Gamma-Ray Burst Redshifts Could Indicate Non-Uniformity and Structure Within Universe

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Abstract

We study all gamma-ray bursts (GRBs) with spectroscopic-confirmed redshifts observed between the dates of November 20, 2004 through July 2, 2014, and look for abnormal patterns of potentially non-random behavior. Such behavior might consist of clusters of GRBs in certain BAT RA and Dec coordinates, or clustering within certain redshift intervals. Additionally, we look for areas in the sky that might have more GRB activity than others, or conversely, certain areas that have significantly less activity. The method used to search for these abnormal patterns is a traditional counting approach that was initially done by hand, but after preliminary testing yielded interesting results, we turned to computational power. We analyze the data for peaks in GRB activity within three standard deviations from the mean. At this time, we do not offer theoretical explanations for the results presented in this paper.

1 Introduction

1.1 Discovery

Gamma-ray bursts (GRBs) are a relatively new phenomenon, accidentally discovered less than fifty years ago by Los Alamos National Lab on July 2, 1967 [1]. After the same satellite, Vela, detected over a dozen more events, the first paper was published on GRBs entitled *Observations of Gamma-Ray Bursts of Cosmic Origin* in 1973. Since the detection of the very first gamma-ray burst, thousands of GRBs have been detected [2]. Of these, only a small percentage have been identified with having known redshift values, hence this paper samples from a much smaller pool of GRBs. Since their discovery, approximately 5,300 papers on GRBs were published between the years of 1973 and 2001 [3].

1.2 Gamma-Ray Bursts

The most powerful events that have ever been observed in the Universe are gamma-ray bursts, whose energy levels are expected to rival only that of the Big Bang [2]. GRB luminosity is around a million trillion times that of our sun [4]. There are two classes recognized: short bursts (defined as two seconds or less) and long bursts (greater than two seconds), although there is a possibility more could exist [5],[6]. The first class is believed to arise as a result of the merging of two neutron stars, while the second class is believed to originate from the death of massive stars in supernovas, but the end result in both cases is the formation of a black hole [4].

Although much work has been dedicated to understanding this phenomenon, it is still uncertain what causes these events [2]. To unravel more of the mysteries surrounding gamma-ray bursts, powerful satellites such as BATSE, Fermi and Swift have been commissioned to probe the origin of these events as well as to gain insight into the nature of the early Universe [7].

2 Motivation

Current views in the Astrophysical community rest on the results provided by NASA BATSE satellite (see Figure 1) that indicate GRBs are distributed uniformly throughout the sky and are not associated with any type of structure in the Universe [8]. However, there has been research over the past ten years into whether or not this conclusion is valid, and whether GRBs actually represent a"physically homogeneous group" [9].

According to a paper published by Attila Meszaros, et al. in 2000, analysis of a sub-class of 181 GRBs yielded a 99.3% confidence level that the angular distribution was nonrandom [10]. However, it is clear that previously published results such as these, suggesting nonrandom behavior and inhomogenous distribution, have not provided sufficiently compelling evidence to disprove the Cosmological Principle, a modern cosmological axiom rooted in the assumption that matter is distributed uniformly and isotropically throughout the Universe [11].

Taking note of previous research into the distribution of GRBs, in particular a paper recently accepted for publication in *Astronomy and Astrophysics* by Istvánc Horváth, et al. in July 2014, *Possible Structure in the GRB Sky Distribution at Redshift Two*, we begin our own study on a distribution of GRBs with known redshift values. What we are looking for here is some indication of greater activity in one region of the sky when compared with all others, as well as any region of the sky that has significantly less activity. This may indicate a pattern in the distribution of matter throughout the Universe, and hence, this distribution could no longer be described as random.

