

Finding the Best Fit Models of Afterglows of Gamma Ray Bursts

Mauricio Corona

B.S. Candidate, Department of Physics, California State University Stanislaus, 1 University Circle, Turlock, CA 95382

Received June 3, 2023; accepted June 4, 2023

Abstract

Gamma Ray Bursts (GRBs) are one of the strongest and brightest explosions in the universe. They produce an afterglow after the explosion, and there are two types of GRBs: short GRBs, where the afterglow lasts less than two seconds, and long GRBs, lasting more than two seconds. We are focusing on the afterglow of the short GRB, GRB130603B. This was a complex, well-observed afterglow with detections in X-Ray, optical, and radio, and evidence for a jet break. This was observed using the Swift satellite. We are going to use the fit from GW170817, a structured jet, and apply the same assumption to GRB130603B. The program is going to do Markov Chain Monte Carlo iterations with the data set from GRB130603B to find the best fit line settling on values for the best fit parameters. Our goal is to see if all short GRBs can be fit with the same structured jet, or, if not, what range of jet shapes and energies may be needed.

Introduction and Background

GRBs are the most energetic events to occur in our own Universe. Releasing more energy in 10 seconds than our own Sun would in its entire 10-billion-year lifetime.¹ They were accidentally discovered when the US had sent up Vela satellites that are able to detect (γ -rays). In 1963, the US, Great Britain, and the Soviet Union signed the Nuclear Test Ban Treaty that banned nuclear weapons testing in the atmosphere, outer space, and under water.² The US did not trust the Soviets to uphold the Nuclear Test Ban Treaty which lead to the launch of these satellites in 1965 because gamma rays were created from the splitting of atoms in these nuclear weapons. γ -rays are simply light like the same light that allows your eyes to see colors, and is only a small section of the electromagnetic spectrum shown in Figure 1.

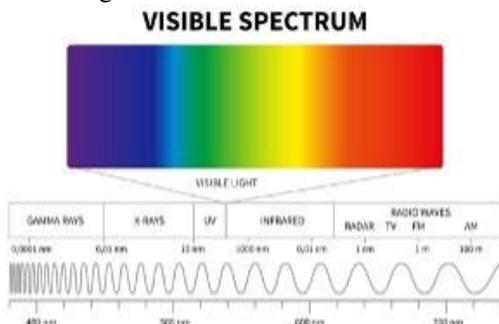


FIG. 1: The electromagnetic spectrum where light can take many forms, and needed instruments to see other sections other than light.

A scientist named Ray Klebesadel of Los Alamos Scientific Laboratory assumed the continuing programatic responsibility for the γ -ray instrument. They were detecting γ -rays, but 53 were not coming from earth. It was not until in 1972, scientists were able to deduce that the detections were of "cosmic origin".³ After measuring the distance to GRB, scientist found that they release more than 10^{50} ergs.

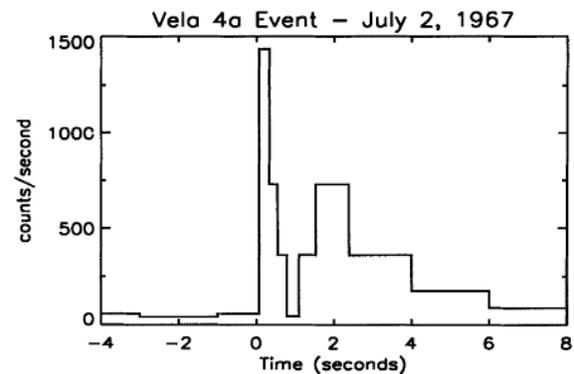


FIG. 2: First observed GRB by one of the Vela Satellites: Vela 4a. The y-axis is the number of γ -rays photons the satellite is detecting over time.

