Redefining a Gamma-Ray Burst Pulse

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A catalog of Gamma-Ray Burst pulses is being compiled using data collected by NASAs Burst And Transient Source Experiment. Pulses are the smallest units of gamma-ray burst prompt emission, and have been found to undergo hard to soft evolution while exhibiting recognizable substructures. The catalog is being upgraded and improved to redefine pulses on the basis of their spectrotemporal characteristics: bursts that were previously thought to contain multiple pulses have been determined to contain single pulses having prominent substructures.

I. INTRODUCTION

Gamma-Ray Bursts are observed as emissions of gamma radiation originating from the most powerful events in the universe [1]. Theories as to what causes them are currently incomplete [2]. GRB emissions contain a prompt high energy emission followed by an afterglow of steadily decreasing energy which can last from a few minutes up to several days [3]. Even though the true origins of GRBs are unknown, GRB data have been collected for decades [1]. One of the most prominent data collection projects was the Burst and Transient Source Experiment, BATSE, launched on board NASA's Compton Gamma-Ray observatory in 1991 [4]. BATSE recorded the counts of gamma-ray photons coming into its detectors in 64 ms time bins in four different energy channels. These energy channels range from 25 - 50, 50 - 100, 100 - 300, and > 300 keV [2].

II. PULSE FITTING

A. The Norris Pulse Fit Model

Pulses are the smallest temporal unit of GRBs [5]. Historically, GRB pulse models have been monotonically increasing and decreasing with only a single peak. Many different simple models have been developed. The Norris model [1] was used over other models because it used only 4 parameters as opposed to 5, 6, or more. This is important because any kind of pulse could be fit given enough free parameters which does not allow for analysis of the model. The Norris model is a function of intensity in terms of time:

$$I(t) = A\lambda e^{[-\tau_1/(t-t_s)-(t-t_s)/\tau_2]} \tag{1}$$

All times are measured in seconds. The four parameters are the amplitude, A the start time t_s, and two variables related to the rise and decay, τ_1 and τ_2 [2]. Where $\lambda = Exp[2(\tau_1/\tau_2)^{1/2}]$ and the peak of the pulse occurs at time $\tau_{peak} = t_s + \sqrt{\tau_1\tau_2}$ [2].

B. Problems with the Norris Pulse Fit Model

After extensive research, it was discovered that the Norris fit misses pulses in a predictable and reproducible pattern which results in the form of three peaks [5]. These discontinuities could be picked out by subtracting the Norris fit from the data and plotting the residuals as seen in Figure 2. The model for these residuals are a four parameter function of time:

$$res(x) = \begin{cases} AJ_0(\sqrt{\Omega[t_0 - t - 0.005]} & \text{if } t < t_0 - 0.005 \\ A & \text{if } t_0 - 0.005 \le t \le t_0 + 0.005 \\ AJ_0(\sqrt{s\Omega[t_0 - t - 0.005]} & \text{if } t > t_0 + 0.005 \end{cases} \tag{2}$$

$J_0(x)$ is the integer Bessel function of the first degree. The four parameters are the time of the central peak t_0, the amplitude of the normalized peak A, the angular frequency of the Bessel function Ω, and the scaling factor in front of and behind the peak s [1].

III. GRB PULSE CATALOG

The last iteration of the catalog is from a time before the residuals have been examined to the extent they are today. Thus there are assumptions made about pulses that are clearly seen as incorrect by current standards. Using the increased understanding of the structure of a gamma-ray burst pulse, fits from the previous edition of the catalog can be improved upon. Bursts that were thought to contain multiple pulses were shown to only contain single pulses through the residual structure of the pulse. Adding the residual pulse fit to the Norris fit