Additionally, we are also searching for clues regarding the formation of the Universe, which might be found by study of the redshifts, if indeed it appears that certain redshifts are more active in certain areas of the sky. Specifically,

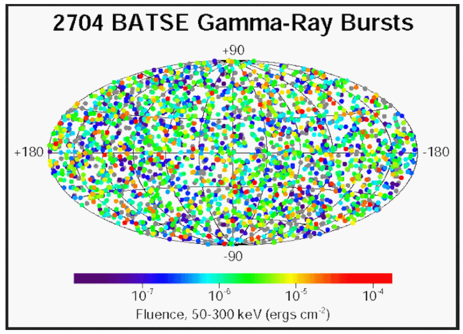

Figure 1: BATSE GRB Skymap: The nearly 3,000 GRBs detected by NASA's BATSE (Burst and Transient Source Experiment) satellite indeed appear uniformly distributed throughout the sky upon first glance.

we are looking for certain parts of the sky to have greater activity in more distant redshifts, and all other areas of the sky to have more activity in nearer redshifts. These clues could perhaps provide details as to how the Universe has expanded, which might differ from the metric of space-time established in 1935 by Robertson and Walker, which is based on a homogenous, isotropic and uniformly expanding Universe [11].

The redshift associated with GRB distance is known as the cosmological redshift, and determined using the following equation,

$$z = \frac{\lambda_{observed} - \lambda_{emitted}}{\lambda_{emitted}}. \tag{1}$$

The cosmological redshift is correlated with the expansion of the Universe, measuring the expansion of spacetime as given by Lemaître's Equation [12],

$$\frac{R(t)}{R(t_e)} = (1 + z), \tag{2}$$

which is derived from the Robertson Walker metric. As the Universe expands, light waves are stretched. Stretched wavelengths become longer, and when they become longer, they become more red [13]. To summarize the effect of redshift: "If we measure a redshift of $z = 2$, the Universe is $3x$ bigger now than it was when that photon was emitted"[12].

3 Method

Similar to the approach taken in the previously mentioned Istváńc Horváth, et al. paper, we analyze the angular distribution of the GRBs as a function of distance [14], apply a similar counting approach, vary the redshift bin size and then compare the GRB counts in different regions. In contrast to said paper's approach, we also vary the BAT RA and the BAT Dec (see following section's

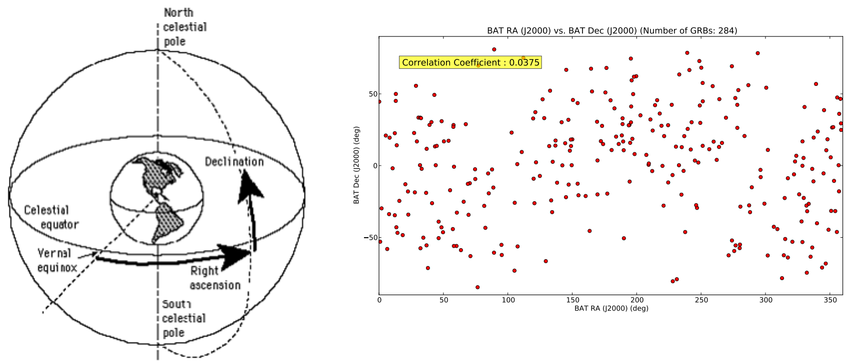

Figure 2: Left: RA and Dec coordinate system, taken from the NASA Swift website at Sonoma State. Right: The GRB pool used in this study, which totals 284.

definitions) bin sizes, resulting in a partitioning of the sky into 16, 36 or 64 equivalently sized squares for each redshift bin size.

3.1 The GRB Catalog

The GRBs used in this study were taken from *The GRB Catalog*, a database founded and maintained by former postdoc at Michigan State University and NASA's Swift satellite team member Tilan Ukwatta. Measurements made by Swift are "of great interest to the astronomical community" [7], and all data is made public immediately. The database includes only the GRBs detected after the launch on November 20, 2004 of Swift, which total 983 as of July 31, 2014. The majority of the GRBs used in this study were detected by Swift (98%), while the remaining 2% were detected by other sources such as Fermi, Ground Analysis or HETE.

For the purpose of this study, we are only interested in GRBs with known redshifts. Furthermore, of the GRBs with known redshifts, we are interested in only those which have had redshifts confirmed using the spectroscopic technique, which is believed to be a more reliable method of measurement than the photometric technique. The total pool of GRBs used in this project is 284 (see Figure 2).

