Uncovering The Intrinsic Variability of Gamma-Ray Bursts

V. Z. Golkhou, Nathaniel R. Butler and Owen M. Littlejohns

School of Earth and Space Exploration & Cosmology Initiative, Arizona State University, Tempe, AZ 85287, USA

Abstract

Identification of the shortest timescale of intensity variations in GRBs is vital to define the length scales in these explosions and to shed light on the emission mechanism. We study a wavelet formulation for the first order structure function (related to the auto-correlation function) to richly characterize GRB lightcurve variability as a function of timescale. This approach averages over the time series captured for a given GRB, providing robust measures on minimum variability timescales.

We will examine how these variability signatures depend on GRB redshifts and other observables, potentially discovering key source frame signatures in the lightcurves. We found the shortest timescale variability of GRBs is of order of $10^{-2}$ s and millisecond variability is not common, at all.

Mathematical Basics

The Structure Function (SF) is measure of intensity of fluctuations of flux, $S(t)$, over a timescale less than or equal to time lag, $\tau$, which is defined as:

$$D^{(1)}(\tau) = \langle |S(t) - S(t + \tau)| \rangle$$

It can provide information on the nature of the process that causes variation.

Data Source

We use data from Burst Alert Telescope (BAT; Barthelmy et al., 2005) the Swift satellite (Gehrels et al., 2004). Data for all bursts detected by BAT are downloaded in near real time. The Arizona State University pipeline processes these data to produce lightcurves and spectra (Butler et al., 2007).

Sample:

- > 744 GRBs detected by Swift to 10/27/2013. (~ 251 have measured redshift.)
- 517/744 being used. (have enough data points w/ high S/N.)
- 281/517 have reliable measurement. (we can announce the upper-limit for the rest.)
- 265/281 are Long GRBs.
- 98/265 with measured redshift.

The Naked-Eye Burst (GRB 080319B)

- GRB 080319B was detected by the Swift satellite.
- Peak apparent magnitude of 5.8.
- Remained visible to human eyes for $\sim 30$ s.
- Used as a testbed to illustrate the capability of our proposed algorithm.

The Ensemble of GRBs

- The median minimum timescale for long-duration GRBs is $\Delta t_{\text{min}} = 2.5$ s, and for short-duration GRBs is $\Delta t_{\text{min}} = 0.2$ s. The same quantities in source frame (right panel) are $\Delta t_{\text{min}} = 0.5$ s and $\Delta t_{\text{min}} = 2.1$ s.

Conclusions

- GRB prompt lightcurves show rapid variability.
- This variability can be characterized used the Haar structure function.
- From the Haar SF we define $\Delta t_{\text{min}}$, which may be a diagnostic of the central engine.
- The median minimum timescale for long GRBs is $\Delta t_{\text{min}} = 2.5$ s ($\Delta t_{\text{min}}/(1 + z) = 0.5$ s).
- Only 0.3% (3% with a survival analysis) of all GRBs have a minimum timescale below 10 ms.
- For 517 bursts where 1 ms variability could have been measured, none show such short-timescale variability (in conflict with Walker et al., 2000).
- We also find a correlation between $\Delta t_{\text{min}}$ and $z$.
- We plan to expand the analysis to the Fermi GRB sample.

Schematic Pipeline of Extracting $\Delta t_{\text{min}}$

- A gallery of Haar wavecograms
- A corrrelation between $\Delta t_{\text{min}}$ and $z$

Figure 1: $\Delta t_{\text{min}}$ is measured as a departure from a straight line, which corresponds to a smooth (non-variable) lightcurve. Here, $\Delta t_{\text{min}} = 0.04$ s, that it corresponds to the zoomed region in the top curve.

Figure 2: The histograms of $\Delta t_{\text{snr}}$ with reliable measurement and for GRBs allowing for upper limits only. In observer frame (middle panel) the median minimum timescale for long-duration GRBs is $\Delta t_{\text{min}} = 2.5$ s, and for short-duration GRBs is $\Delta t_{\text{min}} = 0.2$ s. The same quantities in source frame (right panel) are $\Delta t_{\text{min}} = 0.5$ s and $\Delta t_{\text{min}} = 2.1$ s.

Correlation

- $\Delta t_{\text{snr}} \sim 0.3(1+z)^{1.4\pm0.4}$
- $\Delta t_{\text{min}} \sim 0.2(1+z)^{1.2\pm0.3}$

References

- http://butlerlab.asu.edu/swift