Exploring multi-pulse GRB prompt emission via novel pulse shape model

Gowri A[a,b], Asaf Pe'er[b], Felix Ryde[c], Hüsne Dereli-Bégué[b]
[a]Indian Institute of Science Education and Research, Mohali, India
[b]Bar Ilan University, Ramat Gan, Israel
[c]KTH, Stockholm, Sweden

Abstract

We study the individual pulse shapes in a Gamma-Ray Burst (GRB), and its relation with the underlying emission mechanism.

- In order to analyze shape asymmetry and its evolution during the burst, a novel pulse shape function was introduced.
- Time-resolved spectroscopy with maximum likelihood analysis was performed, and the spectra fitted with Band Function using threeML package (vianello et al).
- **The pulse shape evolves during the burst, initially tending to be predominantly symmetric, while later pulses have more FRED-like lightcurve.**
- A positive correlation between pulse shape and the low energy spectral slope α indicates **an evolution in emission mechanism from thermal to non-thermal in nature**.

Introduction

The X-ray and γ-ray light curves of the prompt phase of GRBs exhibit erratic and diverse behaviour, often with multiple pulses. The origin of individual pulse shapes, spectrum and the relation between the different pulses are needed to deduce the complete physical model of GRBs.

- The temporal pulse shape is often modelled as a Fast Rise Exponential Decay (FRED).
- A novel pulse shape model was implemented on the newer Fermi/GBM bursts to ascertain the general variation in pulse shapes over multi-pulsed bursts.
- α values, indicative of the emission mechanism (e.g., photospheric or synchrotron), become progressively softer for each pulse in a multi-pulse GRB. This, along with changes in pulse shape over a burst, offers insights into the jet's emission mechanisms and radii.

Sample selection - I

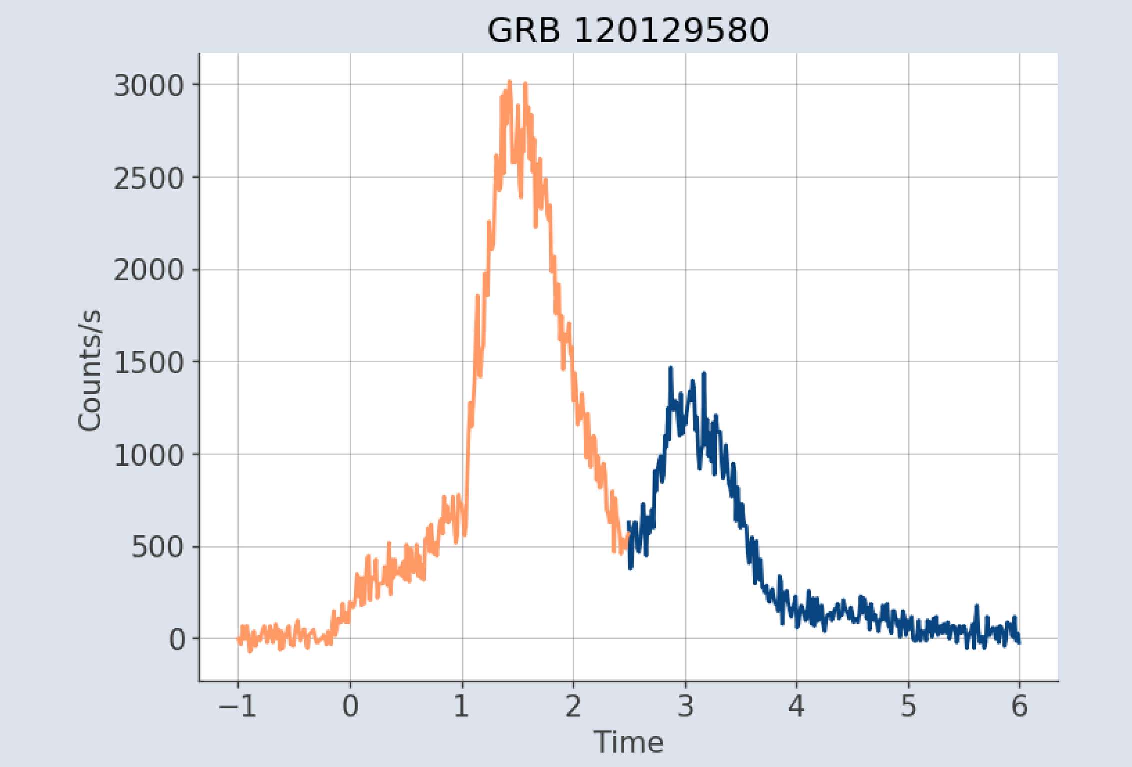


Figure 1: First pulse spans from -0.7s to 2.5s and the second pulse from 2.5s to 4s. The pulse number is defined as the order in which a pulse appears in a burst.