The celestial coordinate system can be seen on the left in Figure 2, where Right Ascension (RA) can be described by the x-axis, and Declination (Dec) can be described by the y-axis. The coordinate system used in the GRB Catalog has x-axis values of BAT RA (J2000), which range from 0° to 360° and y-axis values of BAT Dec (J2000), from -90° to 90°. *J*2000 refers to the current standard epoch, which is January 1, 2000 at 12:00 TT, where the *J* stands for Julian epoch and the *TT* stands for Terrestrial Time. *BAT* stands for Burst Alert Telescope, one of three detectors aboard the Swift satellite and the primary detector of gamma-ray bursts.

3.2 By Hand

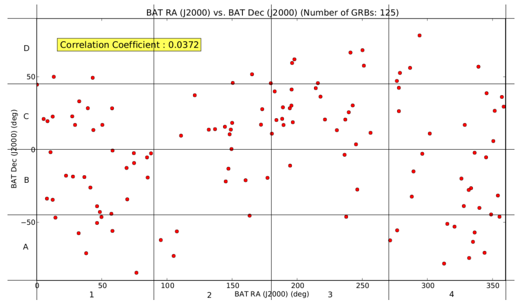

Figure 3: 4 x 4 superimposed grid binning. This particular example is for the redshift interval 0.0-1.5. Dec coordinates are labeled with letters and RA coordinates are labeled with numbers.

Preliminary results were initially calculated by hand. One of the features of the GRB Catalog is that the user has the ability to generate publication-quality plots using any group of selected GRBs desired. The axes can be chosen from a selection of various measures and can also be rescaled, while plots can be saved as PDFs. The list of corresponding GRB coordinates can also be downloaded from the site. Using the *GNU Image Manipulation Program*, we superimposed customized grids in 4x4 binning, 6x6 and 8x8 (see Figures 3 and 4).

Since all plots were generated over the same scale, and all GRB coordinates were known, we counted the number of GRBs per square in each plot. We used this method to obtain results for redshift intervals of length 1.5, where three plots were made for each interval. For example, the redshift plot for 0.0-1.5 was grouped in the following three ways: 4x4 binning, 6x6 and then 8x8. The next redshift plot, 1.5001-3.0 was grouped in the same manner. After counting the GRBs, we cross-checked coordinates for any questionable GRB locations (those that landed directly on the grid lines) by referencing the GRB list downloaded for that particular plot.

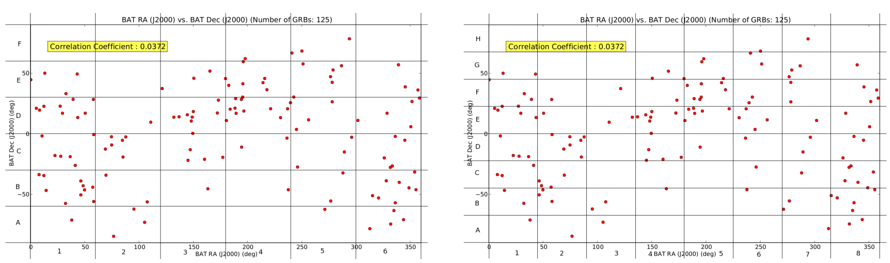

Figure 4: Grid binning for the redshift interval 0.0-1.5. 6 x 6 superimposed grid is shown on the left and 8 x 8 is on the right.

3.3 Computationally

Taking the data by hand is significantly labor intensive, and we initially decided to collect data for five varying redshift intervals. We turned to Python, and wrote a program to first count redshift intervals, then the BAT RA binning, followed by the BAT Dec binning. We can change the length of any x interval (BAT RA), y interval (BAT Dec) or z interval (redshift) by simply changing bin lengths in three lines of code, and the returned values were copied and pasted into a spreadsheet program. Once the code began counting the GRBs per bin for us, we had the freedom to choose any redshift interval we pleased.

4 Analysis

In this study, we are primarily interested in finding a GRB count that peaks in a particular region of the sky and remains significant across all three grid sizes of 4x4, 6x6 and 8x8. To find peaks in GRB activity, our approach was to plot the GRB count along the y-axis versus the BAT RA and BAT Dec grid sizes 4, 6 and 8 along the x-axis (see Figures 3 and 4). This approach allows us to plot the GRB count for the entire region of the sky, which has been divided into cubes as a result of the partitioning of the x, y and z coordinates (BAT RA, BAT Dec and redshift, respectively). Therefore, we analyzed the GRB activity of different redshift intervals by plotting GRB count versus 16, 36, or 64 bins depending on the grid size.

