nuclear detonation is found in an X-ray flash lasting less than ms

GRB670702 – the first GRB
Simultaneous detection by Vela IV and III a,b
(Klebesadel+ 1973 – Cline 1973)

First GRB: precursor + main event → no nuclear test !!!

First models: Colgate 1968 → GRB connected with Sne !!!
**GRB properties**

**Temporal features**

duration distribution : T90 classification
- GRBs with T90 < 2s → short GRBs
- GRBs with T90 > 2s → long GRBs

*(Kouveliotou 1993)*

Physical link → short GRBs are harder, long GRBs are softer

Environmental link : host galaxy of long GRBs are star forming
- Short GRBs location offset with respect to the galaxy
  → possibly explained by “kicks”

*(Fryer+ 1999)*
GRB properties

Additional temporal features

- power spectra analyses suggest GRBs are “chaotic” systems (Beloborodov 2000, Greco 2013)
- more bursts have more of their emission at the beginning (like a short …)
- FRED pulses and spiky emissions (Norris+ 1996)
- existence of precursors → a problem for many models No difference properties than the main events (Koshut+ 1995)
- distinct pulses in GRBs tend to be similar to each other (Ramirez Ruiz 1999)
GRB properties

Spectral properties

→ Non-thermal spectrum !!!

Integrated spectrum best-fitted with an “empirical” function
The Band model – two power-laws joined smoothly at a break energy
E0 (tens of keV)

\[
N_E(E) = \begin{cases} 
A \left( \frac{E}{100 \text{ keV}} \right)^\alpha \exp \left( - \frac{E}{E_0} \right), & \text{if } (\alpha - \beta) E_0 \geq E, \\
A \left[ \frac{(\alpha - \beta) E_0}{100 \text{ keV}} \right]^{\alpha - \beta} \exp (\beta - \alpha) \left( \frac{E}{100 \text{ keV}} \right)^\beta, & \text{if } (\alpha - \beta) E_0 \leq E,
\end{cases}
\]  

(1)

- not absolutely true → presence of other components
  1) at higher energies
  2) thermal component
GRB properties

"Typical" Prompt GRB Spectrum

$E^2 N_E$ (erg cm$^{-2}$ s$^{-1}$)

Photon Energy (MeV)

GBM
LAT

(Band+ 1993)
GRB properties

"Typical" Prompt GRB Spectrum

$E^2 N_E$ (erg cm$^{-2}$ s$^{-1}$)

Photon Energy (MeV)

Additional component At higher energies

(Ryde+ 2010)
GRB properties

"Typical" Prompt GRB Spectrum

$E^2 N_E$ (erg cm$^{-2}$ s$^{-1}$)

Photon Energy (MeV)

Thermal Component (?) seen in few GRBs

(Guiric+ 2011)
GRB properties
GRB properties

"Typical" Prompt GRB Spectrum

$E^2 N_E$ (erg cm$^{-2}$ s$^{-1}$) vs. Photon Energy (MeV)

Wrong Estimation of the GRB spectrum
GRB properties

GRB – SN connection

Long GRBs are commonly associated with the death of massive stars

The energy emitted in a GRB – corrected for the collimation - is comparable to the energy release in a typical SN ($10^{50} - 10^{52}$ erg)

(Paczynski 1986)

The close proximity of GRBs to star formation regions is not expected from degenerate merger models

(Bloom+ 1999, Fryer+ 1999)

Discovery of the energetic CC-SN associated with the underluminous GRB 980425

(Galama+ 1998)
**GRB properties**

**GRB – SN connection**

SN signatures emerge from GRB optical afterglow after 10-20 days

SNe Ibc characterized by broad lines (0.1c) - hypernovae

Two different GRBs associated with SNe ?

NB only spectroscopic confirmed SNe !!!