Sample selection - II

We select 27 **multi-pulsed** GRBs with 75 individual pulses from the Fermi/Gamma-Ray Burst Monitor. A pulse selection example is shown in **Figure 1**. The samples follow the given criteria:

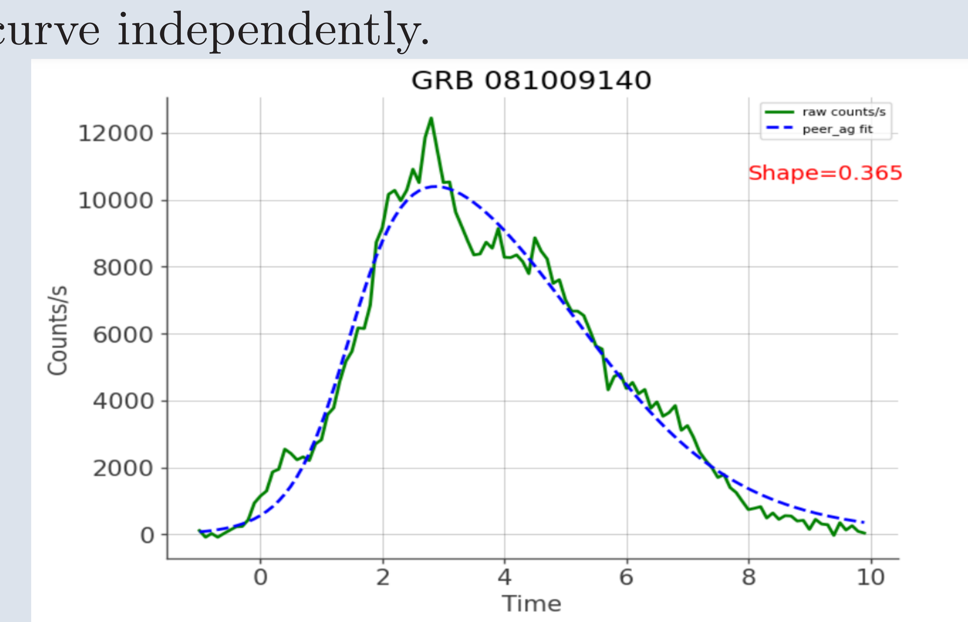
- Each pulse is defined if the counts/s at the start and end of the pulse are at most 55% of the peak counts/s or equal to the background levels.
- The shape function goodness of fit $r^2 \geq 0.7$.
- The temporal binning of the pulse interval is performed via Bayesian block, and the significance of at least two bins must be $S \geq 20$.

Novel pulse shape function

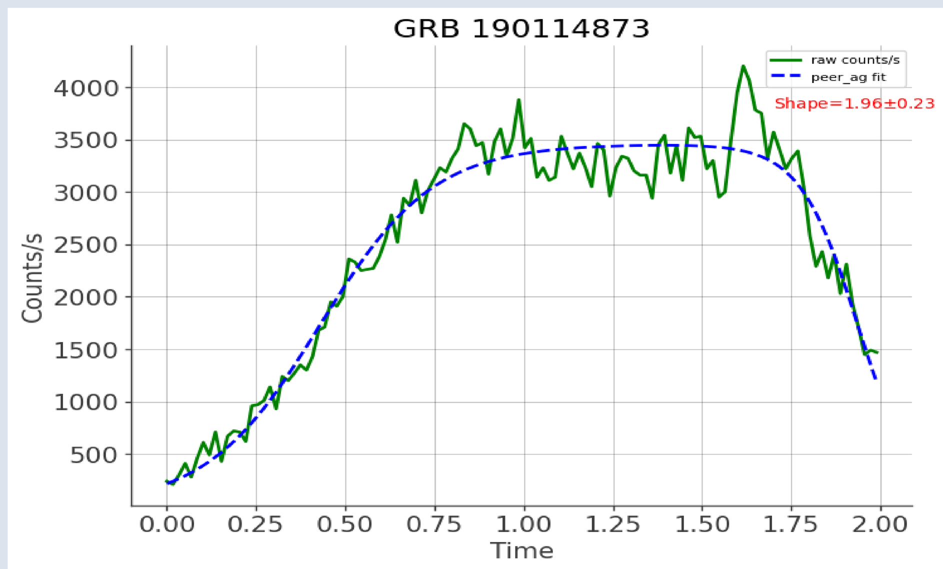
$$I(t) = A\left[\frac{1-\tanh(t-r_l)}{s_l} + \frac{1+\tanh(t-r_r)}{s_r}\right]$$

$$Pulse\ Shape = s_l/s_r$$

s_l, s_r are the slope of rise(left) and decay(right) sides of lightcurve r_l, r_r are the half-time of lighturve rise and fall. Five degrees of Freedom of the function enables one to capture the rise and decay phases of the lightcurve independently.