Their origins were associated with black holes, neutron stars, and supernovae. To put that into perspective, 10^{51} ergs is equal to 10^{45} Joules(J). One kilogram of TNT releases about 4.2×10^6 J. You would need to fill up about 120,000,000 Earths worth of TNT to equate that power.⁴ There are two types of GRBs: short GRBs and long GRBs. Short GRBs last less than

2 seconds, and long GRBs last more than 2 seconds. They have found strong correlations between supernovae and long GRBs.⁴ The origin of short GRBs, however, was unknown until 2017, when simultaneous detections of gravitational waves and a burst of γ -rays were detected, GW170817 GRB170817A, creating an after-glow in x-rays, optical, and radio indicating the merging of two neutron stars (NS-NS merger) created the short GRB.⁵ Gravitational waves are 'ripples' in space-time, shown in Figure 3, caused by some of the most violent and energetic processes, such as neutron star mergers, in the Universe, and the Laser Interferometer Gravitational-Wave Observatory (LIGO) has many resources to dive deeper into gravitational waves, the only importance to us is confirming the correlation.⁶

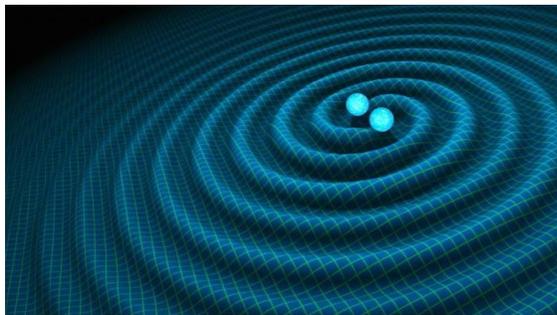


FIG. 3: Illustration of an engine, neutron star merger, powering the GRB jet. As the jet sweeps up more material, the light becomes less energetic become different forms of light such as x-ray, optical, and radio.

Efforts by various groups (e.g. Lazzati et al. 2018, Mooley 2018)^{3,7} were able to create physical models of this event and theorize what kind of environment the stars had to be in for us to see this afterglow. Afterglows happen when the blast wave starts expanding, it sweeps up material from the surrounding environment which is shown in Figure 4.⁷

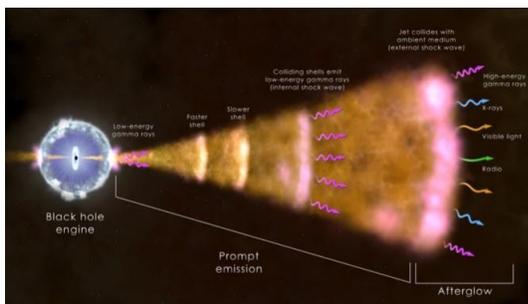


FIG. 4: Dense neutron stars spinning around each other 60,000 a minute creating ripples, stretching, and contracting space, like the ripples in a pond.

This causes the blast to slow down into smaller less energetic wavelengths such as: x-ray, optical, and radio. The Chandra X-ray Observatory saw the afterglow in X-ray, VLA and among other facilities saw it radio, and several ground-based telescopes saw it in optical later on. My mentor, Dr. Brian Morsony, and others collaborated on a paper trying to find the best fit parameters of this NS-NS merger.⁸ What they were able to conclude is that the jet was pointed 30 degrees away from Earth, and it was a structured jet. Meaning the more relativistic and energetic part of the jet was in the middle. Which is why the afterglow slowly rising, peaking, and then quickly fading away shown in Figure 5.

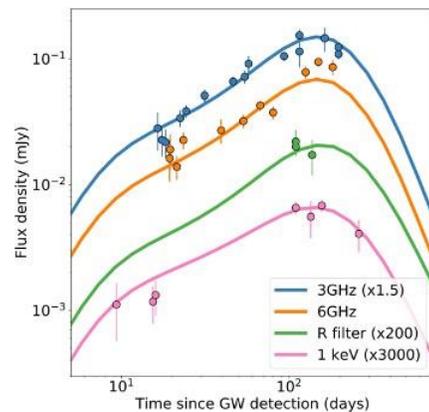


FIG. 5: This is the plot my mentor, Dr. Brian Morsony, and others collaborated. The points are the observational data. The line is the best fit line they calculated. The blue and orange are radio observations, green is optical, and pink is x-ray.

The importance of this is we want to take this same method of fitting GW170817, and applying it to another GRB afterglow, in this case, GRB130603B. This was a complex, well-observed afterglow with detections in x-ray, optical, and radio, and evidence for a jet break. We want to test the idea can we fit all GRBs with this same method, and with the assumption that all GRBs are structured jets that come from NS-NS mergers.

Methods

To make any meaning to the data, we are going to be using the computer programming language Python, and an after-glow program that my mentor, Dr. Brian Morsony has created, to do all the fitting. The basic idea of doing fits in Python is you have a set of points on a plot like in Figure 6.

