Unraveling the Origins of GRB X-ray Plateaus through a Study of X-ray Flares

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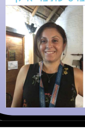


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I- INTRODUCTION

The plateau phase observed in the early X-ray light curve of GRBs (lasting up to thousands of seconds) has been a subject of debate since its discovery by the Neil Gehrels *Swift* Observatory in 2005.

Recently, we suggested that the observed plateau signal originates from an outflow characterized by a maximum Lorentz factor of several tens at most and expanding into a wind-like low-density medium [1].

II- Analysis Method

In this work, we study and contrast the properties of X-ray flares in bursts with and without an X-ray plateau [2]:

- **Sample:**
  - X-ray data from the *Swift* archive (2014–2022)
  - Known redshift
  - Well-sampled X-ray light curves
- **Models:** Superposition of flares and a standard afterglow
  - **Flare model:** "Norris" function
  - **Afterglow model:** Power-law segments with physically motivated indices for a stellar wind-like medium and a constant-density ISM
  - In total, this corresponds to 36 models
- **Method:**
  - Bayesian inference with MultiNest for all 36 models
  - **Model selection:** Models were compared using Bayes factors, AIC, and AICc, with additional criteria ensuring sufficient data near flare peaks for reliable fits

The Figure below illustrates the tested model configurations, with the best-fit model including two flares, a steep decay, and an afterglow evolving in a wind-like medium. The afterglow is characterized by a plateau phase followed by a self-similar decay, without requiring a jet break.

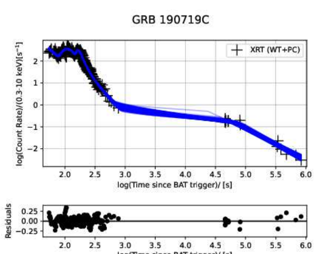

Figure 1: Top: The X-ray LC of GRB 190719C. The black crosses represent the XRT-WTSLEW, XRT-WT, XRT-PC mode data. The errors correspond to a significance of one sigma. The blue lines represent the posterior distributions of the best fit model. Bottom: The residuals between the best model and the data.

III- Independence of Flares and Plateaus in GRBs

- The GRBs with flares represent 69% (61) of our sample. Among them, 42 (68%) have a plateau while 19 bursts do not.
- Our results show that the occurrence of flares in GRBs with (42/57 = 73%) and without plateau (19/32 = 59%) is not statistically different.
- This strongly suggests that the presence of flares is independent of the existence of a plateau, indicating that these two phenomena, namely plateaus and flares are most likely not related or dependent on each other.

Conclusion – (1): The existence of flares is independent of the existence of a plateau.

IV- Flare properties

- The distribution of $t_{\rm pk}$ in Figure 2 shows that flares typically occur within the first 1000 s, with no significant differences between bursts with and without plateaus.

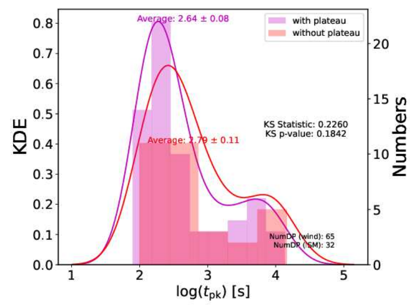

Figure 2: Distributions of the flare peak time, $t_{\rm pk}$. The 65 flares obtained from the 42 bursts with a plateau phase are in purple, while the 32 flares obtained from the 19 GRBs without a plateau phase are in red. In each panel, the right-hand ordinate shows the number of bursts in each bin while the left-hand ordinate shows the value of the kernel density estimation (KDE) drawn by the purple and red solid lines.

- The ratio of the flare width to the flare peak time ($w/t_{\rm pk}$) in Figure 3 follows a similar distribution across bursts.

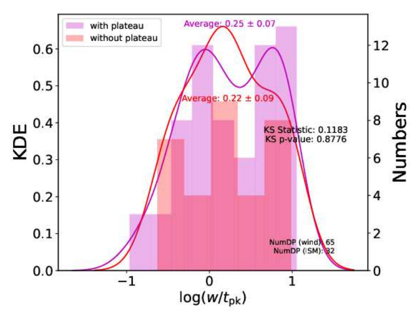

Figure 3: Distributions of the ratio of the flare width to the flare peak time $w/t_{\rm pk}$. Same color coding as in Figure 2.

Conclusion – (2): No notable differences between flare properties.

V- Proposed theoretical models for the origin of the plateau phase

- **Late-time continuous energy injection**: The central engine injects energy for an extended period, delaying shock deceleration and light curve decay. The plateau ends when the injection stops.
- **Viewing angle effects**: The plateau is a geometric effect, where observers at different angles see different temporal structures due to relativistic beaming and jet structure.
- **Low Lorentz factor during the coasting phase**: The plateau phase arises from synchrotron emission during the coasting phase of the forward shock, where an on-axis jet with a moderate Lorentz factor (a few tens) propagates into a low-density stellar wind environment before transitioning to the self-similar decaying phase.

V- Physical Interpretation

We compare the properties of X-ray flares in bursts both with and without an X-ray plateau and found two key results:

(1) The distributions of the flare peak time, $t_{\rm pk}$, as seen in Figure 2, are the same for both sub-samples, with and without plateau phases.

(2) Similarly, $w/t_{\rm pk}$, as shown in Figure 3, is approximately unity, irrespective of the existence of a plateau. We further show that removing possible prompt contamination or considering only early flares does not change these results.

We know that there are 3 main suggestions for the origin of the plateau phase:

- **The late time central engine activity:** In this model, flares are expected to occur later or that time variability ($w/t_{\rm pk}$) will have different distributions, but this contradicts results (1) and (2). The fact that time variability ($w/t_{\rm pk}$) ~ 1 is a strong indication for a similar motion (e.g., internal expansion of shells that is proportional to the radius).
- **The viewing angle effect:** This model contradicts result (1), since in this case, on average, all collisions would occur at the same radius, R, and observers viewing at different angles will see different times, as $t \sim R/D^2c$ (where D is the Doppler boost). We would therefore expect plateau GRBs to show flares occurring at later times, which we do not see.
- **Low Lorentz factor during the coasting phase:** This model does not contradict anything in our results (1) and (2). Simply, for GRBs with lower Lorentz factor, the collisions (or other dissipation that produces the flares) occur at smaller radii than for high-Lorentz factor GRBs.

Conclusion – (3): Thus, the results we have provided independently support the model considering the outflow expanding in low-density wind-like medium with a low Lorentz factor during the coasting phase [1].

References :

[1] Dereli-Bégué H., Pe'er A., Ryde F., Oates S.-R, Zhang B., & Dainotti M.-G. 2022, Nat Commun 13, 5611

[2] Dereli-Bégué H., Pe'er A., Bégué D. & Ryde F., 2024, submitted to ApJ, arXiv:2412.11533