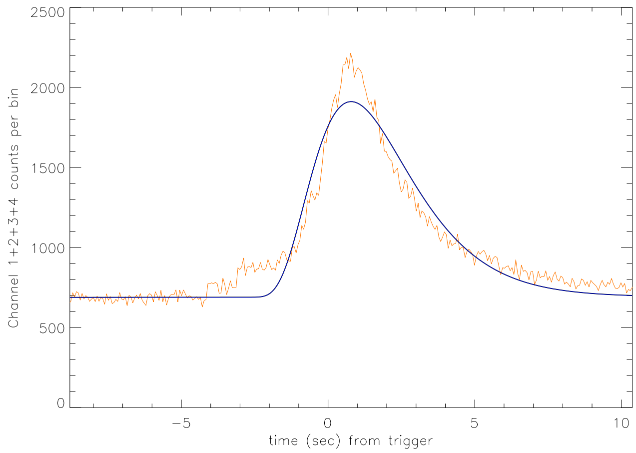

FIG. 1. BATSE Trigger 03954: This is an example of a standard pulse. While the Norris model often fits pulses, there are many where it simply cannot fit properly to the structure. However, the fit often misses the pulse at the same positions, before the pulse, on the rise, at the peak, on the decay, and after the pulse.

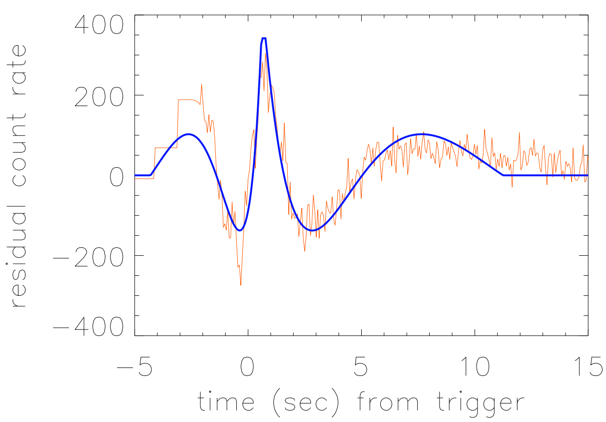

FIG. 2. BATSE Trigger 03954: The residuals of the pulse in Figure 1 are taken by subtracting the Norris fit from the data. The residuals (orange line) closely follow the residual model (blue line).

causes the chi-squared per degree of freedom to be closer to one, indicating an improvement in the accuracy of fit.

An example of one of these improvements this can be seen in Figures 3, 4, and 5. These show a pulse which was initially thought to contain two pulses due to the intensity of the initial peak as shown in Figure 3. However, this peak lines up with that of the residual model shown in Figure 5. This suggests that this is in fact a single pulse instead of two separate ones.

The catalog itself contains information for four all energy channels. The data that is collected for the catalog are the four parameters of the Norris fit for each energy

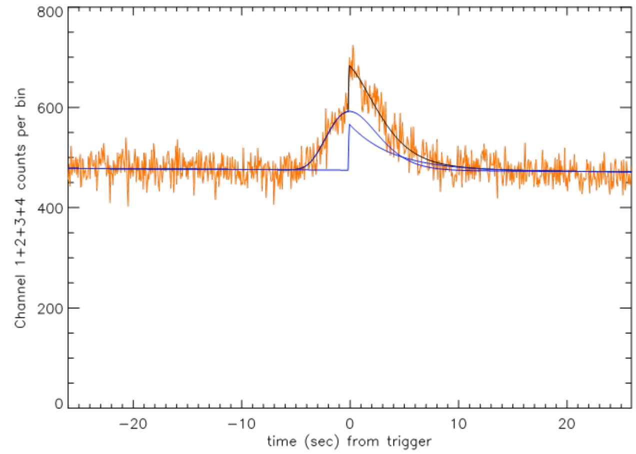

FIG. 3. BATSE Trigger 00516: This GRB emission is peculiar due to the sharp intensity spike at the peak. This was originally thought to be two pulses due to the fluctuation in intensity.

