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Anomalies in the GRB spatial distribution

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Swift's remarkable ability to quickly localize gamma-ray bursts has led to the accumulation of a sizable burst sample for which both angular locations and redshifts are measured. This sample has become large enough that it can potentially be used to probe angular anisotropies indicative of large-scale universal structure. In a previous work, a large clustering of gamma-ray bursts at redshift $z \approx 2$ was reported in the general direction of the constellations of Hercules and Corona Borealis. Since that report, a 42% increase in the number of $z \approx 2$ gamma-ray bursts has been observed, warranting an updated analysis. Surprisingly, the cluster is more pronounced now than it was when it was first reported.

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1. Introduction

Gamma-ray bursts (GRBs) are the most luminous objects known; they are luminous enough that their positions can potentially be used to help map out large-scale universal structures. GRBs are tracers of the stellar matter from which they formed, and they significantly outshine their host galaxies so that they can be mapped even when the distribution of underlying galaxies cannot. The drawback is that the detection rate is small (95 per year by Swift; [14]), and the rate at which redshifts are measured for the detected bursts is even smaller (roughly 35 per year).

The angular distribution of GRBs has been studied in detail over the past two decades ([3, 1, 2, 12, 11, 15]). Initially, the distribution's angular isotropy was examined in response to the hypothesis that GRBs had Galactic origins. After the cosmological nature of GRBs was established, however, the focus of isotropy studies shifted to subsamples having potentially different angular distributions ([1, 4, 12, 10, 11, 15]). These studies, originally dependent on GRBs for which redshifts had not been measured, became more reliable as the number of GRBs with known redshifts increased, but remain limited by small sample sizes. Swift's compilation of a large number of GRBs having known redshifts has reinvigorated large-scale isotropy studies, although the small numbers of GRBs in specific redshift ranges (corresponding to radial shells) limits these studies to the detection of large, pronounced anisotropies.

We have recently identified a surprisingly large anisotropy suggestive of clustering in the GRB angular distribution at around redshift $z \approx 2$ ([8, 9]) in the general directions of the constellations of Hercules and Corona Borealis. The scale on which the clustering occurs is disturbingly large: the underlying distribution of matter suggested by this cluster is big enough to question standard assumptions about Universal homogeneity and isotropy. Fortunately, Swift's continued detection of GRBs makes the hypothesis testable: if the anisotropy is attributable to statistical sampling, then the cluster should become less pronounced as more GRBs are detected.

As of November 2013, the redshifts of 361 GRBs have been measured[1] with the sky distribution shown in Fig.1; most of these GRBs were detected by Swift. This sample represents a 28% increase over that used in our previous analysis (283 bursts observed until July 2012). The number of GRBs in the $1.6 < z < 2.1$ redshift range ([8]) (where the cluster resides) has increased from 31 bursts to 44 bursts, a 42% sample size increase that is large enough to warrant an updated analysis.

2. Data Analysis

We analyze the angular distributions in each or our predefined redshift z bins using the k^{th} nearest neighbor and the bootstrap point radius methods. These statistical tests are chosen so that we can directly compare our new results with our previous ones.

The redshift (radial) bins used in this study are chosen to be the same as those defined in our previous work. In theory the small uncertainties associated with redshift measurements allow the GRB sample to be easily subdivided into as many redshift bins as desired. In practice, small number statistics limit the confidence with which anisotropies can be detected in each bin.

We have subdivided the total sample of 361 bursts into different numbers of redshift bins ranging from two bins (note that a choice of one bin corresponds to the bulk angular GRB distribution