(a) Example fit for a pulse in GRB 081009 with our function. Here the shape parameter = 0.36, and the pulse is **FRED-like.**



(b) Example fit for a pulse in GRB 190114 with our function. Here the shape parameter = 1.96, and the pulse is **Symmetric-like.**

Pulse shape studies

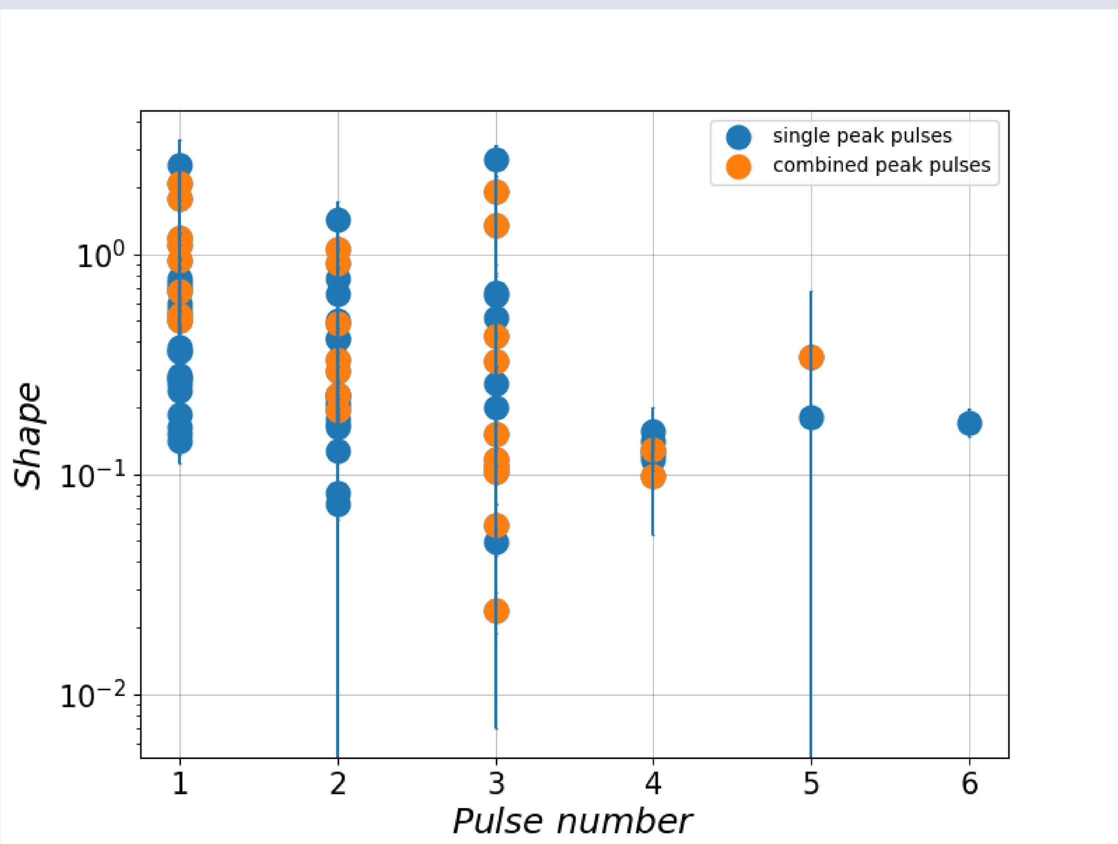


Figure 3: Pulse shape vs pulse number. Pulses with *shape* ≤ 0.3 are FRED-like, and *shape* ≥ 0.7 are Symmetric-like. The pulse shape changes over time with the pulse number.

Results

- **Temporal pulse shape changes from symmetric-like to FRED-like as burst evolves.**
- 13/49 =26% of the first pulses have shape function$\geq$0.7, indicating that they are nearly symmetric. However, the picture changes when looking at later (3rd onward) pulses: only 3/26 = 11% have shape $\geq$ 0.7. • shape - pulse number of pulses in a burst shows a moderate positive Spearman correlation coefficient $r_s = 0.42$.
- Correlation between the hardest value of α, α_{max} with the shape parameter given by $r_s = 0.35$
- **Symmetric-like pulses have harder α_{max} values compared to FRED-like pulses.**
- 33% of the pulses lie between the α_{max} bounds of fast cooling and slow cooling synchrotron. 64% of the pulses lie between the bounds of slow cooling synchrotron and Non-dissipative photospheric (NDP) emission.