For these plots, we looked at data from different redshift binnings. For all plots where a noticeable peak was observed, either the population or the sample standard deviation was computed. The population standard deviation was found using Equation 3, and the sample standard deviation was determined using Equation 4.

$$\sigma = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(x_i - \bar{\mu})^2}. \tag{3}$$

$$S_{n-1} = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(x_i - \bar{x})^2}. \tag{4}$$

These formulas differ only in the division of the variance by either n or $n-1$. The sample standard deviation is most likely the better estimate, since the GRB pool used in this study is rather large.

As previously stated, we looked for a peak in the sky that was significant across all three grid sizes of 4x4, 6x6 and 8x8, where we quantify "significant" as being three standard deviations from the mean. The mean was calculated treating the GRB counts per bin as data points. For the 4x4 grid size, we have 16 bins and therefore 16 data points. The mean was the sum of the 16 data points, divided by 16. The 6x6 and 8x8 means were similarly determined, dividing the sum of data points by either 36 or 64.

5 Results

In this study, we found an area of the sky that has GRB activity reaching three standard deviations from the mean in a particular redshift interval. We also found in the 4 x 4 grid partitioning that this area has greater activity over all redshift regions than any other area of the sky.

5.1 Redshift 0.0 - 10.0

This was our preliminary result upon taking the data by hand, and is what prompted us to create a code and take a much closer look at this GRB sky distribution. Figure 5 shows the results of the 284 GRBs partitioned into a 4 x 4 grid, with BAT RA and Dec values consequently partitioned into 16 bins.

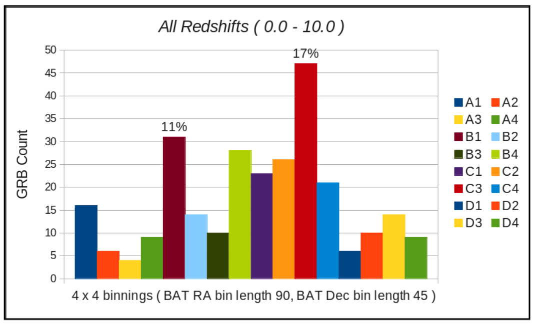

Figure 5: Results for 4 x 4 grid size in the redshift region 0.0 - 10.0.

Here we see that a particular region of the sky has noticeably greater activity than the others. This area of the sky is “C3”, which is taken from the naming scheme for the grids (the numbers in this case are the RA values while the letters are the Dec values; See Figure 3). The exact coordinates of C3 are BAT RA (J2000) $180-270°$ and BAT Dec (J2000) $0-45°$. After seeing these preliminary results, we decided to focus on this particular region in the xy plane (RA and Dec plane) and test for significant activity across all three grid sizes over a specific redshift interval. The results of this testing are discussed in section 5.2.

5.2 Redshift 1.6 - 2.7

We found significant activity for an area of the sky we denote C3 (see section 5.1) across all three grid sizes in the redshift interval $1.6-2.7$. The region C3 reaches three standard deviations from the mean in the redshift interval $1.6-2.7$. This standard deviation is the population standard deviation, which as previously stated, is not as accurate of an estimate of the total GRB distribution as the sample standard deviation. The activity level for this region is shown in Figure 6. Again, the area of C3 ranges from BAT RA (J2000) $180-270°$ and BAT Dec (J2000) $0-45°$. See Figure 6 for results of C3.

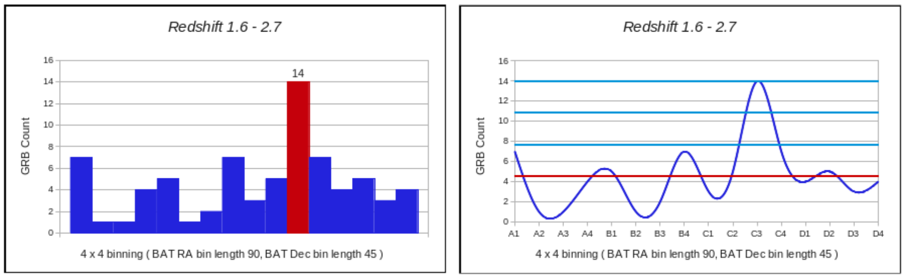

Figure 6: Results for 4 x 4 grid size in the redshift region 1.6 - 2.7. The graph on the right marks the population standard deviations taken from the mean GRB count.

