Using Python to Analyze Minimum Variability Timescale of Gamma-Ray Bursts to Identify their Progenitors

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Gamma-ray bursts (GRBs) are extremely energetic explosions that are caused by two major events: binary neutron star (BNS) mergers and the collapse of certain exotic massive stars. BNS mergers in particular are excellent emitters of gravitational waves (GW). GRBs are classified as either short or long duration, typically resulting from BNS mergers and collapsars, respectively. Short duration bursts last from several milliseconds to several seconds, and are spectrally hard. In contrast, long duration bursts are spectrally soft and can last from several seconds to several hundreds of seconds. GRBs caused by BNS mergers, especially, are prime candidates for analysis using tools like PyGRB, which detect gravitational wave emission from these electromagnetically bright sources. However, due to the high computational expense of running PyGRB it cannot be done for all GRBs, so rapid classification is employed to prioritize events. This process naturally misses outliers to the traditional classification schemes. In particular, certain long duration GRBs thought to originate from BNS mergers have been found that would be missed by typical match filtering. It may be possible to categorize these outliers by examining the minimum variability timescale (MVT) of the light curves produced by GRB prompt emissions. Using Python and data from the *Fermi GBM Burst Catalog*, we estimate the MVT for GRB 211211A, a notable classification outlier, so that the same method can be applied to future GRBs.

I. Introduction

The first gamma-ray bursts (GRBs) were detected in the late 1960's by *Vela*, a military satellite system launched by the United States.[12] After their initial discovery, progress regarding the analysis of GRBs was slow, in part due to the nature of observational breakthroughs coming only when new detectors and telescopes come into use. By 1993, analysis of the first *BATSE GRB catalog* by Chryssa Kouveliotou et al.[7] provided indications of two distinct duration classifications for GRBs, without providing much insight into their origins. The origin of long duration GRBs was not solved until the late 1990's. The Italian-Dutch satellite *BeppoSAX*, launched in 1996, detected evidence for the relationship between massive star collapse and long-duration bursts in the form of SN 1998bw, a Type Ic supernova located within the error box of *BeppoSAX* long-duration burst GRB 980425. In 2003, the association between GRBs and exotic supernovae was established for the satellite *High Energy Transient Explorer 2(HETE-2)*'s burst GRB 030329/SN 2003dh. The field of GRB observation was revolutionized after the launching of the *Swift* observatory on 20 November 2004. A joint mission between the USA, UK, and Italy, *Swift* allowed for the detection of the afterglow of short-duration GRBs. *Swift* identified the host galaxies of several short GRBs in 2005 as well as their relative locations within the hosts. As the results were very different from those of long GRBs, it followed that short GRBs are likely from a different population entirely and are not produced by the deaths of massive stars. The leading model produced from these results is the merging of two neutron stars or one neutron star and one black hole. The long-duration-collapsar, short-duration-kilonova paradigm gained additional reinforcement after the launch of the *Fermi* Gamma-Ray Space Telescope in 2008. *Fermi*, with its Large Area Telescope and Gamma-ray Burst Monitor (GBM), was a huge leap forward in terms of GRB observation technology and allowed for the study of GRB emissions in unprecedented detail.

Binary neutron star (BNS) mergers have long been theorized to be emitters of gravitational waves (GW).[5, 9, 12] In fact, *GW170817*, the first ever detected GW to be confirmed with an electromagnetic signal, done so in 2017 by the *Laser Interferometer Gravitational-Wave Observatory (LIGO) Collaboration* and *Virgo Collaboration*, was sourced from a BNS merger[1]. As such, *GRB 170817A*, the GRB initially de-

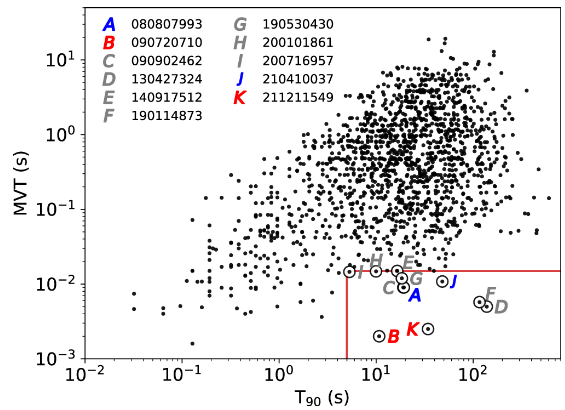

FIG. 1. When plotting the Fermi GBM GRBs by their MVT values as a function of T_{90}, a group of outliers to the two main species appear in the box bounded by $T_{90} \geq 5s$ and MVT $\leq 15ms$. GRB 211211A, or **K** in the figure, is the particular GRB that was analyzed as part of this project.[10]