(Astori+2014)
GRB properties

GRB – SN connection

PROBLEM → when the GRB emission becomes sub-relativistic, it is no longer collimated so that the energy initially released in the jet must become visible to the observer (mainly in radio)  

(Waxman 2004)

No evidence of such emission...  
(Kulkarni+ 1998)

...also in SNe/HNe Ibc not related with GRBs  
(Soderberg+ 2004)

GRB progenitor problem (not discussed here)
GRB 090618

One of the most energetic and near GRBs

\[ E_{\text{iso}} = 3 \times 10^{53} \text{ erg} \]

\[ Z = 0.54 \]

complete e.m. coverage (radio to gamma)

Swift XRT afterglow
**GRB 090618**

**Mixed thermal – non thermal model:**

Blackbody + power-law

<table>
<thead>
<tr>
<th>Time Interval (s)</th>
<th>α</th>
<th>β</th>
<th>$E_0$(keV)</th>
<th>$\tilde{\chi}^2_{RAN,D}$</th>
<th>$kT$(keV)</th>
<th>γ</th>
<th>$\tilde{\chi}^2_{BB+po}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>A 0 - 50</td>
<td>-0.74 ± 0.10</td>
<td>-2.32 ± 0.16</td>
<td>118.99 ± 21.71</td>
<td>1.12</td>
<td>29.84 ± 1.38</td>
<td>1.67 ± 0.03</td>
<td>1.28</td>
</tr>
<tr>
<td>B 50 - 58</td>
<td>-1.12 ± 0.06</td>
<td>-3.50 ± 1.97</td>
<td>200.221 ± 30.94</td>
<td>1.19</td>
<td>30.14 ± 1.68</td>
<td>1.79 ± 0.04</td>
<td>1.37</td>
</tr>
<tr>
<td>C 58 - 69</td>
<td>-0.98 ± 0.02</td>
<td>-2.56 ± 0.09</td>
<td>302.664 ± 13.85</td>
<td>2.17</td>
<td>45.73 ± 0.66</td>
<td>1.67 ± 0.08</td>
<td>6.95</td>
</tr>
<tr>
<td>D 69 - 78</td>
<td>-1.04 ± 0.03</td>
<td>-2.42 ± 0.06</td>
<td>161.53 ± 11.64</td>
<td>1.55</td>
<td>29.29 ± 0.57</td>
<td>1.78 ± 0.01</td>
<td>3.05</td>
</tr>
<tr>
<td>E 78 - 105</td>
<td>-1.06 ± 0.03</td>
<td>-2.62 ± 0.09</td>
<td>124.51 ± 7.93</td>
<td>1.20</td>
<td>24.42 ± 0.43</td>
<td>1.86 ± 0.01</td>
<td>2.28</td>
</tr>
<tr>
<td>F 105 - 151</td>
<td>-2.63 ± 1</td>
<td>-2.06 ± 0.02</td>
<td>unconstrained</td>
<td>1.74</td>
<td>16.24 ± 0.84</td>
<td>2.23 ± 0.05</td>
<td>1.15</td>
</tr>
</tbody>
</table>

Counts

- **BB+po**
- **Band**
- **Power-law**

Time(s)
### GRB 090618

<table>
<thead>
<tr>
<th>Time</th>
<th>$\alpha$</th>
<th>$\beta$</th>
<th>$E_0$ (keV)</th>
<th>$\tilde{\chi}^2_{\text{BAND}}$</th>
<th>$kT$ (keV)</th>
<th>$\gamma$</th>
<th>$\tilde{\chi}^2_{\text{BB+po}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>A: 0 - 5</td>
<td>-0.45 ± 0.11</td>
<td>-2.89 ± 0.78</td>
<td>208.9 ± 36.13</td>
<td>0.93</td>
<td>59.86 ± 2.72</td>
<td>1.62 ± 0.07</td>
<td>1.07</td>
</tr>
<tr>
<td>B: 5 - 10</td>
<td>-0.16 ± 0.17</td>
<td>-2.34 ± 0.18</td>
<td>89.84 ± 17.69</td>
<td>1.14</td>
<td>37.57 ± 1.76</td>
<td>1.56 ± 0.05</td>
<td>1.36</td>
</tr>
<tr>
<td>C: 10 - 17</td>
<td>-0.74 ± 0.08</td>
<td>-3.36 ± 1.34</td>
<td>149.7 ± 21.1</td>
<td>0.98</td>
<td>34.90 ± 1.63</td>
<td>1.72 ± 0.05</td>
<td>1.20</td>
</tr>
<tr>
<td>D: 17 - 23</td>
<td>-0.51 ± 0.17</td>
<td>-2.56 ± 0.26</td>
<td>75.57 ± 16.35</td>
<td>1.11</td>
<td>25.47 ± 1.38</td>
<td>1.75 ± 0.06</td>
<td>1.19</td>
</tr>
<tr>
<td>E: 23 - 31</td>
<td>-0.93 ± 0.13</td>
<td>unconstr.</td>
<td>104.7 ± 21.29</td>
<td>1.08</td>
<td>23.75 ± 1.68</td>
<td>1.93 ± 0.10</td>
<td>1.13</td>
</tr>
<tr>
<td>F: 31 - 39</td>
<td>-1.27 ± 0.28</td>
<td>-3.20 ± 1.00</td>
<td>113.28 ± 64.7</td>
<td>1.17</td>
<td>18.44 ± 1.46</td>
<td>2.77 ± 0.83</td>
<td>1.10</td>
</tr>
<tr>
<td>G: 39 - 49</td>
<td>-3.62 ± 1.00</td>
<td>-2.19 ± 0.17</td>
<td>57.48 ± 50.0</td>
<td>1.15</td>
<td>14.03 ± 2.35</td>
<td>3.20 ± 1.38</td>
<td>1.10</td>
</tr>
</tbody>
</table>

