

## DO GAMMA-RAY BURST SOURCES REPEAT?

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## ABSTRACT

The demonstration of repeated gamma-ray bursts from an individual source would severely constrain burst source models. Recent reports (Quashnock and Lamb 1993; Wang & Lingefelter 1993; Ryan *et al.* 1994) of evidence for repetition in the first BATSE burst catalog have generated renewed interest in this issue. Here, we analyze the angular distribution of 585 bursts of the second BATSE catalog (Meegan *et al.* 1994). We search for evidence of burst recurrence using the nearest and farthest neighbor statistic and the two-point angular correlation function. We find the data to be consistent with the hypothesis that burst sources do not repeat; however, a repeater fraction of up to about 20% of the bursts cannot be excluded.

*Subject headings:* gamma-rays: bursts

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## 1. INTRODUCTION

The observed isotropy and inhomogeneous spatial distribution derived from BATSE burst data (Meegan *et al.* 1992; Fishman *et al.* 1994) severely constrain possible Galactic distributions and argue in favor of sources at cosmological distances. Although neutron stars in an extended Galactic halo (Brainerd 1992; Li & Dermer 1992; Eichler & Silk 1992; Hartmann 1992, 1993; Hartmann *et al.* 1994a) were considered as an alternative to cosmological models, the observational constraints are now so severe that a halo origin of bursts appears unlikely (Hakkila *et al.* 1994; Hartmann *et al.* 1994a,b). Cosmological models, however, naturally explain the observed isotropy and inhomogeneity. The most popular cosmological models involve mergers between compact stellar remnants (see Hartmann 1994 for a recent review), and the observations suggest that BATSE has sampled the host galaxies for these events out to redshifts of order unity (Fenimore *et al.* 1993, Wickramasinghe *et al.* 1994). In such models, it is not likely that repetitions would be observed.

The absence of an excess of overlapping error circles in pre-BATSE burst localizations provided a model-dependent upper limit of  $\sim 10$  years for a burst repetition time scale (Schaefer & Cline 1985; Atteia *et al.* 1987). Several recent reports, however, have cited evidence for repetition on much shorter times. Quashnock & Lamb found an excess of close neighbors in the 1B burst catalog, and concluded that a large fraction of classical bursts repeat on timescales of order months (Quashnock & Lamb 1993). Wang & Lingenfelter (1993) claimed evidence for repetition with recurrence times perhaps as short as  $\sim$  days from one particular location (0855-00). Also, the coincidence of the locations of GRB940301 and GRB930704 determined with COMPTEL has a 3% chance probability, suggesting a possible repeater (Ryan *et al.* 1994). If confirmed, any example of repetition would impose strong constraints on source models, particular in the cosmological scenarios.

To investigate burst repetition, we test the null hypothesis that "the angular distribution of GRBs is consistent with an isotropic distribution", i.e., equal probability per unit solid angle. Tests of isotropy have varying sensitivities to clustering, which can indicate the presence of repetition, as well as to large-scale anisotropies. In this paper we

focus on the implications of these tests for burst repetition. We do not consider possible time dependent repetition, as suggested by Wang and Lingenfelter (1993), which will be presented in a separate paper (Brainerd *et al.* 1994a). We consider only the “classical” gamma-ray bursts, which are distinct from Soft Gamma Repeaters (Kouveliotou 1994).

We analyze the 2B catalog of bursts observed by BATSE between 19 April, 1991 and 9 March, 1993, comprising 585 bursts (Meegan *et al.* 1994) and various subsets. Data after March 1992 contain numerous gaps due to CGRO tape recorder errors. For 100 bursts that were most seriously affected by these gaps, the determination of burst location relied on MAXBC data, which consists of the maximum background-subtracted rates in each detector on a 1.024 second timescale in the 50 to 300 keV energy range. The location errors using this data type have not yet been determined very accurately. We believe that the systematic error is unaffected, and the statistical error usually slightly larger due to integrating counts over only the peak.

Our subsets, which are listed in Table 1, are of consecutive triggers limited by the listed trigger numbers. We also apply two types of cuts to some of the datasets: datasets marked with “yes” in the MAXBC column contain bursts located with the MAXBC technique while such bursts have been removed from datasets with “no” in this column. Similarly, datasets with “yes” in the column “> 9°” contain bursts with statistical location errors > 9°, while datasets with no in this column omit bursts with statistical errors > 6°. The total location error of a burst is estimated as the rms sum of its statistical error and a 4° systematic error.

