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Unveiling the origins of steep decay in γ-ray bursts

S. Ronchini(1)(2)

(1) *Gran Sasso Science Institute - Viale F. Crispi 7, L'Aquila, Italy*
(2) *INFN, Laboratori Nazionali del Gran Sasso - Assergi (AQ), Italy*

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Summary. — γ-ray bursts (GRBs) are cataclysmic transient events which release most of their energy in the keV-MeV range. GRBs are originated from internal dissipation of the energy carried by ultra-relativistic jets launched by the remnant of a massive star's death or a compact binary coalescence. With the discovery of gravitational waves associated to short GRBs, the investigation of this class of phenomena is crucial for the development of multi-messenger astrophysics. Though, we still have an incomplete understanding of where and how the radiation is generated in the jet. Performing a time-resolved spectral analysis of the X-ray tails of a sample of 8 bright GRBs, we discover a unique relation between the spectral index and flux. This relation is incompatible with the common scenario used to interpret X-ray tails, and requires to be explained with the adiabatic cooling of the emitting particles, suggesting a proton-synchrotron origin of the GRB emission.

1. – Introduction

The initial high-energy emission of GRBs is known as *prompt phase* and it is characterized by the presence of multiple pulses, whose spectrum typically peaks in the keV-MeV energies. Its physical origin is still matter of discussion and the main open questions regard the composition of the jet (matter [1] or magnetic [2] dominated), the energy dissipation mechanisms (sub-photospheric emission [3], internal shocks [4] or magnetic reconnection [5]), and the nature of particle radiation. At the end of the prompt emission, the light curve usually presents a steep decay phase [6] (tail), well visible in the X-ray band. The duration of the steep decay is around 10^2–10^3 s and it is characterized by a typical decay power-law slope of 3–5. Once the jet dissipated most of its internal energy during the prompt phase, it interacts with the interstellar medium, producing the so called afterglow emission [7, 8]. The afterglow models cannot account for such steep slopes and the origin of the steep decay is attributed to the fade-off of the emission mechanism that is responsible of the prompt phase.

Due to the curvature of the jet surface, if the emission abruptly ceases, the observer first receives photons from the line of sight and later photons from higher latitudes [9], which are less Doppler boosted. Such effect is known as High Latitude Emission (HLE). Under the assumption of a single power-law spectrum ($F_\nu \propto \nu^{-\beta}$), the HLE predicts that the flux decays as $F_\nu(t_{\rm obs}) \propto \nu^{-\beta} t_{\rm obs}^{-(\beta+2)}$. If the spectrum is peaked, the HLE can also lead to the apparent transition of the spectral peak across the observing band [10], causing a spectral evolution, as often observed in the soft X-rays [11, 12]. Due to the

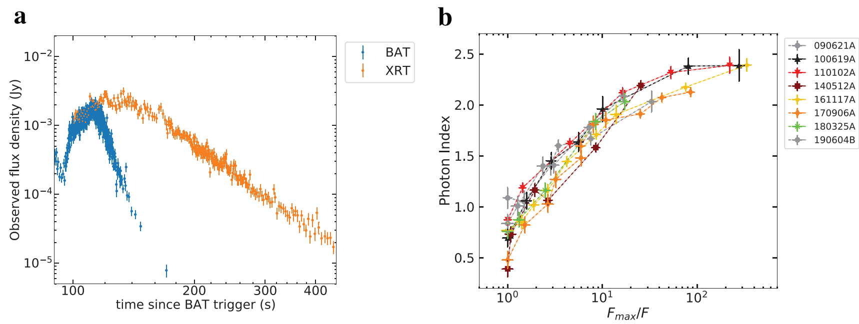

Fig. 1. – The steep decay phase and the correspondent spectral evolution. (a) Example of a light curve of an X-ray tail selected from our sample, taken from the GRB 161117A. We show on the same plot the XRT (orange) and the BAT (blue) flux density at 1 keV and 50 keV, respectively. (b) Spectral evolution of the X-ray tail for all the GRBs of our sample (shown with different colors). The photon index α is represented as a function of the reciprocal of the normalized flux $F_{\max}/F$. Figure taken from [14].

narrowness of the band of soft X-ray instruments, the Doppler shift of the spectrum just causes a softening of the photon index.

