Preliminary Spatial Analysis of Combined BATSE/*Ulysses* Gamma-Ray Burst Locations

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Abstract. We present the preliminary spatial analysis of 278 bursts that have been localized by BATSE and the two-spacecraft *Compton*/*Ulysses* Interplanetary Network. The large number and superior accuracy of the combined BATSE/*Ulysses* locations provides improved sensitivity to small-angle source properties. We find that the locations are consistent with large- and small-scale isotropy, with no significant small-angle clustering. We constrain the fraction of sources in clusters and discuss the implications for burst repetition.

INTRODUCTION

The BATSE sky monitor on the *Compton Gamma-Ray Observatory* has provided more observational data on gamma-ray bursts (GRBs) than 20 years of previous missions. BATSE has measured the locations of nearly 2000 bursts, yielding an unparalleled characterization of the large-scale isotropy of sources [1,3,2]. In contrast, little is known about the *small-scale* angular source distribution, because the locations measured with BATSE are not sufficiently accurate, and instruments that do provide precise locations do not observe many bursts. Accurate characterization of the small-scale angular source distribution is important as it can provide valuable insight into the nature of the source objects. For instance, apparent small-angle source clustering due to recurrence of individual sources strongly constrains energy release mechanisms, particularly for cosmological models that require infrequent events per host galaxy. Furthermore, intrinsic source clustering could directly reveal the underlying structure of the GRB host population, possibly providing correlations with catalogs of known objects.

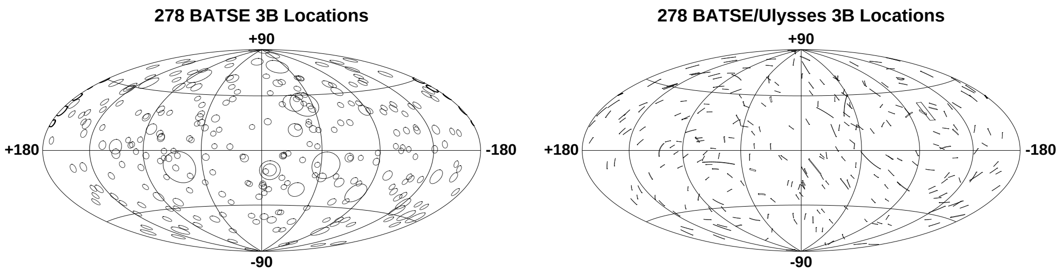

FIGURE 1. Locations of 278 GRBs observed by BATSE and *Ulysses* in Galactic coordinates. At *left* are the BATSE 1σ total error circles and at *right* are the preliminary combined BATSE/*Ulysses* total uncertainty bounds (1σ).

In this paper we present the preliminary analysis of the largest sample of accurate GRB locations currently available: the bursts observed simultaneously by BATSE and the GRB detector aboard *Ulysses* [4]. The objectives of this on-going study are to provide an improved characterization of the small-scale angular distribution of GRB sources and to investigate their correlation with known objects. Here, we concentrate only on the self-clustering properties using bursts from the BATSE 3B catalog [3].

ANALYSIS OF BATSE/*ULYSSES* LOCATIONS

Of the 1122 bursts in the BATSE 3B catalog, 278 have been detected by *Ulysses* [5] and are therefore constrained to originate from thin annuli by the arrival-time differences between the two 3rd Interplanetary Network (IPN) spacecraft. The IPN annuli alone are too large to avoid source confusion. However, the burst directions are also constrained by independent BATSE location measurements. Through the combination of BATSE and IPN information, the location of each burst is limited (approximately) to a thin annular ring-segment, with a typical area of only $\sim$0.2 deg^2 (68% confidence). In the actual combination process, we model the BATSE localizations with a Fisher distribution [6], whose width parameter is derived from the total BATSE 68% confidence error radius (observed statistical error radius and 1.6° systematic error added in quadrature). The combined localization of a burst is the product of this distribution and an IPN annulus in spherical coordinates, whose Gaussian width describes the total IPN timing and positioning errors. While it is possible, in principle, to include timing data from other IPN spacecraft in the location combination process (e.g., PVO and *Mars Observer*), this would severely complicate the location errors and the non-uniform sky-exposure correction.

