Constraints on the rate of particle acceleration using late X-ray observations of GRB afterglows

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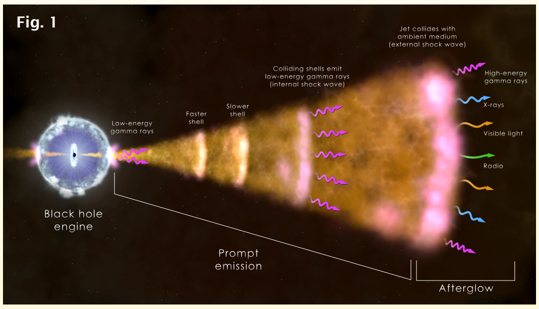
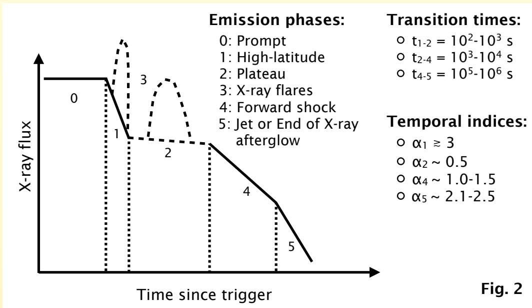
GRB afterglows: models and observations

The fireball model

- Gamma-ray bursts (GRBs) are the most luminous explosions in the universe and have central engines that drive the outbursts in highly relativistic jets (e.g. Mészáros 2006).
- The afterglow emission consists of synchrotron radiation produced by the interaction of a forward shock and the surrounding medium (Fig. 1).
- Two types of environments based on the density profile: ISM (homogeneous) and wind (inhomogeneous).
- Emission is characterised by six parameters: kinetic energy (E_k), initial Lorentz factor (Γ), electron spectral index (p), equipartition fractions of electrons (ε_e) and magnetic fields (ε_B) and the density of the circumburst environment (*n*, or *A* for the wind model).

Credit: NASA





X-ray GRB afterglows

- The observed flux can be described as: $F \propto \nu^{-\beta} t^{-\alpha}$, where β is the energy spectral index.
- The X-ray light curve (Fig. 2) is characterised by a series of temporal segments with different decay slopes (e.g. Nousek et al. 2006).
- At 10^6 s after the GRB trigger the observed flux is $F_{obs} < 10^{-13}$ erg cm^{-2} s^{-1} limiting the number of GRBs with detections at such late times (Fig. 3). This can also explain the lack of late jet breaks in the *Swift* sample (Fig. 4).

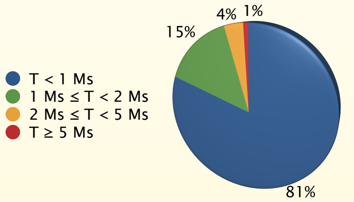


Fig. 3: Percentage of GRB afterglows detected by *Swift*/XRT up to 1 Ms, 2 Ms and 5 Ms after the burst trigger. The sample includes a total of 646 GRBs since 2004.

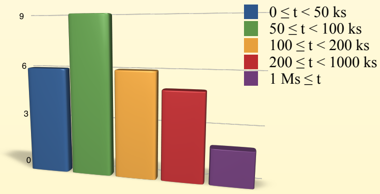


Fig. 4: Histogram indicating the typical location of the jet break time from the burst trigger for GRBs with prominent jet breaks shown in Racusin et al. (2009).

Particle acceleration in GRB afterglows

Maximum observed energy

- In the forward shock model, the particle acceleration is produced through diffusive shock acceleration in weakly magnetised relativistic collisionless shocks (e.g. Piran 2005).
- The maximum observed energy is limited by Confinement (Conf), Synchrotron or Inverse Compton (IC) as shown in Fig. 5.

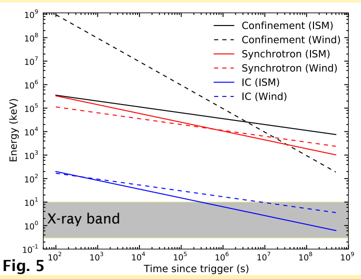


Fig. 5

- These limits depend on:
  - forward shock emission parameters,
  - upstream magnetic field (B_u~10 μG)
  - diffusion efficiency (*g*~1-10), that describes the rate at which the acceleration happens considering the deflection suffered by the electrons in the upstream region (e.g. Sagi & Nakar 2012).

> In X-rays the IC limit is the most important, except at late times in the wind environment when $\nu_{obs} > \nu_c$, when Confinement is more important

Steepening of the afterglow light curve

- Maximal observed energy of the electrons crossing the X-ray band, assuming an electron spectral index p=2.4 and a power-law with exponential cutoff distribution (Fig. 6).
- Breaks are smooth with index, |s|~0.66.

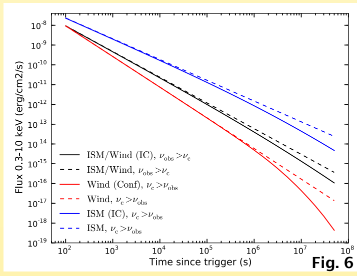


Fig. 6

Results

Prediction:

Type 1: Jet breaks

- Change of slope (Kumar & Panaitescu 2000):
  - ISM: Δα~0.7
  - Wind: Δα~0.4
- No spectral variations.

Type 2: End of X-ray emission breaks

- Temporal breaks caused by the inability of the shock to accelerate electrons that emit in the X-ray band will be observed at late times (t >10^6 s after the GRB trigger).
  - ISM/Wind (IC limit): Δα~0.3
  - Wind (confinement limit): Δα~1.0
- No difference between ISM and wind when $\nu_{obs} > \nu_c$.
- Softening of the spectrum.

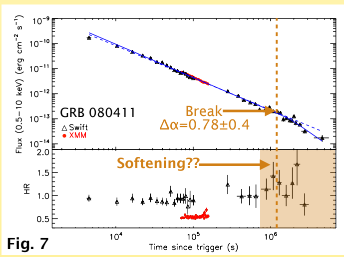


Fig. 7

GRB 080411- modelled with a type 2 break

- $\nu_{obs} > \nu_c$ (post-break) in ISM
- $\Gamma(t_{break})$~6

a) No B_u amplification: B_u~10 μG => *g*~5

b) B_u amplification: B_u~0.1 mG => *g*~500

> If B_u is amplified, the efficiency of particle acceleration decreases for shocks moving at mildly relativistic velocities

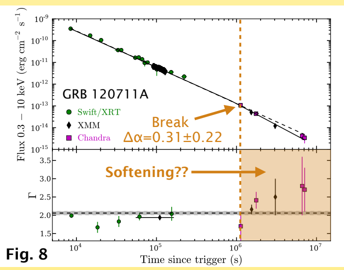


Fig. 8

GRB 120711A- modelled with a type 2 break

- $\nu_{obs} > \nu_c$ (post-break) in wind-like
- $\Gamma(t_{break})$~10-30

a) No B_u amplification: B_u~10 μG => *g*~23-240

b) B_u attenuation: B_u~1 μG => *g*~2-24

> Strong indication of decreasing efficiency of particle acceleration at late times when compared with GeV observations (*g*~1)

References

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Acknowledgements

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