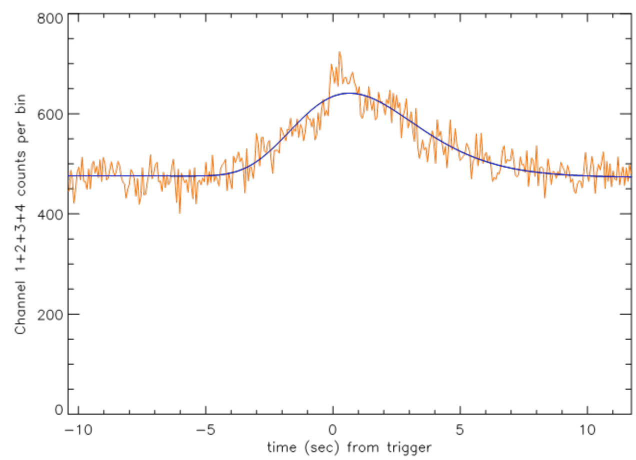

FIG. 4. BATSE Trigger 00516: The current model of a GRB leads us to believe that this emission is in fact a single pulse. While it may appear that the two pulse fit shown in Figure 3 was closer to the data, the single pulse fit to this data shows characteristics of the residual model.

channel and the four parameters of the residual fit for the summed four channel, along with the uncertainties for each of these parameters. These parameters combine to produce the observable values: pulse duration, fluence, time of peak intensity, dual flux, hardness, and asymmetry.

During this research, I developed tools to assist in the development of the catalog. The pulses are fit multiple times until the fit is accepted by the collaboration of the research group. After this, the residuals are taken for the pulse. However, this was a process for which the data had to be copied into the residual program by hand so I developed a tool to insert this data automatically. The pulse

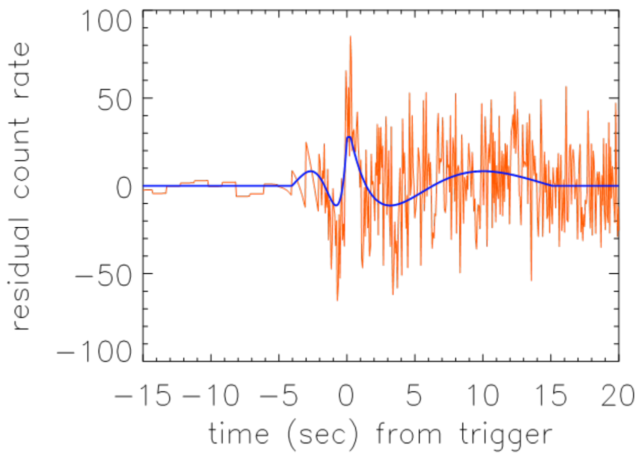

FIG. 5. BATSE Trigger 00516: These are the residual taken from Figure 4. The residual function shows a close fit to the data. This implies that the pulse in fact has strong residuals instead of being two separate pulses.

residuals are also inspected as a group. The data from these fits then needs to be entered into the GRB catalog. This was originally done by manually so I developed a program in IDL that would allow the information to be entered into the catalog more efficiently. An example of the data in the catalog can be seen in Table 1.

IV. FUTURE WORK

The majority of pulses that are not able to be fit by the current models are generally complex in nature. My senior thesis will catalog these complex bursts and analyze the residuals in an attempt to discover the underlying structure which causes the complexity. An evolution will be examined between standard single pulses and complex pulses.

TABLE I. An example row of the information input into the GRB pulse catalog. This is for Burst ID 111.

Parameter	Value	Uncertainty
Background	542.195	0.433513
Background slope	0.00204862	0.000253043
Amplitude	86.1679	1.43042
Taupeak	3.82349	2.0212
Start Time	-16.6921	0.915364
Duration	113.562	4.74817
Asymmetry	0.940495	0.0138324
Tau1	15.8394	2.68038
Tau2	26.5722	1.2536
Fluence	4249.92	65.1914
Dual Timescale Peak Flux	56.7865	2.43875

[1] Hakkila, J., Lien, A., Sakamoto, T., et al. 2015, Astrophys. J., 815, 134

[2] Norris, J. P., Bonnell, J. T., Kazanas, D., et al. 2005, Astrophys. J., 627, 324

[3] Hakkila, J., Giblin, T., & Preece, R. D. 2000, Gamma-ray Bursts, 5th Huntsville Symposium, 526, 399

[4] NASA's BATSE Gamma-Ray Burst Database, `http://gammaray.nsstc.nasa.gov/batse/`.

[5] Hakkila, J., & Preece, R. D. 2014, Astrophys. J., 783, 88