## 2. TWO-POINT ANGULAR CORRELATION FUNCTION

One mathematical function that is used to test for anisotropy is the two-point angular correlation function,  $w(\theta)$ , defined in the following manner. Consider an ensemble of points distributed on the sky. Then for any given point, the number of pairs (averaged over the ensemble) with angular separation  $\theta$  and within the solid angle  $d\Omega$  is given by (e.g., Peebles 1980)

$$dN_p = \frac{N-1}{4\pi} [1 + w(\theta)] d\Omega \quad (1)$$

The application of angular correlation analysis to GRB data was introduced by Hartmann

& Blumenthal (1989) for point sources and refined for fuzzy sources by Hartmann, Linder, & Blumenthal (1991). The effect of poor angular resolution is loss of information on any intrinsic correlation function on angular scales less than  $\sim 1.72 \sigma \sim 7^\circ$  (for BATSE). However, if some of the observed bursts are repeaters, each of their coincident positions on the sky will be smeared by the brightness-dependent instrumental resolution, causing an excess correlation within several smearing scales. We define  $f$  as the fraction of all observed bursts that can be labeled as repeaters and  $\nu$  as the average number of observed events from sources that repeat. With Gaussian smoothing characterized by a standard deviation  $\sigma_*$  and only one observed repetition per repeating source ( $\nu = 2$ ), the observed correlation function becomes (Hartmann, *et al.* 1994c)

$$(N - 1) w(\theta) = -f + \frac{2f}{\sigma_*^2} \exp\left(-\frac{\theta^2}{2\sigma_*^2}\right). \quad (2)$$

This equation shows the effect of fuzzy observations on the assumed correlation function; the amplitude at  $\theta = 0$  is reduced and excess correlation is spread over an angular scale  $\sigma_*$  ( $\sim 7^\circ$  for BATSE). The negative correlation at larger angles occurs because of obvious integral constraints on the correlation function. To generalize this equation to the case in which each source had exactly  $\nu$  repeaters, substitute  $f \rightarrow f(\nu - 1)$ . For a given repeater fraction  $f$  it is easier to detect a smaller number of sources that each have a larger number of recurrences.

Figure 1 shows the two-point correlation functions for datasets 1, 5 and 6 (Table 1), which are the revised 1B catalog, the 2B catalog and the 2B catalog less MAXBC-located bursts. In the 1B data two regions with excess at the  $2\sigma$  level are apparent, one near zero degrees and one near 180 degrees. The excess near zero degrees was interpreted by Quashnock and Lamb (1993) in terms of repetition. The 180 degree excess was used to argue against this interpretation (Narayan & Piran 1993; but see Lamb & Quashnock 1994). We have also argued against recurrences from the absence of clustering on any angular scale based on preliminary 2B locations (Blumenthal, Hartmann, & Linder 1994; Hartmann *et al.* 1994b). Here we use the final localizations of the 2B BATSE catalog and confirm the earlier conclusion that there are no significant angular correlations on any scale in the current data set. Burst data obtained after the 1B period do not show the

excesses that were apparent in the 1B set. The combined data sets still show some residual effects of the 1B excesses but the deviations are not significant. Consistency with the null hypothesis of zero correlations was evaluated with the Kuiper (1960) statistic which has certain advantages over the usual KS test in the current context (Hartmann *et al.* 1994c). We have also applied various cuts in angular resolution, using subsets of the data with better localization accuracy. None of these sets shows evidence for significant deviations from zero clustering (Hartmann *et al.* 1994c). To derive upper limits on the product of repeater fraction and mean number of recurrences per source,  $f(\nu - 1)$ , we attempted to fit the data with model correlation functions including a non-zero fraction of repeaters and Gaussian smearing relevant for BATSE's mean angular resolution. The fits become unacceptable at the 99% confidence level if  $f(\nu - 1)$  exceeds  $\sim 20\%$ .

#### NEAREST NEIGHBOR TEST

Another approach to detecting burst recurrences is the nearest neighbor test, which tests whether the separations between bursts are consistent with the separations found for an isotropic distribution. For isotropically distributed bursts one expects the cumulative distribution of nearest neighbors to be (Scott & Tout 1989)

$$D_{NN}(\theta) = 1 - \left( \frac{1 + \cos \theta}{2} \right)^{N-1} \quad (3)$$

Burst repetition will create small scale anisotropies in the burst densities. The nearest neighbor test can indicate the existence of such anisotropies if the average distance between bursts is greater than the location error. For BATSE, this requires that the sample size be less than about 500 bursts (Brainerd *et al.* 1994b).