[1] http://lyra.berkeley.edu/grbox/grbox.php

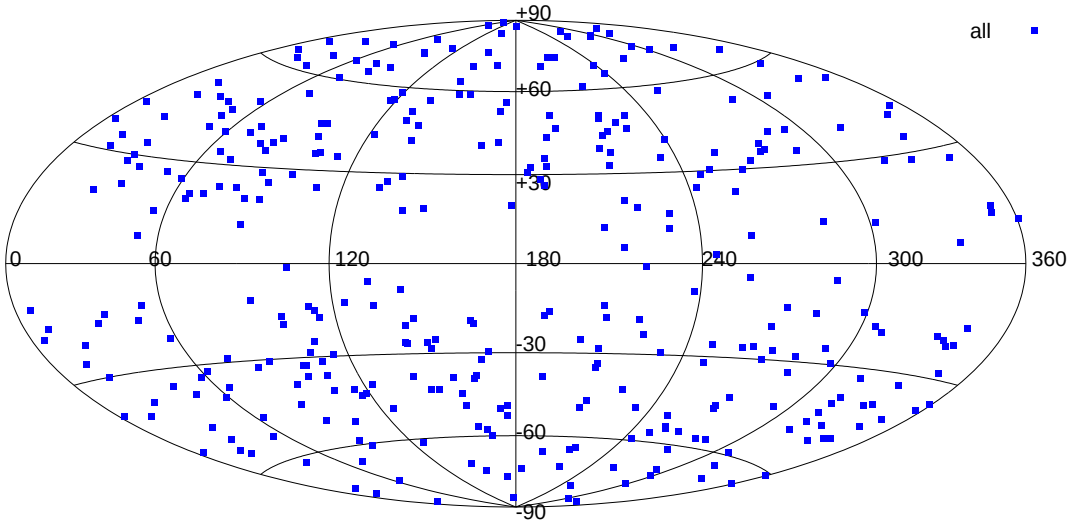

Figure 1: The sky distribution of GRBs with measured redshift. Although the distribution of all GRBs is fairly isotropic, extinction causes this sample to miss GRBs near the Galactic plane.

Table 1: An example of the 31st nearest-neighbor test for four radial groups, with redshift boundaries defined in the text. Tabulated numbers represent the KS-test significance that two groups have different 31st nearest-neighbor distributions. Boldface type indicates that significant (more than 3σ) differences exist between group 2 ($1.61 \leq z < 2.68$) and other radial groups.

	z_{min}	gr2	gr3	gr4
gr1	2.68	**0.9999999**	0.942	0.672
gr2	1.61		**0.99904**	**0.9999988**
gr3	0.85			0.960

in the plane of the sky) to nine bins. These choices not only allow us to explore the angular characteristics of a variety of radial bins corresponding to redshift intervals, but also allow us to identify the redshift range within which any anisotropies lie, should we discover them. The choice of nine radial bins provides us with narrow z-bins having the smallest number of bursts per bin (≈ 40) for which we feel we can make reasonable, quantifiable estimates on bulk anisotropies. When choosing between 2 and 9 radial divisions, we select the bin sizes that allow us to maintain similar numbers of bursts in each radial bin. When we choose a number of bins that does not allow an equal number of bursts to be placed in each bin, then we redefine the bin boundaries so that the excess GRBs are those with the smallest redshifts; these are subsequently excluded from the analysis.

The first statistical test we apply to the radially binned distributions is the kth nearest-neighbor statistic; this test looks at the angular separation between each burst and the kth closest burst to it. When this test considers only the nearest neighbor ($k = 1$), it is sensitive to anisotropies on small angular scales corresponding to paired bursts. When looking at widely-separated bursts with large k values, the test is sensitive to anisotropies on much larger angular scales.

We apply the kth nearest-neighbor statistic to all burst pairs in each of our radial bins, for

the bins in each sample of two to nine radial bins. Most of the times the results are statistically consistent with isotropy, regardless of the value of k, the number of radial bins chosen, or the particular radial bin being examined. The exceptions arise in the radial bin containing GRBs with redshifts of $z \approx 2$, where anisotropies are observed for medium-sized k values consistent with clustering. These anisotropies are most pronounced in the $1.6 \leq z < 2.1$ radial bin, to which this clustering appears confined. This result is consistent with our previous findings for a smaller data set [8, 9].

We demonstrate typical results based on a choice of four radial bins. Each bin contains 90 GRBs, with the bins defined by $2.68 \leq z < 9.4$ (group 1), $1.61 \leq z < 2.68$ (group 2), $0.85 \leq z < 1.61$ (group 3), and $0 \leq z < 0.85$ (group 4). Table 1 shows the significance of the null hypothesis for this example using the Kolmogorov-Smirnov test that the two distributions are different. Boldface type indicates that the significance that the two group's 31st nearest-neighbor distributions differ by more than 3σ. There are no significant differences within the group 1, group 3, or group 4 distributions, but the 31st nearest-neighbor distributions in group 2 indicate a significant anisotropy. The same indication of a large-scale anisotropy in this radial group is found from all nearest neighbor distributions spanning the range $22 \leq k \leq 55$, indicating that the anisotropy occurs on an angular scale of intermediate size.

The significance, angular size, and location of the large, loose GRB cluster in the redshift range $1.6 < z \leq 2.1$ can also be estimated using the bootstrap point-radius method described in section 5 of Horvath et al. 2014 ([9]). This test compares the 44 GRBs found in the $1.6 < z \leq 2.1$ radial bin to 44 randomly selected GRBs drawn from the rest of the sample. This technique counts the number of $1.6 < z \leq 2.1$ bursts within a circle of predefined radius θ surrounding a random 'cluster center' location. Comparison samples are created by randomly drawing 44 bursts from the rest of the dataset and counting the number of bursts lying within the same angular circle. Statistics are generated by repeating this process 10000 times and counting the largest number of bursts found within the circle during these runs. Once results have been obtained, θ is increased and the process is repeated for eighty different θ values in equal area steps ranging from $\theta = 12.84^\circ$ to $\theta = 180^\circ$.