Preliminary combined locations of the 278 BATSE/*Ulysses* 3B bursts are compared to BATSE-only locations of the same events in Figure 1. For display purposes, the combined localizations are approximated with annular ringsegments—the actual shape is more complicated. It should be noted that a small fraction of these bursts ($\lesssim$5%) suffer from errors in the preliminary *Ulysses* timing data. Furthermore, a few of the weaker *Ulysses* events may be falsely identified with gamma-ray bursts. Our final analysis (to be published elsewhere) will correct these errors and remove the false detections.

The identification and characterization of angular structure in any source catalog requires specialized statistical analysis. An important part of this analysis is accurate description of the null hypothesis. In GRB angular studies, the simplest null hypothesis is an isotropic intrinsic source distribution. The expected observed distribution is modified by non-uniform sky-exposure and location errors. Fortunately, the *Ulysses* GRB detector is nearly omnidirectional in its response, has a high (>95%) duty cycle, and is not occulted by the earth [4]. We therefore employ, in good approximation, the BATSE 3B sky-exposure function [2] for spatial analysis of combined BATSE/*Ulysses* bursts.

Because the combined location errors and sky-exposure function are not easily described analytically, we employ Monte Carlo simulations to predict the observed null-hypothesis. In the simulations, mock catalogs of GRB sources are randomly sampled from an isotropic distribution, weighted by the sky-exposure function. The resulting source locations are then randomly blurred according to the observed BATSE/*Ulysses* errors. Location blurring is important, for the combined BATSE/*Ulysses* location errors are correlated with sky-position—a result of the fact that the *Ulysses* spacecraft follows a non-random trajectory.

We employ two standard tests for measuring small-angle clustering: the two-point angular auto-correlation function ($w(\theta)$ [7]) and the nearest neighbor test ($nn(\theta)$ [8]). While there are subtle differences between the two techniques, they both in essence measure excess numbers of sources with small angular separations θ, compared to what is expected from the null-hypothesis. In our application, θ is the angle between the most probable measured locations of pairs of bursts. Location errors are accounted for in the Monte Carlo catalogs.

RESULTS

To test the choice of an isotropic distribution for the null-hypothesis and the validity of the sky-exposure function, we begin by applying the dipole and quadrupole moment statistics. If the exposure function were in error, we would expect to find the most significant anisotropy in Equatorial coordinates. Rather, we find that the dipole and quadrupole moments of the combined burst locations are statistically consistent with large-scale, exposure-weighted isotropy in both Galactic and Equatorial coordinates.

The small-scale angular clustering statistics discussed above are shown in Figure 2, where the data have been combined in 1° bins. The statistical