tected immediately following the GW signal, was a short-duration burst. As BNS mergers, along with other compact binary mergers, are the likely progenitors of most short GRBs, they are the primary targets of GW searches[2]. Astrophysicists use matched filtering to search for GWs from BNS mergers using PyGRB[6, 11], software written specifically to perform this task. As PyGRB is computationally expensive, it cannot be run on all events. Furthermore, PyGRB should only be run on GRBs in which a signal is expected, because otherwise it introduces a statistical effect called a "trial's factor" that reduces sensitivity. As such, in order to run PyGRB efficiently, GRBs need to be classified and subsequently prioritized for analysis according to what their progenitor system is likely to be. The classification scheme of short vs long GRBs, as well as the "spectral hardness" (see Fig. 2) of the electromagnetic signal they output, result in one fairly straightforward and quick way to achieve the required prioritization.

However, after the somewhat recent discovery of *GRB 211211A*, at first glance a typical long-duration GRB which nonetheless resulted from a BNS merger, it became clear that simply using timescales and spectral hardness to identify BNS mergers would not be sufficient.[8, 10] Thankfully, there exist other methods to determine a GRB's progenitor. Research conducted in 2013[3] has shown that the minimum variability timescale (MVT) of a GRB can suggest whether it originated from a binary merger or the collapse of a massive star.

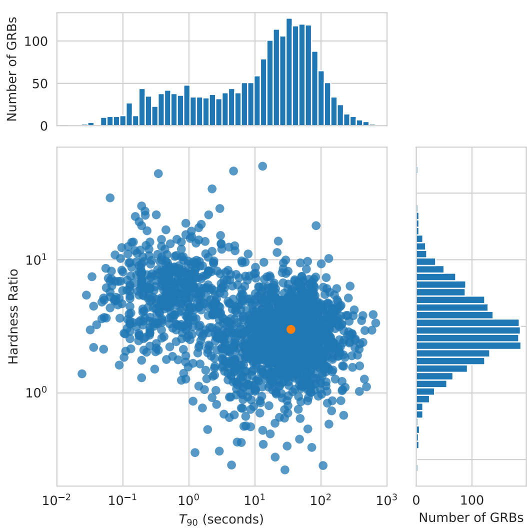

FIG. 2. Spectral hardness refers to the ratio of high-energy photons to lower-energy photons in a spectrum. The relation between hardness and burst duration can clearly be seen. The orange dot is GRB 211211A, somewhat close to the middle of the cluster of long-duration GRBs.[8]

Calculating the MVT for a given GRB is a relatively straightforward process, but requires quite a bit of manual data acquisition, statistical calculation, and direct interaction with different types of software. *GW170817* marked the advent of modern multi-messenger astronomy, and due to the relative infancy of this field, some techniques known to the gamma ray community are still in the process of being adopted by the gravitational wave community. By utilizing Python's many astronomy-focused packages, as well as taking advantage of its capabilities to enable automation, we aim to create a toolkit that allows for large-scale, relatively automatic MVT estimation. A database of MVTs on such a scale, when combined with existing filtering techniques, should help prioritize long-duration BNS merger GRBs for study with PyGRB.

II. Methods

In order to perform any kind of statistical analysis on a GRB, astronomical data is required. This data was sourced from the *Fermi GBM Burst Catalog*. At time of writing, the *Fermi* catalog contains data on 3736 GRBs detected since June 11$^{\text{th}}$, 2008. The name, trigger time, and T_{90}[1] of each burst is collected from the catalog and put into a data class so that our Python code can easily access it. In addition, a

[1] T_{90} is a measure of the time interval, in seconds, in which 90% of the GRBs total energy output is contained.

'FITS' file, containing electromagnetic spectrum data, must be acquired for any GRBs for which MVT values are to be calculated. As *Fermi* has 14 individual detectors on its GBM instrument (12 sodium iodide (NaI) and 2 bismuth germanate (BG)), any given GRB will have up to 14 different FITS files to choose from. For the purposes of this project, the ideal FITS file is one that displays the most well defined curve with sufficient pulse height.

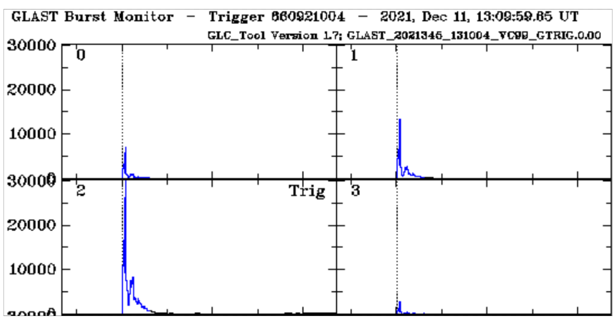

FIG. 3. A snippet of the FITS data collected by the first 4 NaI detectors for GRB 211211A. Detector 2 contains the most well defined light curve, so its corresponding FITS file was the one utilized by our code.