The First BATSE Gamma-Ray Burst Catalog was analyzed by Quashnock & Lamb (1993) for burst repetition by comparing the cumulative distribution of nearest neighbor separations with that expected for a uniform sky distribution, using the KS statistic. This was done for the full catalog of 260 bursts and for various subsets. They found a deviation from isotropy of 2% significance for the full catalog and of  $1.1 \times 10^{-4}$  significance for the 202 bursts with statistical errors less than 9 degrees. The selection of the 9 degree error cut maximizes the signal but introduces uncertainty in the calculation of statistical significance, since the value of 9 degrees was not specified *a priori*. Such techniques are

useful for exploring a dataset for unanticipated effects but must be subsequently tested based on fixed predictions and probabilities.

Results of our nearest neighbor analysis of the Second BATSE Catalog and various subsets are given in Table 1. Figure 2 shows the nearest neighbor cumulative distribution for four of these subsets. We find the maximum deviation  $D$  of each data set from the isotropic cumulative distribution and derive the Kolmogorov-Smirnov statistic  $K = D\sqrt{N}$ , where  $N$  is the sample size. The sign of  $D$  is positive if the maximum deviation is above the model curve and negative if below the model curve. The nearest neighbors are not statistically independent, so the value of  $S$  is larger than expected for a statistically independent data set. Therefore, the significance  $S$  of the magnitude of  $K$ —that is, the fraction of trials that produce a greater deviation from the model curve—is determined through Monte Carlo simulation. The results are given in Table 1 for both the celestial coordinate frame ( $K_{cel}$  and  $S_{cel}$ ) and the CGRO coordinate frame ( $K_{gro}$  and  $S_{gro}$ ). The analysis in CGRO coordinates is particularly sensitive to systematic effects relating to the angular response of the BATSE detectors. The CGRO orientation is routinely changed at one or two week intervals. We reproduce the effect seen by Quashnock & Lamb in our data set 7. The other subsets exhibit no statistically significant deviation from isotropy.

An upper limit on the number of repeating sources can be found from both the nearest neighbor test and the farthest neighbor test. Through Monte Carlo simulation we derived these limits for an isotropic distribution of burst sources. The model that the various data sets were tested against consists of  $N_s$  sources that each produce one observed burst and  $N_r$  sources that each produce  $n$  observed bursts. The burst locations of the repeating sources are given a Gaussian distribution with a  $9^\circ$  standard deviation about the source location. The simulations constrain the total number  $N_r n$  of bursts that can be labeled as repeaters. In general, repeater fractions of greater than  $\sim 20\%$  are excluded with 99% confidence, except for set 7.

## DISCUSSION

To search for evidence of burst repetition in the second BATSE catalog, we tested the null hypothesis of isotropy using angular correlation functions and neighbor distributions.

Post facto analysis of the 1B catalog using a sliding location error cut found evidence for burst repetition (our set 7). We have tested the hypothesis that generated this evidence with new data (our set 8) and do not find evidence for repeaters. As explained in the next paragraphs, we calculate that BATSE remains sensitive to repeaters. Thus the results of datasets 7 and 8 are contradictory. Considering the difficulty of evaluating the significance of the evidence for repeaters found by retrospective analysis of the 1B catalog and the non-confirmation of the effect in the post-1B data, we conclude that the data are consistent with the null hypothesis of isotropy.

If the MAXBC-located bursts are removed from the sample, the effective exposure decreases. Exposure is defined here as the fraction of bursts above trigger threshold that would be observed, and is less than unity due to earth blockage, SAA passes, and intervals during which the burst trigger is disabled. We have investigated the effect of exposure on the detectability of repeaters. If the number of detectable bursts from a repeating source is large, then the average number of bursts observed for each source remains large, and the fraction of bursts identified as bursts from repeater sources changes little. If, however, the number of bursts from a repeater source is small, so that the average observed number of bursts is small, then the number of repeater sources that appear as single burst sources increases significantly as the efficiency of detecting a burst drops. The effect of this is to decrease the fraction of bursts that are identifiable as bursts from repeaters.