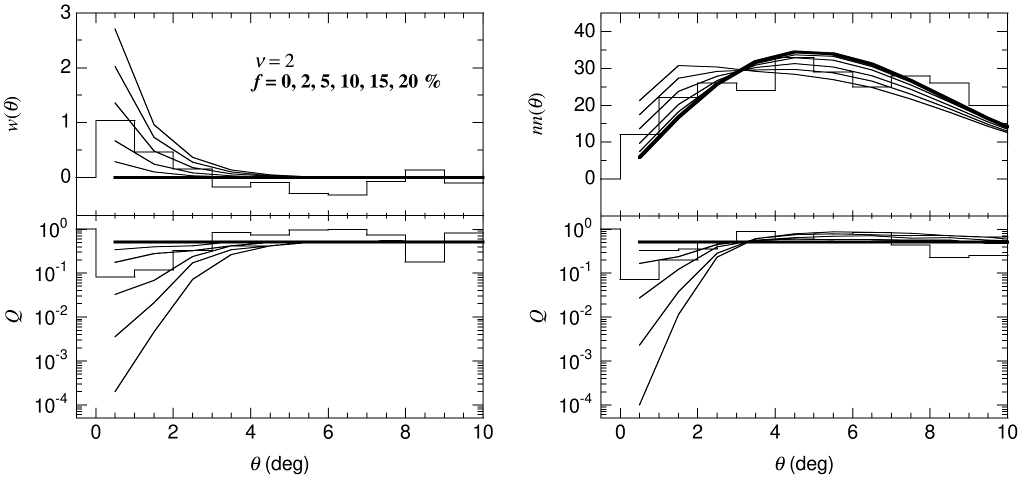

FIGURE 2. Angular auto-correlation function $w(\theta)$ (*left*) and nearest neighbor function $nn(\theta)$ (*right*) for the 278 preliminary BATSE/*Ulysses* burst locations. Upper panels compare the observed distributions (histograms) to those expected from an isotropic distribution with a fraction of clustered sources f (assuming $\nu = 2$ bursts are observed from each cluster). Lower panels show the statistical significance Q of deviations from isotropy.

significance of the data compared to the null-hypothesis is evaluated by the fraction of Monte Carlo burst catalogs with equal or greater excess in the bin of question. The largest excess is found in the first 1° bin. This is where one would expect the strongest signal from clustered sources, but the excess is only significant at the ∼8% level. To further study clustering, we used the K-S test on the cumulative distributions of $w(\theta)$ and $nn(\theta)$. The probabilities for rejecting the null-hypothesis are 0.57 and 0.34, respectively—indicating that the marginal excess in the first 1° bin is statistical in nature. This indication is supported by applying the clustering statistics to the sub-set of 200 GRB locations with the smallest errors. In this case, we find no excess at small angles. We thus conclude that the combined GRB locations are consistent with no clustering.

Given that no significant clustering was found, we may ask how much the data allow. To do this, we parameterize clustering (or "observed repetition") with two parameters: the fraction of sources in clusters (f) and the number of observed bursts per cluster (ν). This parameterization is realized in the Monte Carlo simulations by randomly blurring the clustered bursts around a single location according to the measured location errors. The plots in Figure 2 show how such "point clusters" affect $w(\theta)$ and $nn(\theta)$ for the case of $\nu = 2$ (the most difficult case to detect). Using the K-S test described above, we find that the data rule out clustering at the 99% confidence level when $f(\nu - 1) > 0.12$. This is a factor of ∼2.3 more constraining than similar analysis of the same bursts using BATSE-only locations, and a factor of ∼2.2 improvement over the similar analysis of all 1122 BATSE 3B locations [3].

DISCUSSION

We have accumulated the largest available sample of accurate GRB locations to investigate the small-scale angular distribution of sources. Our analysis of the preliminary BATSE/*Ulysses* locations provides improved limits on the lack of small-angle clustering. As mentioned above, observed clustering could arise from actual, spatially-extended clustering, or from burst repetition. Our constraint on the lack of observed clustering also limits the fraction of observed bursts that could have been repeaters. Note, however, that this limit does not directly constrain the intrinsic burst repetition rate, since the observed effects of burst repetition are highly model dependent. For instance, repeater models predicting a wide intensity distribution are not significantly constrained by BATSE/*Ulysses* locations, since *Ulysses* only detects stronger bursts. The full BATSE catalog is the most sensitive sample of bursts to investigate such intensity-dependent repetition models [9].

An important part of our analysis involves careful consideration of location errors—the largest of which are due to BATSE. For example, doubling the size of the BATSE systematic error from 1.6° to 3.2° weakens the upper limit on $f(\nu-1)$ to 0.17. The BATSE team has recently improved the characterization of systematic errors [10], which we will include in our final analysis. We also plan to implement a more sensitive clustering statistic [11] that incorporates the highly asymmetric shape of the BATSE/*Ulysses* localizations and apply it to a larger set of bursts. The current BATSE/*Ulysses* GRB sample exceeds 500 events—offering a significant increase in sensitivity to small-angle clustering.

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