After data acquisition, the first automation our code provides can be utilized. For the purposes of MVT estimation, we must generate a number of light curves at different time bin widths. This is done using 'gtbin', a Python-based tool provided by NASA. Typically, gtbin is utilized from the command line to generate individual light curve (lc) files from a given FITS file based on manually inputted parameters. The three input parameters of note are start time (the point of the lc where gtbin should start exporting data, given in Fermi mission elapsed time (MET) in seconds), stop time (also given in Fermi MET), and bin size (once again given in seconds). The start and stop time parameters are calculated once per GRB in a straightforward manner. The GRB's T_{90} is subtracted from its trigger time (given in Fermi MET, also known as T_0). The resultant value is simply the $T_0 - T_{90}$ and becomes our start time. Similarly, we add the T_{90} to the trigger time, resulting in the $T_0 + T_{90}$ which serves as our stop time. The result is a lc centered on T_0 in which the first half is entirely background radiation and the second half contains the actual GRB emission data.

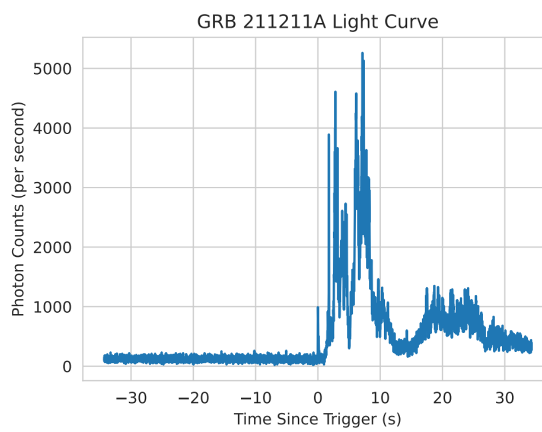

FIG. 4. An lc plot of GRB 211211A generated by gtbin. Note that the emission data is contained entirely to the right of our trigger time. The bin width used to generate this lc was 0.1s

Bin size is similarly straightforward, but given that we need to generate on order 10^4 light curve files at various time binnings, we use Python to automate this process. For GRB 211211A, we generate lc files with bin size ranging from 1μs to 1s, increasing by 1μs each iteration, such that the result is 10^4 distinct lc files. At last, we are ready to generate our MVT curve. The statistical method used to estimate MVT comes courtesy of Dr. Narayana P. Bhat, who described it in his 2013 paper *Variability Time Scales of Long and Short GRBs.*[3]

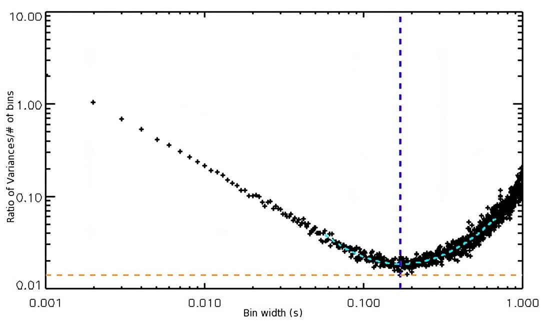

FIG. 5. A MVT curve generated for a typical long-duration GRB. The cyan dashed line shows a fitted parabola around the curve's minimum, with the vertical dashed line indicating the bin width that corresponds to the MVT. This curve serves as a model for the curves generated by our code.[3]

Once again, the statistical MVT estimation is a process that we automate using Python. Our module begins by taking the first lc file generated with the smallest bin size and splitting it in half, separating the background radiation from the emission data. For each half, a differential between each time bin is taken. We then separately calculate the variance of the of the background differential, as well as the emission differential, then take the ratio of the emission to the background. This ratio is then normalized by the bin size and the resultant value is stored. This entire process is repeated for every lc file at each bin size. Finally, the collected ratios of variances per bin size are plotted as a function of bin size in order to produce our MVT curve.

The theoretical result of a MVT curve generated using Bhat's method starts at a maximum at low bin size, eventually smoothly curves into a parabolic minimum (the actual MVT we are concerned with), and then increases again. By thinking about the parameters involved in plotting each individual point, we can understand why this shape is formed. Initially, at very small bin sizes, the ratios of variances between background radiation and emission data approach 1, as the differential between any two subsequent bins will be very small. This means the y position of our plotted points at this part of the curve can roughly be defined as $y = \frac{1}{x}$, where $x =$ bin size, and since bin size is very small here, vertical position is maximized. The ratios continue to decrease according to this function until our curve reaches a bin size in which the variance of the emission data begins to dominate over the variance of the background radiation, at which point the curve reaches an inflection point and starts to increase again. The value of the given bin size at this inflection point is the MVT value that we hope to estimate.