Figure 3 illustrates the effect of a varying exposure on the detectability of repetitions from an ensemble of sources that each produce 10 bursts above threshold, not all of which are detected. The dashed line gives the average fraction of bursts observed for sources that produce at least 2 observed bursts. The solid line gives the fraction of observed bursts that are observed to be single events. As this curve rises with decreasing exposure, the ability to discern burst repetition declines. The vertical dashed line at 0.35 indicates the exposure of the 1B catalog. Here, an average of about 3.5 bursts will be observed from each repeating source, and about 3% of the observed bursts will be misidentified as non-repeaters. Note that this number of observed repetitions per observed repeater agrees with that suggested by Quashnock & Lamb (1993), based on the angular scale of the clumpings seen in the

1B catalog. The vertical dashed line at 0.25 indicates the exposure of the post-1B portion of the 2B catalog when MAXBC-located bursts have been removed. Here, an average of about 3.0 bursts will be observed from each repeating source, and about 8% of the observed bursts will be misidentified as non-repeaters. Such a small change has a negligible effect on the burst repetition limit derived for the 2B catalog from the nearest neighbor analysis. The limit from the two point angular correlation function is increased by  $\sim 15\%$ .

While we find no evidence of isotropy, we derive model-dependent limits on the total fraction of repeaters in the BATSE data. Both angular correlation function and nearest neighbor analysis suggest that no more than  $\sim 20\%$  of all BATSE bursts observed during the first two years of operation could be members of a hypothetical class of classical repeaters.

Several avenues are being explored to improve upon these results. First, statistical limits will be reduced as BATSE continues to accumulate burst locations. Since the 2B catalog, software changes have eliminated the need for MAXBC locations, and the daily exposure exceeds that even of the 1B era. Second, we continue to refine the burst location algorithm to reduce systematic errors. Third, new statistical techniques for analyzing the isotropy are being developed (Hartmann *et al.* 1994c).



## FIGURES:

Fig. 1 – The angular correlation function of gamma-ray bursts. Shown are the results for 262 bursts in the 1B catalog (data set 1), the full 2B set of 585 bursts (data set 5), and the modified 2B set with 485 bursts in which MAXBC events (see text) were removed from the sample (data set 6). The addition of second year data clearly reduces both excesses near  $0^\circ$  and near  $180^\circ$  originally found in the 1B set.

Fig. 2 – Nearest neighbor cumulative distributions from the 2B catalog, plotted as functions of  $1 - \cos \theta$ , where  $\theta$  is the angle to the nearest neighbor. The data are plotted as a histogram while the model curve for isotropy is plotted as a smooth curve. The four plots are for data sets 1, 3, 7, and 8 of Table 1. Data sets 1 and 7 correspond to the 1B catalog while data sets 3 and 8 correspond to the 2B - 1B catalog. Data sets 1 and 3 are consecutive sets of 262 gamma-ray bursts. Data sets 7 and 8 are bursts with position errors  $< 9^\circ$ .

Fig. 3 – Efficiency of observing burst repetition as a function of sky exposure. It is assumed that a gamma-ray burst source produces 10 outbursts. The solid curve gives the fraction of observed bursts from repeaters that have no observed companion bursts from the same source. The dashed curve gives the average value of  $\nu/10$ , where  $\nu$  is the number of repetitions observed from a repeating source. The right hand vertical line is the exposure for the 1B catalog and the left hand vertical line is the exposure for the 2B - 1B catalog.

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Nearest Neighbor Analysis								
Set	Triggers	MAXBC	> 9°	Size	$K_{cel}$	$S_{cel}$	$K_{gro}$	$S_{gro}$
1	105-1466	no	yes	262	1.77	0.028	-1.02	0.50
2	1467-2230	no	yes	223	0.98	0.54	-1.05	0.51
3	1467-2121	yes	yes	262	1.15	0.34	1.02	0.49
4	1467-2230	yes	yes	323	0.61	0.98	-1.23	0.27
5	105-2230	no	yes	485	1.41	0.14	-0.54	0.994
6	105-2230	yes	yes	585	1.03	0.49	-0.75	0.87
7	105-1466	no	no	202	2.66	$1.0 \cdot 10^{-4}$	-0.76	0.85
8	1467-2230	no	no	195	0.86	0.71	-1.03	0.48