### Graphs

- Left: Photon distribution in keV/cm² keV s².
- Right: Plot of $kT$ (keV) vs. time (s).
GRB 090618

Non-relativistic expanding thermal emitter

Matter accretion onto a NS in a binary system

Leading to a GRB

Understanding new physics !!!

See talks by Muccino, Pisani, Enderli...
GRB 090618

Parameter | Value
--- | ---
$E_{\text{tot}}^{e^+e^-}$ | $2.49 \pm 0.02 \times 10^{53}$ ergs
$B$ | $1.98 \pm 0.15 \times 10^{-3}$
$\Gamma_0$ | $495 \pm 40$
$kT_{th}$ | $29.22 \pm 2.21$ keV
$E_{p-GRB,th}$ | $4.33 \pm 0.28 \times 10^{51}$ ergs
$\langle n \rangle$ | $0.6 \text{ part/cm}^3$
$\langle \delta n/n \rangle$ | $2 \text{ part/cm}^3$
GRB 090423

Detected by Swift BAT and Fermi GBM
(NASA – ASI – PPARC)

Redshift z = 8.2
650 million years after BB

Lyman alpha break
GRB 090423

Episode 3 overlaps with IGC GRBs Sne !!!

See John Pisani talk !!!
GRB 090618 @ z = 8.2

Smaller duration, similar spectrum

<table>
<thead>
<tr>
<th></th>
<th>α</th>
<th>β</th>
<th>$E_{pi}$ (keV)</th>
<th>norm. (ph/cm²/s/keV)</th>
<th>$\chi^2$</th>
<th>$\Delta t_{obs}$ (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>090618</td>
<td>-0.66 ± 0.57</td>
<td>-1.99 ± 0.05</td>
<td>284.57 ± 172.10</td>
<td>0.3566 ± 0.16</td>
<td>0.924</td>
<td>6.1</td>
</tr>
<tr>
<td>090423</td>
<td>-0.78 ± 0.34</td>
<td>-3.5 ± 0.5</td>
<td>433.6 ± 133.5</td>
<td>0.015 ± 0.010</td>
<td>0.856</td>
<td>10.4</td>
</tr>
</tbody>
</table>
On the Induced Gravitational Collapse at extreme cosmological distances: the case of GRB 090423

R. Ruffini\textsuperscript{1,2,3,4}, L. Izzo\textsuperscript{1,2}, M. Muccino\textsuperscript{1}, G. B. Pisani\textsuperscript{1,3}, J. A. Rueda\textsuperscript{1,2,4}, Y. Wang\textsuperscript{1}, C. Barbarino\textsuperscript{1,5}, C. L. Bianco\textsuperscript{1,2}, M. Enderli\textsuperscript{1,3}, M. Kovacevic\textsuperscript{1,3}

- No first episode detected → too distant
- Second episode detected → the "tip of the iceberg" of a more extended emission
- Perfect overlap of the third episode
- No SN → impossible for the distance

→ IGC works at very high redshifts – very massive stars as progenitor
GRB 970828

Thermal emission reported in literature
(Pe'er et al. 2007)

