PROBING THE SMALL-SCALE ANGULAR DISTRIBUTION OF GAMMA-RAY BURSTS WITH COMBINED BATSE/ULYSSES 4B LOCATIONS

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ABSTRACT
We investigate the angular distribution of gamma-ray bursts using the largest catalog of well-localized events that is currently available—combined BATSE/Ulysses burst locations. We present the preliminary spatial analysis of 415 BATSE/Ulysses bursts included in the BATSE 4B catalog. We find that the locations are consistent with large- and small-scale isotropy, with no significant clustering or repetition. We also search for cross-correlation between the BATSE/Ulysses bursts and known extragalactic objects—such as Abell galaxy clusters, radio-quiet QSO, AGN and supernovae—and place limits on the fraction of bursts that could originate from these objects.

KEYWORDS: gamma-rays: bursts.

1. INTRODUCTION
Gamma-ray burst (GRB) astronomy has thus far been explored in two vastly different realms of angular scale. The large-scale distribution of GRB sources has been probed in detail by the Burst and Transient Source Experiment (BATSE), which finds a highly isotropic scattering of more than 2000 sources. Conversely, few bursts have been localized with high-precision. While these few events have allowed the recent breakthrough discoveries of low-energy afterglows and host galaxy redshift measurements, they have not provided much insight into the small-scale distribution of the GRB source population. We summarize results from our on-going program (see Kippen et al. 1998a) investigating the properties of this distribution using the largest catalog of well-localized events currently available—combined BATSE/Ulysses (B/U) 4B burst locations. We also use this catalog to investigate possible correlations between GRBs and known extragalactic objects.

2. COMBINED BATSE/ULYSSES GRB LOCATIONS
The GRB instrument aboard Ulysses is only sensitive enough to detect the ~25% most highly fluent BATSE bursts. However, because Ulysses is several AU distant, these bursts can be precisely localized to thin (~arc-minute) annuli through BATSE/Ulysses arrival-time analysis. Combination of the timing annuli with independent BATSE location measurements results in precise arc-segment-like uncertainty regions that are typically 25 times smaller in area than the BATSE localizations alone. In computing a combined B/U burst localization, we model the BATSE
location uncertainty $B_i(\hat{r})$ with the “core-plus-tail” distribution empirically determined by Briggs et al. (1998). This is essentially the weighted sum of two Gaussians ($\sigma_1 = 1.85^\circ$, $\sigma_2 = 5.36^\circ$, and $f_1 = 0.78$), convolved with a statistical uncertainty unique to each burst. The timing location uncertainty $U_i(\hat{r})$ is modeled with a spherical annulus of Gaussian width unique for each burst. The combined B/U localization $P_i(\hat{r})$ is the product of $B_i(\hat{r}) \times U_i(\hat{r})$, normalized over the unit sphere.

Of the 1637 events included in the fourth BATSE GRB catalog (4B$^\text{rev}$; Paciesas et al. 1998), 415 were detected by Ulysses and have final timing annuli given by Hurley et al. (1998) and Laros et al. (1998). A map of the combined B/U localizations of these bursts is shown in Figure 1, where, for display purposes, the localizations are approximated with annular ring-segments (the actual shape is more complicated).

3. SPATIAL ANALYSIS TECHNIQUE

In earlier analyses of B/U burst locations, we used the traditional angular auto- and cross-correlation techniques to investigate small-scale clustering and associations with known objects (Kippen et al. 1998a, 1998b; Hurley et al. 1997). These statistics suffer from the fact that they depend on the user’s choice of angular bin size. For this paper, we have developed a more robust and more sensitive tool, called the “Arc Crossing Statistic” (ACS), which is analogous to the “Total Power Statistic” of Tegmark et al. (1996).

For a catalog of $N_b$ burst localizations $P_{i=1,N_b}$, the ACS is defined as

$$\text{ACS} \equiv \left[ \sum_{i=1}^{N_b} \max \{ P_i(\hat{r}) \} \right]^{-1} \sum_{i=1}^{N_b} \sum_{j=1}^{i-1} \max \{ P_i(\hat{r}) \times P_j(\hat{r}) \},$$

(1)

where the term in square brackets is a convenient scale factor chosen so that the result will be of order unity for an isotropic distribution of sources with no clustering. For investigating the spatial association between GRBs and a catalog of $N_x$ objects with known “point” locations $\hat{r}_j$, the statistic is changed to

$$X\text{ACS} \equiv \left[ \frac{N_x}{N_b} \sum_{i=1}^{N_b} \max \{ P_i(\hat{r}) \} \right]^{-1} \sum_{i=1}^{N_b} \sum_{j=1}^{N_x} P_i(\hat{r}_j),$$

(2)
where the leading term is chosen to yield $XACS \sim 1$ for the case of no association. Note that ACS and XACS incorporate the actual shapes of burst localizations in a continuous manner—eliminating the need for any binning. Also, because the $P_i$ burst localizations are independently normalized, the relative contribution of each burst to the ACS or XACS scales with the precision of their localizations.