In this work we systematically analyze the X-ray spectral evolution during the steep decay phase. We find a unique relation between the spectral index and the flux, which holds for all the cases considered. Given the same trend followed by all the GRBs of our sample, we search for a common process at the basis of the spectral relation.

2. – Data analysis and results

We perform a time-resolved spectral analysis of a sample of GRBs selected from the archive of the X-ray Telescope (XRT, 0.3–10 keV) on-board the Neil Gehrels Swift Observatory (Swift) [13]. In order to have data with high enough signal to noise ratio, we select our GRBs (8 in total) on the basis of the pulse brightness in XRT. The duration of the burst is not considered in the selection process. We also require that the XRT peak preceding the X-ray tail has a correspondent emission in the Burst Alert Telescope (BAT, 15–350 keV) (see *e.g.*, the fig. 1(a)). The analysis has been performed on the tail in the 0.5–10 keV band assuming a simple power-law model for the photon spectrum $N_\gamma \propto E^{-\alpha}$ (see "Methods" section in [14]). In fig. 1(b) we report the spectral evolution plotting the photon index α as a function of the 0.5–10 keV flux, hereafter referred to as the α-F relation. The normalization of the flux to the peak value of the X-ray tail makes the result independent of the intrinsic brightness of the pulse and of the distance of the GRB. Our results show a systematic softening of the spectrum whose trend is shared by all the analyzed GRBs. The evident spectral evolution discovered in our analysis is a clear indication of a common physical mechanism responsible for the tail emission of GRBs and in the following we test possible scenarios to interpret our results.

Considering the HLE, when photons are radiated from a curved surface at higher latitude (*i.e.,* the angular distance from the jet symmetry axis), they have a lower the Doppler factor. This results in a shift towards lower energies of the spectrum in the observer frame. Therefore HLE could in principle explain the observed spectral softening. Assuming that the prompt episode has a negligible duration in the comoving frame, we derive the predicted α-F relation in the HLE scenario. Regardless of the choice of the peak energy, the bulk Lorentz factor or the radius of the emitting surface, the HLE predicts an α-F relation whose rise is shallower than the observed one (fig. 2). Our results on HLE are based on the assumption of a common comoving spectrum along

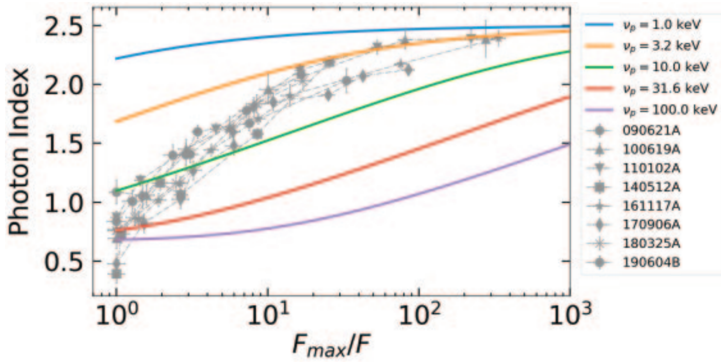

Fig. 2. – Spectral evolution expected for HLE from an infinitesimal duration pulse. The comoving spectrum is assumed to be a SBPL. The several colors indicate the observed peak frequency at the beginning of the decay. In the legend we report the name of each GRB. Figure taken from [14].

the entire jet core. The disagreement with data cannot be solved even if we relax the assumptions about the comoving spectral shape, the pulse duration or the jet structure (see "Methods" in [14]).

In order to explore an alternative scenario able to explain the discovered relation, we assume that particles cool not via radiation losses but mainly through the adiabatic losses [15]. We assume conservation of the entropy of the emitting system $\langle\gamma\rangle^3 V'$ throughout its dynamical evolution, where $\langle\gamma\rangle$ is the average random Lorentz factor of the emitting particles and $V' \propto R^2 \Delta R'$ the comoving volume [16]. We assume a power law radial decay of the magnetic field $B = B_0 (R/R_0)^{-\lambda}$, with $\lambda > 0$, and synchrotron radiation as the dominant emission mechanism. In fig. 3 we report the expected spectral and temporal evolution. Compared to HLE from efficiently cooled particles, adiabatic cooling produces a much better agreement with data. Both spectral softening and flux temporal decay are well reproduced.