1) physical size at the base of the flow
2) Lorentz factor of the flow

<table>
<thead>
<tr>
<th>Spectral model</th>
<th>$\alpha$ (γ)</th>
<th>$\beta$</th>
<th>$\gamma_{\text{ext}}$ (keV)</th>
<th>$E_{\text{peak}}$ (keV)</th>
<th>$kT$ (keV)</th>
<th>$\text{norm}_1$ (ph cm$^{-2}$ s$^{-1}$ keV$^{-1}$)</th>
<th>$\text{norm}_2$ (ph cm$^{-2}$ s$^{-1}$ keV$^{-1}$)</th>
<th>$\chi^2$/DOF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power Law</td>
<td>-1.38 ± 0.01</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.018 ± 0.001</td>
<td>-</td>
<td>6228.1/115</td>
</tr>
<tr>
<td>Cut-off PL</td>
<td>-0.77 ± 0.02</td>
<td>-</td>
<td>-</td>
<td>465.4 ± 10.6</td>
<td>-</td>
<td>0.027 ± 0.001</td>
<td>-</td>
<td>203.83/114</td>
</tr>
<tr>
<td>Band</td>
<td>-0.60 ± 0.03</td>
<td>-2.15 ± 0.05</td>
<td>-</td>
<td>360.5 ± 12.5</td>
<td>-</td>
<td>0.031 ± 0.001</td>
<td>-</td>
<td>106.48/113</td>
</tr>
<tr>
<td>Band+PL</td>
<td>-0.41 ± 0.15</td>
<td>-2.41 ± 0.33</td>
<td>-1.47 ± 0.17</td>
<td>335.8 ± 17.6</td>
<td>-</td>
<td>0.028 ± 0.002</td>
<td>0.003 ± 0.002</td>
<td>104.12/111</td>
</tr>
<tr>
<td>cutoff + PL</td>
<td>-0.47 ± 0.17</td>
<td>-1.28 ± 0.16</td>
<td>-</td>
<td>338.7 ± 17.9</td>
<td>-</td>
<td>0.027 ± 0.002</td>
<td>0.004 ± 0.002</td>
<td>104.28/112</td>
</tr>
<tr>
<td>BB + po</td>
<td>-</td>
<td>-</td>
<td>-1.50 ± 0.01</td>
<td>-</td>
<td>63.71 ± 0.92</td>
<td>(3.21 ± 0.16) $\times 10^{-6}$</td>
<td>0.012 ± 0.001</td>
<td>228.09/113</td>
</tr>
<tr>
<td>BB + BB + po†</td>
<td>-1.53±0.17</td>
<td>-</td>
<td>40.01±2.05*</td>
<td>-</td>
<td>106.8 ± 6.3</td>
<td>(4.85±1.15) $\times 10^{-7}$</td>
<td>(10.15±1.32) $\times 10^{-6}$</td>
<td>101.78/111</td>
</tr>
</tbody>
</table>
GRB 970828

(Izzo et al. b)
GRB 970828

( Izzo et al. b )

Radius evolution

$R \propto t^{0.42}$
### GRB 970828

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_{\text{tot}}^{e^+e^-}$</td>
<td>$(1.60 \pm 0.03) \times 10^{53}$ erg</td>
</tr>
<tr>
<td>$B$</td>
<td>$(7.00 \pm 0.55) \times 10^{-3}$</td>
</tr>
<tr>
<td>$\Gamma_0$</td>
<td>$142.5 \pm 57$</td>
</tr>
<tr>
<td>$kT_{\text{th}}$</td>
<td>$(7.4 \pm 1.3)$ keV</td>
</tr>
<tr>
<td>$E_{\gamma,\text{GRB,th}}$</td>
<td>$(1.46 \pm 0.43) \times 10^{51}$ erg</td>
</tr>
<tr>
<td>$&lt;n&gt;$</td>
<td>$3.4 \times 10^3$ part/cm$^3$</td>
</tr>
<tr>
<td>$\delta n/n$</td>
<td>$10$ part/cm$^3$</td>
</tr>
</tbody>
</table>

![Graph 1](image1.png)

![Graph 2](image2.png)

![Graph 3](image3.png)

![Graph 4](image4.png)
GRB 970828

Large particle matter density in the CBM

Large absorption at optical wavelengths...and column density

Absence of an optical afterglow and possible SN emission
GRB 970828

(Djorgovski et al. 2001)
GRB 970828

( Djorgovski et al. 2001 )
Conclusions

- The Induced Gravitational Collapse explains energetic long \( \text{GRB-SNe} \) events

- Specific sequence of different emission episodes characterizing any IGC system

- But … be care with GRB prompt analysis → possible mistakes can be obtained by using the nested model BB+po instead than Band or Band+po