III. Results

Our Python code was able to produce a MVT curve for GRB 211211A, which we can use to estimate its MVT. Due to less than ideal noise-to-signal ratio near our curve's minimum, we estimate our MVT to be on order 10^{-2} s. It is worth noting that our code produces a significant amount of noise at larger bin sizes. In the case of GRB 211211A, the MVT was positioned before this noise made it impossible to extrapolate, however, in generating curves for other GRBs, this was not always the case (see appendix for two examples).

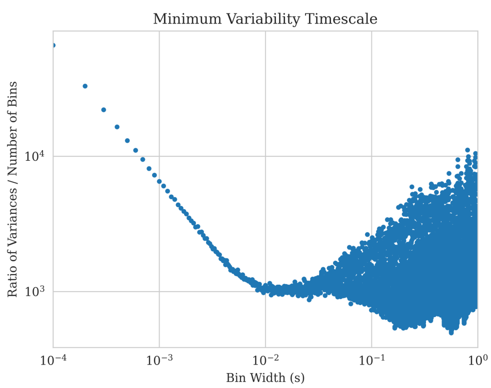

FIG. 6. MVT curve for *GRB 211211A*. Here MVT is estimated to be on order 10^{-2} s, whereas the expected MVT given in fig. 1 is closer to $10^{-2.7}$ s.

IV. Discussion & Conclusion

The Python packages created for this project certainly streamlines much of the MVT calculation process, albeit with several conceits. First of all and most glaringly, MVT values estimated from the curves produced by our code vary in accuracy when compared to expected results. Our curve for GRB 211211A resulted in an estimated MVT on order 10^{-2} s whereas the MVT estimated by Veres et al. was closer to $10^{-2.5}$ s.[10] Furthermore, for several other tested GRBs, the MVT was positioned in a portion of the curve containing enough noise to make MVT extrapolation impossible. These issues can hopefully be fixed by a better sampling process, perhaps by utilizing FITS files from several detectors rather than only one. As part of the data selection performed in the 2012 paper *Temporal Deconvolution Study of Long and Short Gamma-Ray Burst Light Curves*[4], P. N. Bhat et al. summed the FITS data from the four detectors that registered the highest gamma-ray signal for each GRB studied. Implementing a similar process in our code before the lc file generation step would likely result in a more accurate MVT curve with less noise. Additionally, while our code offers a great deal of time savings and automation, these aspects can be improved. One major potential area of improvement is data acquisition. An initial goal of this project was to automate the acquisition of GRB date from the *Fermi* GBM database, with the only two inputs required from the user being GRB name and bin size interval, however we did not have the time to implement this level of automation. Another aspect that can be improved is the general efficiency of the code. Generating 10^4 lc files with gtbin using our code can take an upwards of half an hour, and potentially longer if the FITS file for the inputted GRB contains a larger than average amount of data. Luckily, this project has been selected as an A&S fellowship project to be worked on this summer, and hopefully these issues can be addressed.

Appendix

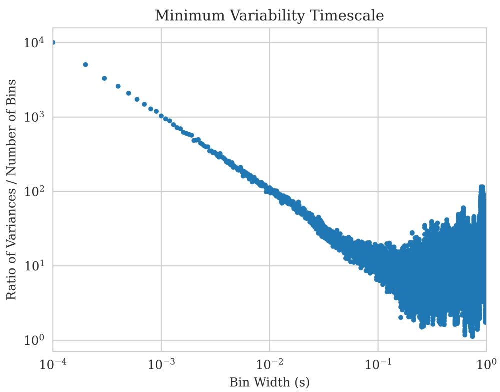

FIG. 7. Attempted MVT curve generation for GRB 090720B. Here we do not see a minimum; it is perhaps lost in the noise near the end of the curve. Furthermore, any potential MVT estimations made in the section of noise would be very inaccurate- the expected value is somewhere near $10^{-2.9}$ s.

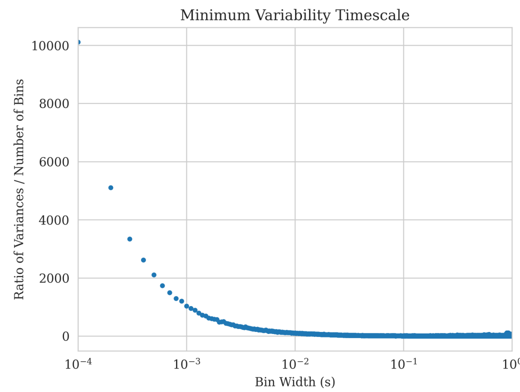

FIG. 8. Attempt at using linear plot scaling to find MVT of GRB 210410A. With typical logarithmic scaling, this plot was even less useful and more noisy than fig.7. It is doubtful that linear scaling is useful for MVT analysis in this context.

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