Table 1

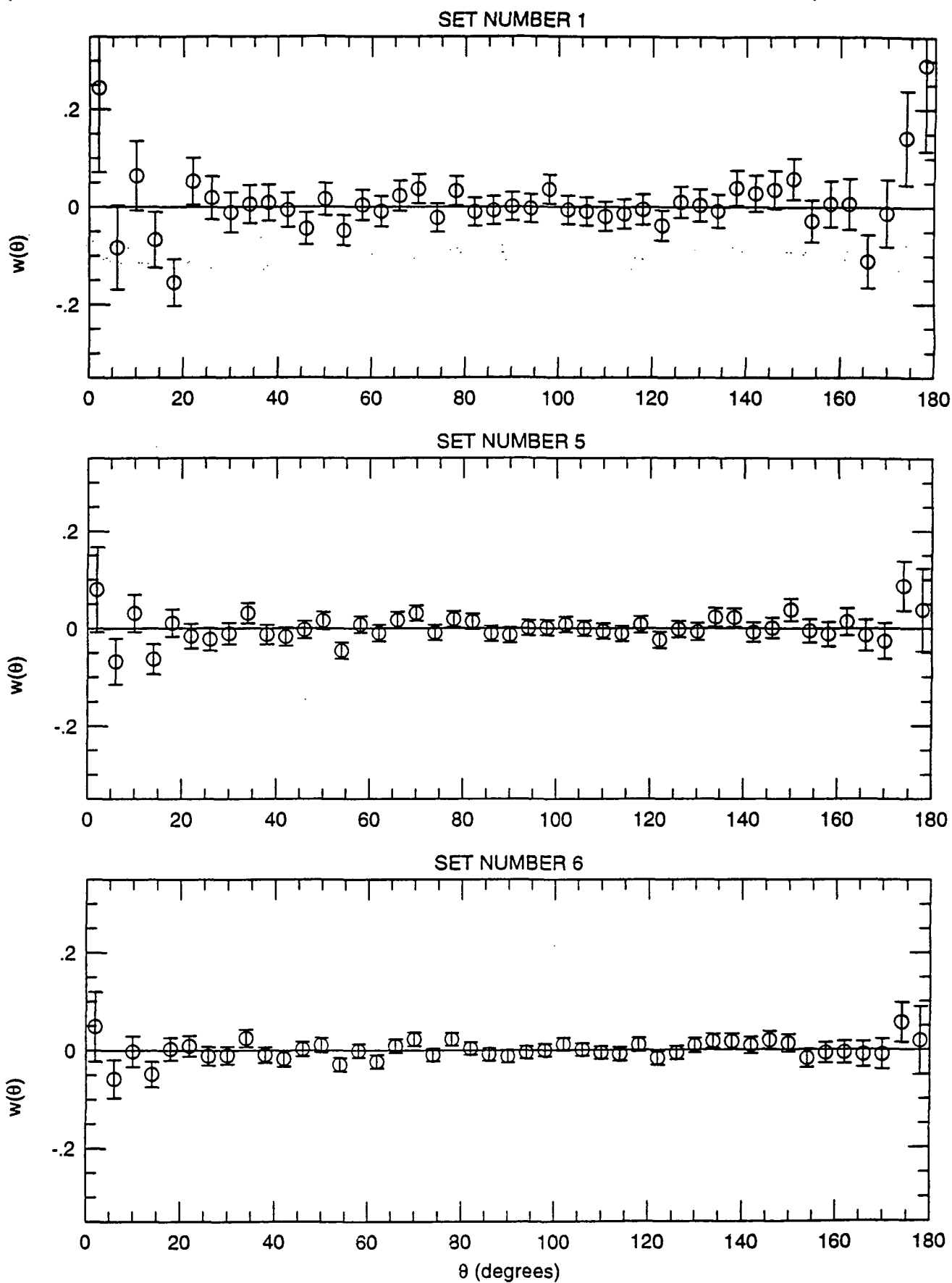


Figure 1

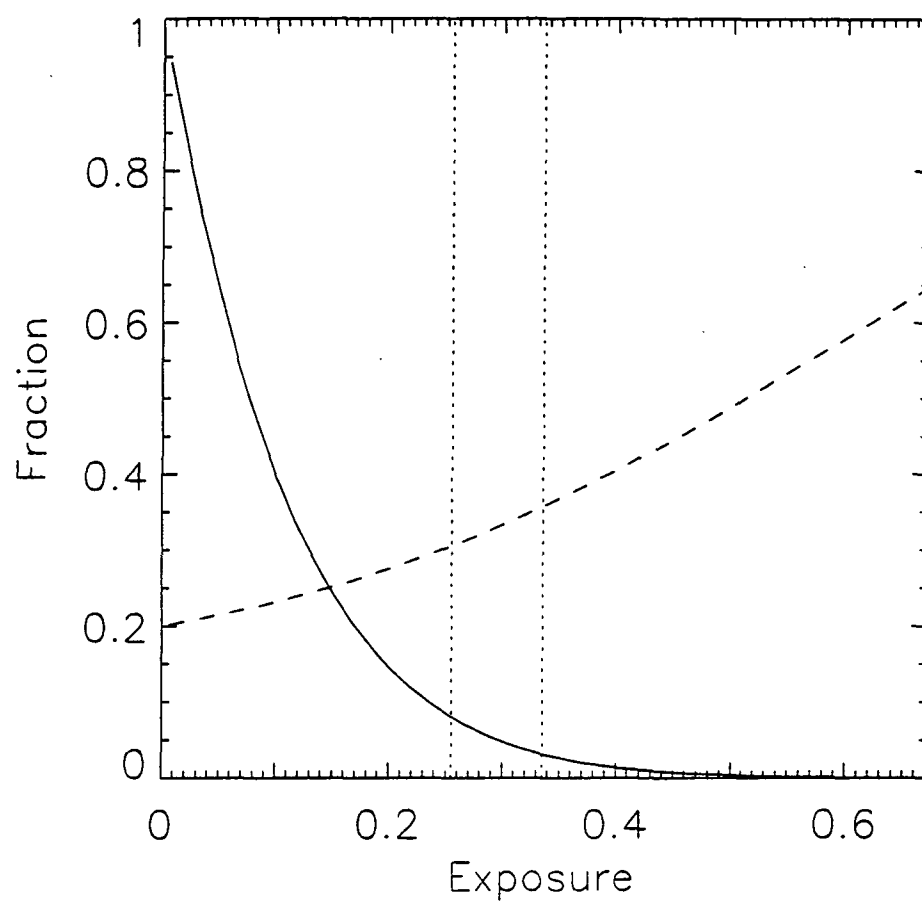