To assess the significance of measured ACS/XACS values, we must compare them to those expected from a random distribution. This is done via Monte Carlo simulations wherein random GRB location catalogs are sampled from an isotropic angular distribution (corrected for non-uniform observing exposure) and given the same uncertainties as the real burst catalog. The ACS/XACS from the random catalogs provides a measure of the statistical distribution of expected values and the significance $Q$ of the measured values $ACS_{obs}$ is given by the fraction of simulated catalogs having $ACS \geq ACS_{obs}$.

4. RESULTS

4.1 Small-Scale Angular Clustering

Results from the ACS test applied to the catalog of 415 combined B/U 4B burst locations are shown in Figure 1. It is evident that the measured ACS value is consistent with the distribution expected for isotropy. Similar results are obtained for sub-catalogs of the most precise locations, and for the sub-set of 3B data. We therefore investigate how much clustering is allowed by the data. To do this we model small-angle clustering with two standard parameters: the fraction of bursts in “point” clusters ($f$) and the number of detected bursts per cluster ($\nu$). Figure 1 shows how the ACS becomes increasingly inconsistent with the data as $f$ increases for $\nu = 2$ (the most difficult case to detect). Overall, we find that the B/U 4B data require $f(\nu - 1) \leq 13\%$ at the 99% confidence level.

4.2 Association with Extragalactic Objects

To examine possible associations between GRBs and known extragalactic objects, we applied the XACS technique between the B/U 4B burst data and various candidate source catalogs—the results are summarized in Table 1. These specific object catalogs were chosen because of past reports of significant correlations with BATSE bursts. As indicated in the table, we find no significant correlation with any of the catalogs (i.e., $Q$ is large). By forcing a fraction of the bursts to originate at known object locations, we can simulate the signal expected from a true correlation. The last column of Table 1 ($f^{99\%}_{max}$) is the largest fraction allowed by the data at the 99% confidence level. Note that although we assume the published object positions are exact points, the XACS technique is, by definition, sensitive to cases where this may not be true.

5. CONCLUSIONS

Our results on small-scale clustering indicate no significant deviations from isotropy and rule-out clustering and/or recurrence in all but a small fraction of bursts. Our limits may appear less constraining than previous results (e.g., Tegmark et al. 1996), but this is entirely because the earlier studies used BATSE location uncertainties now known to be too small. The combined B/U data provide the most constraining
TABLE 1. GRB Associations with Extragalactic Objects.

| Objects                      | Number | Reference(a)    | $Q$ | $f_{99\%\text{ max}}$ (%) |
|------------------------------|--------|-----------------|-----|---------------------------|
| Abell Clusters (all)         | 5250   | Marani et al. (1997) | 0.88 | 1.0                       |
| ’ ’ ($R \geq 1$, $D \leq 4$) | 185    | Marani et al. (1997) | 0.91 | 0.2                       |
| Radio Quiet QSO (all)        | 7146   | Schartel et al. (1997) | 0.10 | 3.9                       |
| ’ ’ ($z \leq 1.0$, $M \leq -24.2$) | 967    | Schartel et al. (1997) | 0.13 | 1.2                       |
| AGN ($M_B < -21$)            | 1390   | Burenin et al. (1998) | 0.07 | 2.7                       |
| ’ ’ ($0.1 \leq z \leq 0.32$) | 543    | Burenin et al. (1998) | 0.64 | 0.7                       |
| Recent SNe                   | 599    | Kippen et al. (1998b) | 0.94 | 0.2                       |

(a) See references for details of catalog selection criteria.

limits on repetition and clustering. These results have important implications if bursts are at large redshift, where gravitational lensing is expected to result in significant apparent small-angle clustering (Holtz, Miller & Quashnock 1999).

Our study also rules-out significant associations with any of the most commonly known extragalactic objects. The data indicate that only very small numbers of bursts can possibly originate from the objects tested. These results are consistent with the currently favored hypothesis that bursts originate from “normal” star forming galaxies at redshift $z \sim 1$.

In conclusion, it should be duly noted that our results are all based on high-fluence B/U bursts. It is possible that clustering and/or correlations could exist for a population of weaker events. Sensitive examination of this possibility could be accomplished by extending our technique to the many weak bursts localized by BATSE, alone.

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