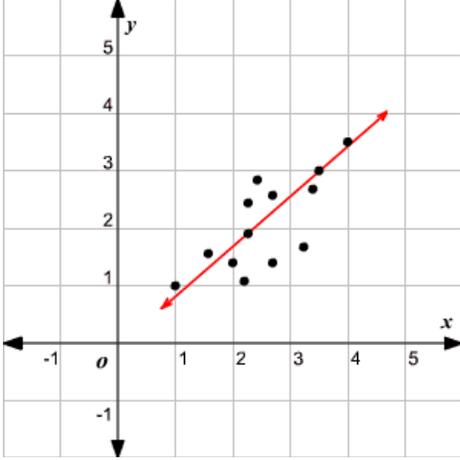


FIG. 6: A set of points with a best fit line going through the points. The form of the line is $y = mx + b$.

The best fit line will be in the form of $y = mx + b$ where the two parameters are the slope and the y-intercept. Now, we want to answer the question, can we fit the same form of the function with another set of points shown in Figure 7. To be extra clear, we are not using this exact slope function. Our function is more complex with 5 parameters. So the question still applies, can we use this complex function that was used all GRBs are structured jets that come from NS-NS mergers. to fit GW170817, to fit GRB130603B.

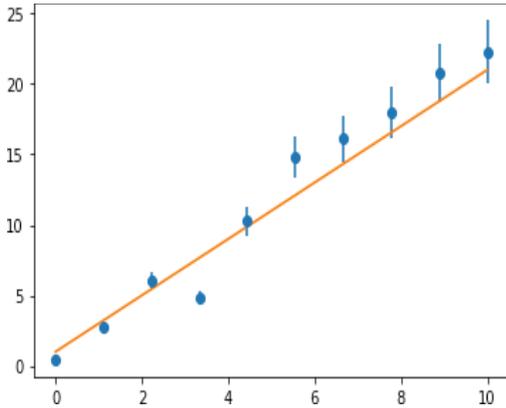


FIG. 7: A different set of points. The x and b will be different, but the important part is that the fit is using the same function.

For this fit, we used an afterglow code made by my mentor Dr. Brian Morsony. What the code utilizes is a Markov Chain Monte Carlo (MCMC) iteration. The reason for this is our function will have 5 parameters. The parameters are the fraction of the shock energy given to accelerate the electrons (ϵ_e), the fraction of shock energy that is converted in magnetic fields (ϵ_b),

the density of the surrounding area of the merger (n_{ism}), the angle pointed away relative to the Earth (θ), and the slope of the power law for the energy distribution between the electrons (p_{index}). In the intro example, we only had x and b . However, there are 5 parameters making parameter space larger. This becomes a problem because in Python, to make fits, you must give it some initial guesses. The reason being is that in the parameter space there are global minimums in which the best fit parameters can fall in shown in Figure 8.

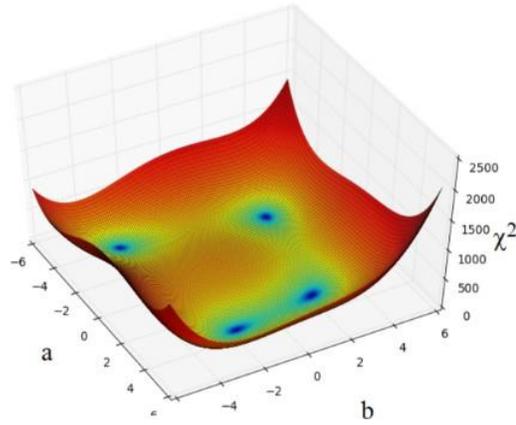


FIG. 8: An example of a parameter space. The goal is to have initial guesses that would fall into the global minimum where chi-squared is the lowest.

There is too many points to guess and check which is where the advantage of MCMC method comes in. The program will be making big jumps around the parameter spaces, checking whether or not the previous step was better than the step it currently is at. The next step will be dependent on this. It will keep jumping around eventually settling in a minimum that it likes. The process of the steps is shown in Figure 9. The range of the values is stated in Table 1.

Parameters	Range
ϵ_e	$1e-04 < \epsilon_e < 1e-01$
n_{ism}	$1e-06 < n_{ism} < 1e4$
θ	$1e-01 < \theta < 15$
ϵ_b	$1e-04 < \epsilon_b < 1e-01$
p_{index}	$2.05 < p_{index} < 3.5$

TABLE I: Range of values that we chose for the MCMC to check for the best fit parameters.