- “Good” GRBs are showing a deviation from the simple Band function → new physics ???
GRB emission mechanisms

GRB as relativistic emitters

- Evidence of relativistic expansion of GRB emitter from radio obs

  \( \text{(Frail+ 1997)} \)

- Detection of GeV photons and reverse shocks \( \rightarrow \) Gamma ~ 1000

- Light curve observed timescale variability \( (\delta t = 10 \text{ ms}) \) as upper limit of the size of the source emitter \( (r_{\text{em}} = c \delta t) \rightarrow \) large optical depth

Compactness problem
If we consider the process of pair formation, which requires the annihilation of two photons with a total energy larger than

\[ 2 m_e c^2 \rightarrow 1 \text{ MeV} \]

the optical depth can be written as

\[
\tau_{\gamma\gamma} \approx \frac{f_e \pm \sigma T A \pi d^2 F}{E_{\gamma} c^2 \delta t} \quad \Rightarrow \quad 10^{15}
\]

\( \text{(Ruderman 1975, Piran 1999)} \)
**GRB emission mechanisms**

We should not see a non-thermal spectrum !!!

If the emitter is moving *relativistically*:
1) the observed photons are blueshifted, so their energy in the rest frame is lower by a factor $\Gamma$
2) the size of the source moving toward us is $c \delta t \Gamma^2$

$$\rightarrow \tau = 10^{15} / \Gamma^{4+2\alpha}$$

$$\rightarrow \Gamma > 100$$

The minimal Lorentz factor depends also on the maximal photon energy, i.e., the energy cutoff of GRB spectrum

*(Lithwick & Sari 2001)*
GRB emission mechanisms - summary

- In the initial phases, the energy released by the central engine is primarily in the form of internal energy: gamma-ray photons and pairs.

- Due to high optical depth, this energy is converted into kinetic energy of a small mass of baryons, until the expanding shell achieves the maximum Lorentz factor.

- Thereafter, the shell continues to expand with constant Gamma into an external medium of density $n$.

- When the swept-up mass is of the order of the initial energy, the shell starts to decelerate.

- At this point the blast wave reconverts its bulk kinetic energy into radiation via synchrotron radiation (and probably IC) by shocks accelerated electrons.

- This emission can start tens of seconds after the prompt event, in agreement with the extrapolation of the afterglow to early times.
GRB emission mechanisms

External shocks cannot produce the prompt observed variability !!!

*(Sari & Piran 1997)*

\[ t_{B} - t_{A} \sim \frac{R(1-\beta)}{c} \sim \frac{R}{2\gamma^2c} \]

\[ t_{C} - t_{A} \sim \frac{R(1-\cos \theta)}{c} \sim \frac{R}{2\gamma^2c} \]

\[ t_{D} - t_{A} \sim \Delta/c \]
**GRB emission mechanisms**

Internal shocks can, but they can be inefficient !!!

\[ T\Delta = \Delta/c > t_{\text{ang}} \]
\( T\Delta \) is the duration of the burst

The variability can be "regulated" by shells of thick \( L \), producing spikes lasting

\[ \frac{L}{c} = t_{\text{ang}} \]

Internal shocks can dissipate only a fraction of the kinetic energy of the burst \( \rightarrow \) high efficiency can be reached only if the relative velocities between different shells are very large
GRB emission mechanisms

\[ F_\nu = \begin{cases} 
(p/\nu_c)^{1/3} F_{\nu,\text{max}}, & \nu_c > \nu, \\
(p/\nu_c)^{-1/2} F_{\nu,\text{max}}, & \nu_m > \nu > \nu_c, \\
(v_m/\nu_c)^{-1/2} (p/\nu_m)^{-p/2} F_{\nu,\text{max}}, & \nu > \nu_m, 
\end{cases} \]

(Sari+ 1998)
GRB emission mechanisms

\[ F_\nu = \begin{cases} 
(v/v_c)^{1/3}F_{\nu,\text{max}}, & \nu_c > \nu, \\
(v/v_c)^{-1/2}F_{\nu,\text{max}}, & \nu_m > \nu > \nu_c, \\
(v_m/v_c)^{-1/2}(\nu/\nu_m)^{-p/2}F_{\nu,\text{max}}, & \nu > \nu_m,
\end{cases} \]

Radio  microwave-IR  visible  X-gamma