Unveiling the origin of steep decay in γ-ray bursts

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CONTEXT

In the X-ray light curve of GRBs, the steep decay represents the transition phase between the shut down of the prompt emission and the onset of the afterglow. When observed in the soft X-ray band of Swift-XRT (0.3-10 keV), the steep decay is usually characterised by a power law drop of flux, and a simultaneous softening of the spectrum.
Such behaviour is usually interpreted as due to the delayed arrival of photons emitted at high latitudes from the jet surface.
Performing a time-resolved spectral analysis of the brightest GRB pulses observed by XRT, we discovered a tight relation between the flux and the photon index. Such relation results to be inconsistent with the simple High Latitude Emission (HLE) scenario (see box below) and we worked on the interpretation including cooling mechanisms.

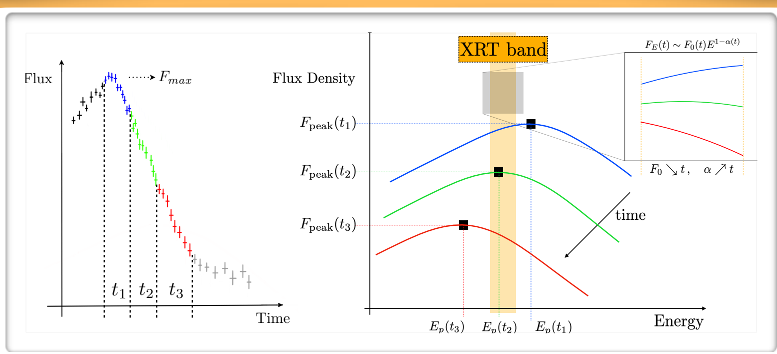
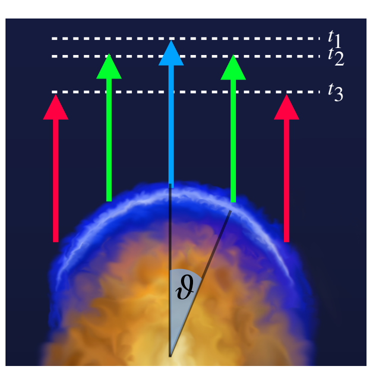


Fig. 1: Schematic representation of the steep decay and the associated spectral softening observed in the XRT band

The High Latitude Emission (HLE)

The photons emitted simultaneously by a curved surface arrive to the observer at different times. Since the latitude is measured from the symmetry axis of the jet, the higher the latitude, the longer is the time delay. Moreover, since the photons at higher latitudes are less Doppler boosted, they are less energetic, leading to an overall softening of the spectrum



$$t_{obs} = t_{em}(1 - \beta\cos\vartheta)$$

$$\mathcal{D}(\vartheta) = \frac{1}{\Gamma(1 - \beta\cos\vartheta)}$$

$$\nu = \nu' \mathcal{D}(\vartheta)$$

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SAMPLE SELECTION AND RESULTS

We selected our golden sample searching in the Swift archive the brightest pulses which are observed simultaneously with XRT and BAT, and are followed by a steep decay phase. The peak time of the pulse must be well identified. The spectral analysis is done adopting an absorbed power law as fitting function. We construct the α-F relation plotting the photon index α as a function of the inverse of the normalised flux (F_{max} is the peak flux, left panels of Fig. 2).
We also extended the sample including those pulses that have only a well defined BAT peak, but XRT starts to monitor the decay after the peak. In this case, F_{max} is extrapolated back to the peak assuming a power law decay (right panels of Fig. 2).
The discovery of a unique relation between flux and photon index indicates the presence of a common process.