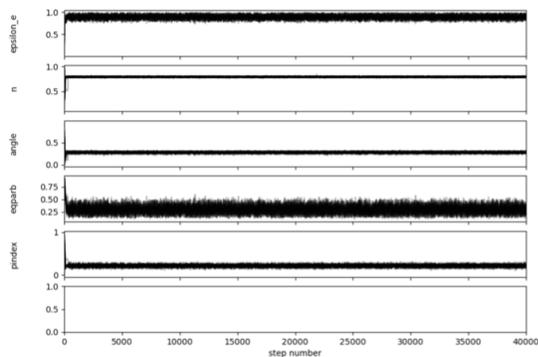


FIG. 9: Step function picking random numbers and settling on a best fit parameter. The first 10,000 samples were removed, so that it doesn't look messy in the beginning.

Then, these values are tested with each other to show if any combination of two parameters are independent or dependent of each other. The corner plot shown in Figure 10, if the box shows a concentrated circle, this means that the parameters are independent of each other. However, if you look in the first column, second row from the bottom, it shows a contracted line. This shows that the two parameters are dependent on each other.

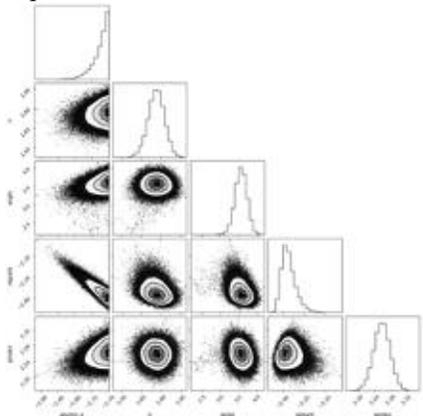


FIG. 10: Corner plot showing the degeneracy of the parameters. The set up is the first column is comparing ϵ_e to the other four parameters. The second column is n_{ism} with p_{index} , ϵ_b , and θ . The it keeps going for the third and fourth column.

From there, the program gives a plot shown in Figure 11. The plot itself can't really tell you if it is a good fit or not. In the statistical analysis, the likelihood will tell you if it is a significant fit. The best fit parameters are shown in Table 2 with the likelihood below it.

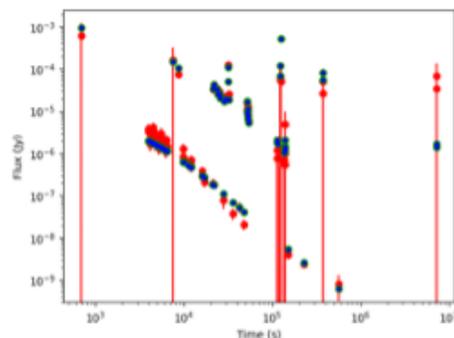


FIG. 11: This plot shows the comparison of observational data (red), and our best fit (blue). The y-axis is the flux of energy we are detecting over the x-axis, time in seconds. The big red lines are non-detections for the observational data.

Parameters	Value	Uncertainty
ϵ_e	0.0191	- 0.0012 + 0.0006
n_{ism}	57.9	-7.7 + 8.5
θ	3.56	- 0.16 + 0.16
ϵ_b	0.0043	- 0.0004 + 0.0006
p_{index}	2.26	-0.02 + 0.02
likelihood	-160.52	

TABLE II: These are the best fit parameters of the models we have. The likelihood at the bottom will tell you how significant the fit is. The more negative the likelihood, the better the fit. For now, is it more of a reference point to compare to other models we will run.

I wanted to elaborate more on the big red lines in Figure 11. These are non-detections where they did not have a high enough probability to be considered a detection, however, it is still enough to be significant. They take the detection, scale it up so that it is a "detection" which results in the very big error bar that falls to the bottom of the plot.

Results and Conclusion

The values in Table 2 3, shows the best fit parameters and the likelihood of the of these values. As ϵ_e becomes lower, the more negative the likelihood meaning the better the fit. The results show us that keeping ϵ_e fixed at some values, in this case 0.1 and 0.01, the program shows that it is pretty likely that ϵ_e can be a fixed parameter. The importance of trying these fixed parameters is finding out that we may not need to include one of these values, and be a constant. These preliminary results shows some significance in tackling the question of whether or not we can use the

same methods to fit GW170817 to fit all other short GRBs by starting with GRB130603B.