Figure 2

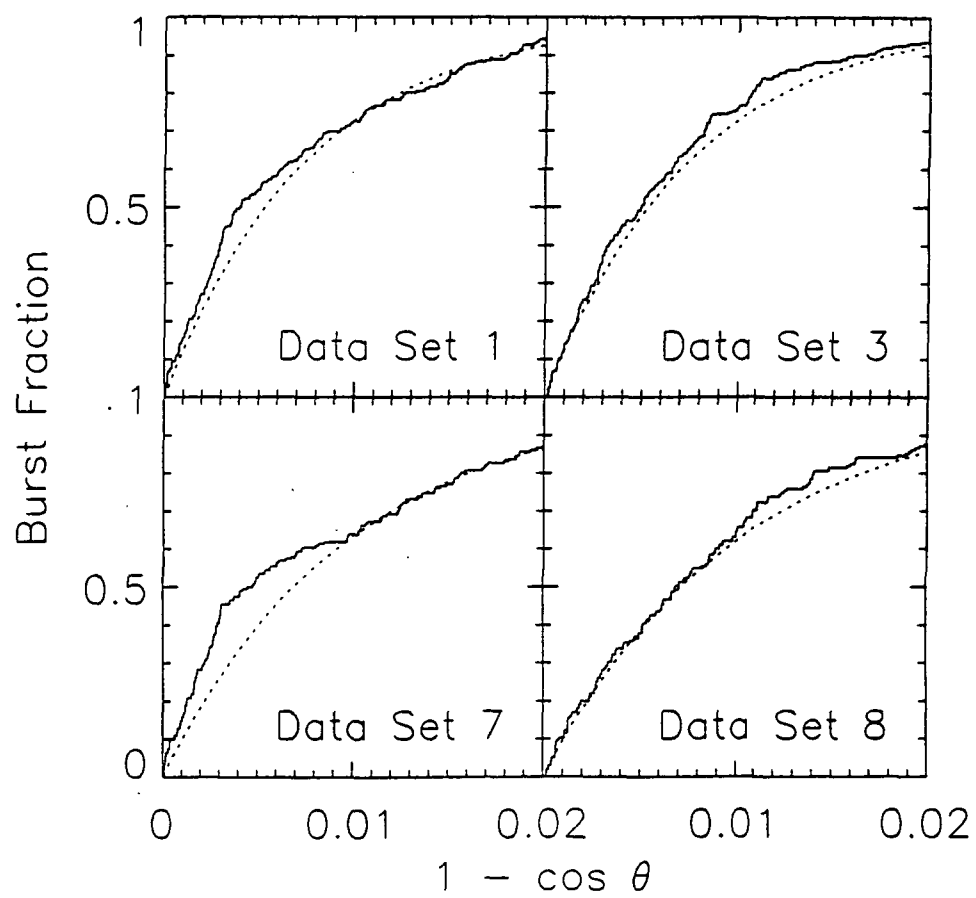


Figure 3