The golden sample | **The extended sample**

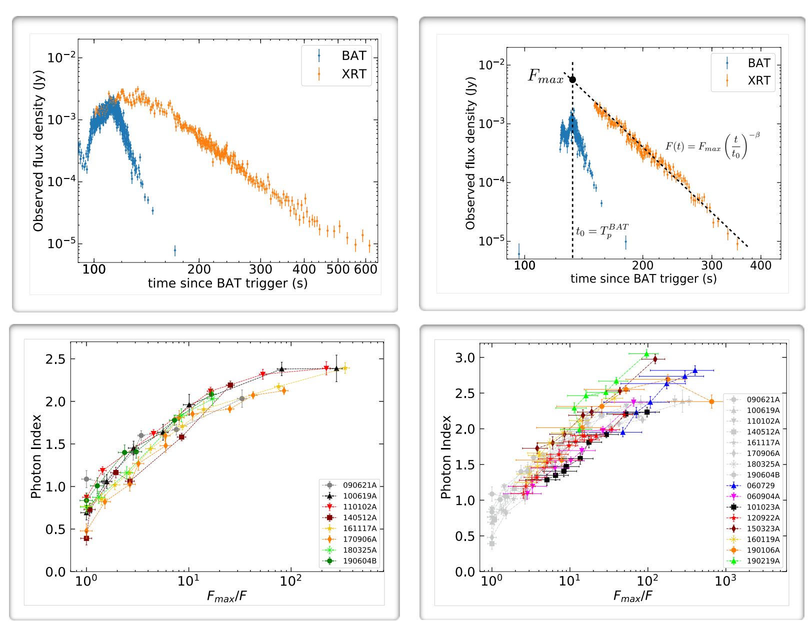

Fig. 2
Top left: an example of light curve (XRT + BAT) of a GRB from the golden sample. Bottom left: the α-F relation for the golden sample. Top right: an example of light curve (XRT + BAT) of a GRB from the extended sample. Bottom right: the α-F relation for the extended sample (golden sample reported in grey)

INTERPRETING THE α-F RELATION

HLE from efficiently cooled particles

We assume that the accelerated particles loose all their energy on a time scale much smaller than the dynamical time scale. In this regime, the emission phase can be approximated as an instantaneous pulse and therefore the flux decay and the spectral softening is totally dominated by HLE effect. The flux is given by

$$F_\nu(t_{obs}) \propto S_{\nu'}(\nu/\mathcal{D}(\vartheta))\mathcal{D}^2(\vartheta)\cos(\vartheta)$$

where $S_{\nu'}$ is the comoving spectral shape. Since the emission is instantaneous, we can associate an observer time to each latitude angle ϑ.

HLE+adiabatic cooling of the emitting particles

Here we assume, instead, that the accelerated particles do not cool efficiently and the energy losses are dominated by the adiabatic expansion of the emitting region. Hence, if V' is the comoving volume of the region and γ the Lorentz factor of the particle, the adiabatic cooling implies:

$$\gamma^3 V' = \text{const}$$

In this case the emission is not instantaneous and the observed flux and spectral evolution is computed integrating along the equal arrival time surfaces.

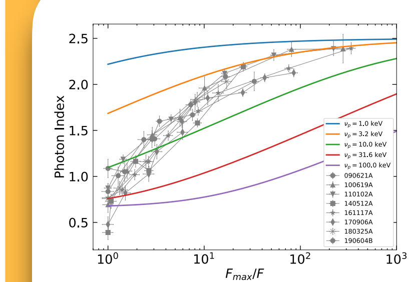

Fig. 3a: α-F relation predicted in case of HLE from efficiently cooled particles. Different colours correspond to different initial peak energy

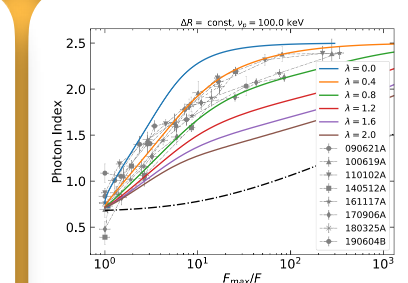

Fig. 3b: α-F relation for spectral evolution dominated by adiabatic cooling. λ is the decay index of the magnetic field, which is assumed to evolve with radius R as $B=B_0\,(R/R_0)^{-\lambda}$

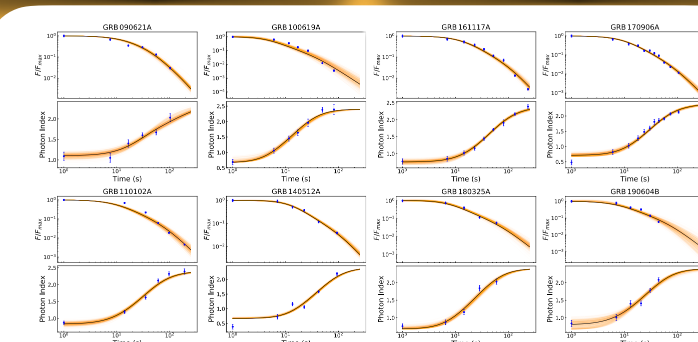

Fig. 4: joint temporal evolution of flux and photon index for the golden sample. The orange lines represent the evolution in case of adiabatic cooling and they are produced with 500 random draws from the posterior sample set of the MCMC.

DISCUSSION AND CONCLUSIONS

As shown in Fig. 3a, the HLE from efficiently cooled particles predict an α-F relation systematically shallower than the observed one, independently of the assumptions of the comoving spectral properties. The adiabatic cooling, instead, well reproduces the data and the match is also confirmed by the use of Monte Carlo Markov Chain technique for the parameter estimation of the model. We show for the first time that the adiabatic cooling scenario is statistically preferred to the HLE from efficiently cooled particles for all the cases analysed. Our analysis strongly indicates that the accelerated particles do not radiate efficiently and a proton-synchrotron dominated emission is favoured against an electron-dominated scenario.