The future work that is in progress now is doing fits where all the models, the data points in blue in Figures 11, 12, 13, are fixed at $\epsilon_e = 0.1$ to see if that gives a better fit or not. This will show that if we need to make new models every time we want to test a fixed parameter. Furthermore, we are going to change the error on the observational data from 15 percent to 5 percent, and see if that gives us a better fit.

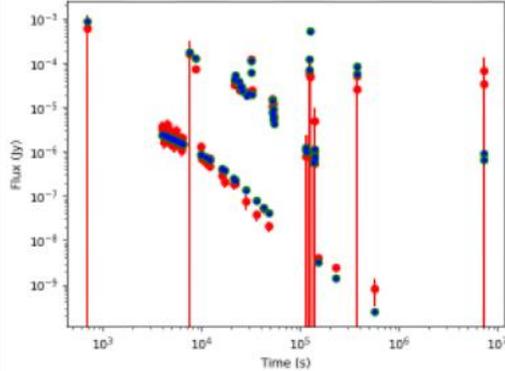


FIG. 12: Plot of ϵ_e fixed at 0.1. The x-axis is time. The y-axis is the flux density.

Parameters	Value	Uncertainty
ϵ_e	0.0999	- 3.24e-06 + 3.33e-06
n_{ism}	99.5	- 14.7 + 14.6
θ	4.67	- 0.11 + 0.12
ϵ_b	0.0002	- 1.55e-05 + 1.82e-05
p_{index}	2.45	-0.02 + 0.02
likelihood	-162.8	

TABLE III: These are the best fit parameters of the models for ϵ_e fixed at 0.1

Citations

- ¹ N. Aeronautics and S. Administration, “Gamma rays,” https://web.archive.org/web/20120502232209/http://missionscience.nasa.gov/ems/12_gamma.html (2012).
- ² J. Bonnell and R. Klebesadel, “A brief history of the discovery of cosmic gamma-ray bursts,” <https://pubs.aip.org/aip/acp/article-abstract/384/1/977/579197/A-brief-history-of-the-discovery-of-cosmic-gamma?redirectedFrom=fulltext> (1996).
- ³ W. Fong *et al.*, “A decade of short-duration gamma-ray burst broadband afterglows: Energetics, circumburst densities, and jet opening angles,” <https://iopscience.iop.org/article/10.1088/0004-637X/815/2/102> (2015).

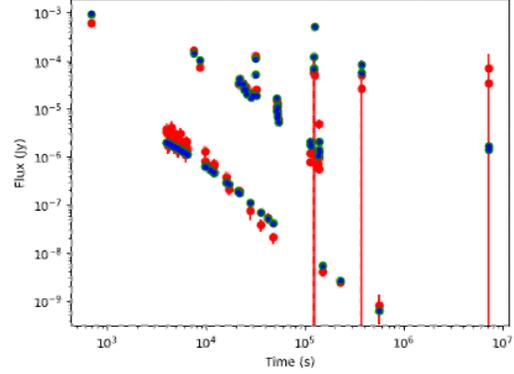


FIG. 13: Plot of ϵ_e fixed at 0.01. The x-axis is time. The y-axis is the flux density.

Parameters	Value	Uncertainty
ϵ_e	0.0099	- 3.33e-07 + 3.29e-07
n_{ism}	44.96	- 6.43 + 6.84
θ	3.03	- 0.16 + 0.16
ϵ_b	0.0149	- 0.0009 + 0.0010
p_{index}	2.184	-0.017 + 0.016
likelihood	-181.6	

TABLE IV: These are the best fit parameters of the models for ϵ_e fixed at 0.01

- ⁴ K. Academy, “The supernova–gamma-ray burst connection,” <https://www.annualreviews.org/doi/10.1146/annurev.astro.43.072103.150558> (2006).
- ⁵ Astrobites, “Multi-messenger observations of a binary neutron star merger,” <https://astrobites.org/2017/10/16/multi-messenger-observations-of-a-binary-neutron-star-merger/> (2017).
- ⁶ LIGO, “What are gravitational waves?” <https://www.ligo.caltech.edu/page/what-are-gw> (2023).
- ⁷ D. Lazzati *et al.*, “Late time afterglow observations reveal a collimated relativistic jet in the ejecta of the binary neutron star merger gw170817,” <https://arxiv.org/abs/1712.03237> (2017).
- ⁸ M. P. Gesellschaft, “The strange afterglow of a gamma-ray burst.”