In order to fully explore the parameter space of the adiabatic cooling model, we used a Monte Carlo Markov Chain (MCMC) algorithm for the parameter estimation. We consider the joint temporal evolution of flux and photon index and we find agreement of the model with data (see "Methods" subsection: "Parameter estimation via Monte Carlo Markov Chain" in [14]). We obtain a value of λ in the range 0.4–0.7 (except for 090621A which prefers $\lambda \sim 2$). On average, these values of λ are smaller than those expected in an emitting region with a transverse magnetic field ($\lambda = 1$ or $\lambda = 2$ for a thick or a thin shell, respectively) or magnetic field in pressure equilibrium with the emitting particles ($\lambda = 4/3$ or $\lambda = 2$ for a thick or a thin shell, respectively [16]). Both HLE and adiabatic cooling have a typical timescale $\tau_{\rm ad} = R_0/2c\Gamma^2$. We find values in the range $0.3\,{\rm s} \lesssim \tau_{\rm ad} \lesssim 24\,{\rm s}$, which corresponds to a range for the emission radius of $1.8 \times 10^{14} (\Gamma/100)^2\,{\rm cm} \lesssim R_0 \lesssim 1.4 \times 10^{16} (\Gamma/100)^2\,{\rm cm}$.

3. – Discussion and conclusions

A systematic time-resolved spectral analysis of bright X-ray tails of GRBs reveals a unique relation which links the spectral index and the flux decay. In the assumption of efficient particle cooling, the jet emission stops almost instantaneously (in comparison with its dynamical evolution) and the X-ray steep decay is dominated by the HLE effect. Though, we find that HLE produces an α-F relation systematically shallower than the observed one. On the other hand, we demonstrate that a combined action of adiabatic cooling of the emitting particles and a mildly decaying magnetic field can easily explain the observed α-F relation. Our findings are generally in agreement with moderately

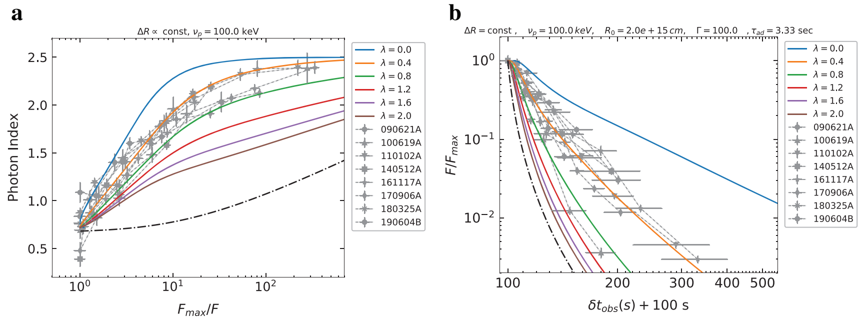

Fig. 3. – Spectral and temporal evolution in case of adiabatic cooling. (a) The α-F relation expected in the case of adiabatic cooling (solid lines). The theoretical curves are computed taking also into account the effect of HLE. The value of λ specifies the evolution of the magnetic field. (b) The temporal evolution of normalized flux expected in case of adiabatic cooling. $\delta t_{\rm obs} + 100\,{\rm s}$ is the time measured from the peak of the decay shifted at 100 s. In both panels, the dot-dashed line is the corresponding HLE model without accounting for adiabatic cooling. Figure taken from [14].

fast and slow cooling regimes of the synchrotron radiation, which is able to reproduce the overall GRB spectral features [17]. If electrons are responsible for the emission, an extremely small magnetic field would be required [18], which is unrealistic for this kind of outflows. Alternatively, synchrotron emission can have a proton origin [19], which radiates less efficiently than electrons, due to the larger mass, explaining why adiabatic cooling dominates the spectral evolution.

In conclusion, the discovery of the dominance of adiabatic losses in GRB outflows represents an important hint to understand better the physics of theses enigmatic objects, the radiation and dissipation mechanisms in ultra-relativistic jets as well as the nature of the emitting particles. The details of this work are published in [14].

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