The Monte-Carlo bootstrap point-radius method verifies that the anisotropy found in the $1.6 < z \leq 2.1$ redshift range is consistent with angular clustering. Forty nine of the 80 angular clustering scales tested exhibit excess numbers of bursts within the defined θ limits. For example, using the measurements from the cluster center locations producing the largest GRB clusters, an angular circle having a radius of $\theta = 22.3^\circ$ (corresponding to 3.75% of the sky) is found to contain 13 of the 44 bursts (30%), a circle with radius $\theta = 34.4^\circ$ (corresponding to 8.75% of the sky) contains 18 of the 44 bursts (41%), and a circle with radius $\theta = 51.3^\circ$ (corresponding to 18.75% of the sky) contains 25 of the 44 bursts (57%). Only two of 17500 bootstrap cases had 25 or more GRBs inside this latter circle indicating a statistically significant (p=0.0001143) deviation (the binomial probability for this being random is $p_b = 2 \times 10^{-8}$).

The 42% increase in sample size should have noticeably decreased the significance of the $1.6 < z \leq 2.1$ cluster if random sampling was responsible for its existence. However, the cluster has become more pronounced in the $4^\circ \leq \theta < 90^\circ$ angular radius range as more GRBs have been added to the sample.

In this range of angular radii, 49 angular circles contain enough GRBs to exceed the 2σ significance level (compared to 28 found in our previous analysis [9]). Additionally, there are 16 angular

circles containing enough GRBs to exceed the 3σ level (compared to only 2 in our previously published result). Therefore, the evidence has strengthened that these bursts are mapping out some large-scale universal structure.

Both of the aforementioned tests are independent of sky exposure; by calculating only the relative angular positions of the detected bursts the techniques assume simply that whatever biases present at different redshifts are the same as those in the $1.6 < z \leq 2.1$ redshift range.

3. Discussion

Gamma-ray bursts are not distributed isotropically in the $1.6 \leq z < 2.1$ redshift range; they exhibit evidence of large-scale clustering. This clustering, first identified in 2013 ([8, 9]), has become more pronounced with recent GRB detections by Swift, supporting the idea that the clustering may be real rather than due to a statistical variation in the detection rate. The k^{th} nearest neighbor test indicates that GRBs in this redshift range are likely to have more neighbors at moderate angular separations than those at other redshifts. The two-dimensional point-radius method also finds evidence for a large-scale angular clustering in this redshift range; the angular diameter encompassed by this clustering is likely many tens of degrees across.

The aforementioned techniques can be used to demonstrate the existence of a large, nebulous GRB cluster, but the nature of the tests used here prevent us from knowing exactly where the cluster is located, what its structure is like, or how big it might be. Selection biases due to instrumental sky exposure and visual extinction by dust complicate this interpretation by reducing the rate of detection in some parts of the sky relative to others. Based on the detected bursts, the cluster covers roughly one-eighth of the sky, and seems to encompass half of the constellations of Bootes, Draco, and Lyra, and all of the constellations of Hercules and Corona Borealis. The name of the structure has been popularized as the *Hercules-Corona Borealis Great Wall*, or Her-CrB GW. However, we note that sampling biases could cause the cluster to be offset by many degrees from where it currently appears to be.

Because GRBs are the most luminous, energetic objects known, they are tracers of the presence of normal matter that can be detected at distances where the matter is otherwise too faint to be observed. Based on the analysis performed here, we estimate the size of the Her-CrB GW to be about 2000-3000 Mpc in diameter. Few limits on its radial thickness exist, other than the fact that it appears to be confined to the $1.6 \leq z < 2.1$ redshift range. This large size makes the structure inconsistent with current inflationary Universal models, as it is larger than the roughly 100 Mpc limit thought to signify the "End of Greatness" at which large-scale structure ceases.

However, the Her-CrB GW is not the first optical/infrared structure found to exceed the 100 Mpc size limit. In the 1980s, Geller and Huchra ([6]) mapped galaxies and galaxy clusters in a portion of the sky to $z \approx 0.03$ and found a 200 Mpc size structure that was later called the CfA2 Great Wall. In 2005 an object twice this size named the Sloan Great Wall ([7]) was reported. In the ensuing years, several other large filamentary structures have also been identified. Roger Clowes and his team have found several large clusters of luminous quasars; the largest of these being the Huge Large Quasar Group (Huge-LQG; [5]) having a length of more than 1400 Mpc.

As large as it appears to be, the Her-CrB GW does not necessarily violate the basic assumptions of the cosmological principle (the assumptions of a homogeneous and isotropic universe). Theo-

retical large-scale structure models indicate that some structures will exceed the End of Greatness on purely statistical grounds ([13]), and this may be one such structure (albeit a very large one). Along these lines, this may not be a single structure, but overlapping smaller adjacent and/or line-of-sight structures; the small number of bursts currently found in the cluster limits our ability to angularly resolve it. In other words, this may become a semantic issue at some point, since a cluster of smaller structures might still be a larger structure.

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