Spectral Shape - Pulse shape

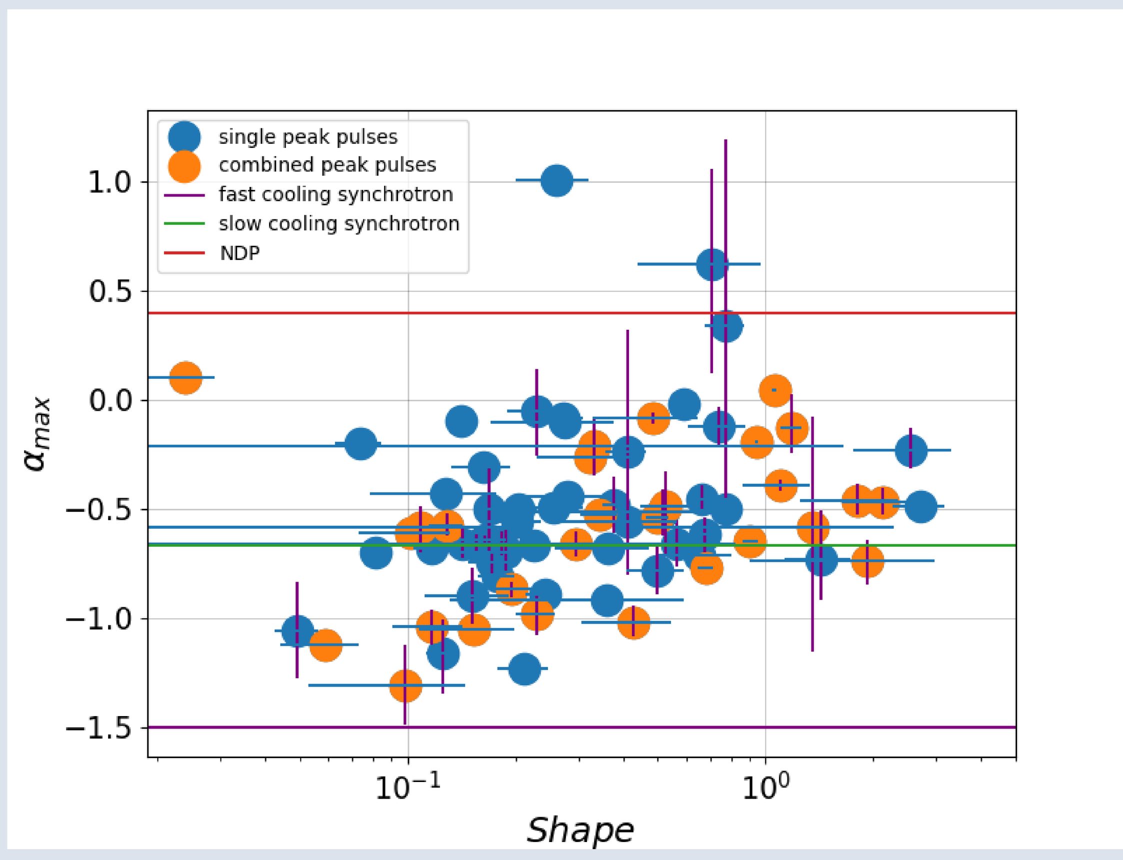


Figure 4: α_{max} vs pulse shape with the α bounds of fast cooling (-3/2), slow cooling synchrotron (-2/3) along with NDP emission (0.4). α_{max} becomes harder as shape symmetry increases.

Conclusions

- The initial pulses are more symmetric-like, and later pulses are more FRED-like. Furthermore, the symmetric-like pulses tend to have harder α_{max} values than the FRED-like pulses. **This indicates that the emission mechanism at different radii is likely changing throughout the burst from thermal to non-thermal.**
- Temporal symmetry detected in pulse shapes using our novel pulse function. This means rise and decay timescales are similar in these pulses. **This may be explained by the photospheric emission, as the photons that are emitted below the photosphere diffuse through the plasma until they escape, causing a more symmetric pulse structure.**

References

1. A Gowri et al (In prep)
2. L. Li, F. Ryde, A. Pe'er, H.-F. Yu, and Z. Acuner, ApJS, vol. 254, no. 2, p. 35, Jun. 2021, doi: 10.3847/1538-4365/abee2a.
3. J. Hakkila and R. S. Cumbee, vol. 1133, pp. 379–384, May 2009, doi: 10.1063/1.3155923.
4. A. Pe'er, P. Mészáros, and M. J. Rees, ApJ, vol. 652, no. 1, p. 482, Nov. 2006, doi: 10.1086/507595.
5. G. Vianello, R. J. Lauer, P. Younk, L. Tibaldo, J. M. Burgess, H. Ayala, P. Harding, M. Hui, N. Omodei, and H. Zhou, arXiv:1507.08343.