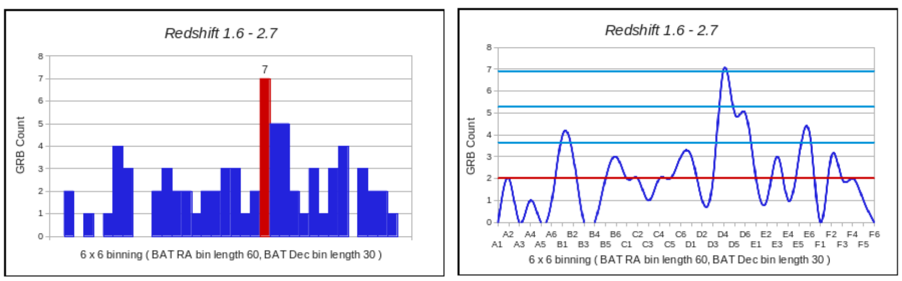

Figure 7: Results for 6 x 6 grid size in the redshift region 1.6 - 2.7. The graph on the right marks the sample standard deviations taken from the mean GRB count.

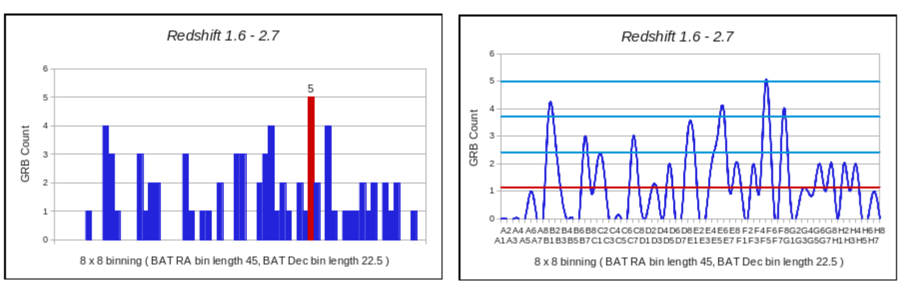

Figure 8: Results for 8 x 8 grid size in the redshift region 1.6 - 2.7. The graph on the right marks the sample standard deviations taken from the mean GRB count.

In the 6 x 6 grid, the coordinates change for C3, and become a bit smaller. The area that corresponds to C3 of the 4 x 4 grid is “D4” in the 6 x 6 grid. This region also reaches three standard deviations from the mean, but the standard deviation calculated here is the sample standard deviation. The area of D4 ranges from BAT RA (J2000) $180 - 240°$ to BAT Dec (J2000) $0 - 30°$, and is a subset of C3. See Figure 7 for results of D4.

We then analyzed the 8 x 8 partitioning data, and again found GRB activity three standard deviations from the mean using the sample standard deviation. The area of the sky is “F5”, with coordinates BAT RA (J2000) $180 - 225°$ and BAT Dec (J2000) $22.5 - 45°$, and is a subset of both C3 and D4. See Figure 8 for results of F5.

6 Conclusion

These results show there is significant activity for a particular RA and Dec region of the sky. Furthermore, this activity reaches 3σ in a redshift interval that overlaps a region identified by Horváth, et al. as possibly containing a structure larger than the Sloan Great Wall [14]. It is worth pointing out that the GRBs used in this study shared no common characteristics beyond having been detected by Swift (281/284) over the past nine years, and having their redshifts determined spectroscopically. Therefore, this sample of GRBs was random. Why would a random sample show correlation?

7 Future Work

In the near months to come, we would like to take a closer look at the results presented in this paper and perform a more sophisticated and detailed analysis of our data to better quantify the GRB activity in this region. We also plan to spend more time studying the redshifts of this particular GRB pool, particularly the finer redshift intervals, and perhaps even try to explain why this region compromises such a higher activity rate than any other region of the sky within the redshift 1.6 - 2.7.

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