GRB Spikes Could Resolve Stars

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ABSTRACT

GRBs vary more rapidly than any other known cosmological phenomena. The lower limits of this variability have not yet been explored. Improvements in detectors would reveal or limit the actual rate of short GRBs. Were microsecond "spike" GRBs to exist and be detectable, they would time-resolve stellar mass objects throughout the universe by their gravitational microlensing effect. Analyzing the time structure of sufficient numbers of GRB spikes would reveal or limit Ω_{star}, Ω_{MACHO}, and/or Ω_{baryon}.

Subject headings: gamma-ray bursts – gravitational lensing – dark matter

1. Introduction

The duration and peak flux distributions of gamma ray bursts (GRBs) have been measured and discussed continually since discovery (Klebesadel, Strong and Olson 1973). Since 1991 these distributions have been best sampled by the relatively sensitive Burst and Transient Source Detector (BATSE) onboard the Compton Gamma Ray Observatory (CGRO). Intrinsic detection thresholds, however, place fundamental limits on the duration and peak fluxes of GRBs BATSE can detect. BATSE's onboard trigger criteria make it most sensitive to GRBs with durations of about 1 second and peak fluxes above 1 photon cm^{-2} sec^{-1} (Fishman et al. 1994a; Meegan et al. 1997). Dimmer and/or shorter bursts, however, may carry significant cosmological utility.

The GRB duration distribution has been studied previously mostly with regard to its unusual bi-modal appearance (Cline & Desai 1974; Norris et al. 1984; Hurley et al. 1991; Kouveliotou et al. 1993). In this paper we will focus more closely on extrapolating the BATSE 3B duration distribution to durations well below the minimum time scale of BATSE's trigger accumulation time: 64 ms. We will implicitly assume that the majority of GRBs occur at cosmological distances for reasons outlined by Paczynski (1995).

The possibility of gravitational lensing of GRBs was first discussed by Paczynski (1987), where the detection of clusters of microlensing images was considered. The possibility of microlensing differentially affecting macro-images created by the lensing of intermediate galaxies was discussed by Nemiroff et al. (1994). Williams & Wijers (1997) showed that in the presence of significant lensing optical depth and shear, the time delay between GRB images could be as long as several milliseconds. Searches for longer duration gravitational lens effects in GRB data have been carried out by Nemiroff et al. (1993, 1994) and Marani et al. (1998).

During BATSE's first three years (i.e. those bursts incorporated in the BATSE 3B

catalog: Meegan et al. 1997), BATSE's onboard trigger criteria were relatively constant. On average, BATSE was trigger sensitive to any point on the sky about 48 % of the time, between 50 and 300 KeV on 64 ms, 256 ms, and 1024 ms time scales (Meegan et al. 1997). Peaks in the time series greater than 5.5 σ over a previous 17 second background triggered the instrument into burst mode, where more detailed time information about the burst was recorded.

These very detection thresholds, however, limit which GRBs BATSE can detect. In particular, GRBs with durations below the BATSE 64 ms trigger threshold are only detected by BATSE when accumulated flux over 64 ms is sufficiently great. Theoretically, a GRB with arbitrarily high peak flux but correspondingly short duration would go undetected by BATSE. Practically, BATSE is increasingly *in*sensitive to shorter GRBs, demanding they have increasingly high peak flux for detection (Fishman et al. 1994a; Norris et al. 1984; Lee & Petrosian 1996). In particular, Lee & Petrosian (1996) model these effects as a bias against the detection of bursts with durations below the minimum 64 ms trigger time scale, extrapolating a best fit on the rate down to a duration of 10 ms.

In §2 the extent to which BATSE 3B data limits the rate of extremely short duration GRBs is explored. In contrast to Lee & Petrosian (1996), we are more interested in what rates are reasonably allowed for short GRBs rather than finding the best fit rate. In §3 the potential utility and detectability of GRB spikes is discussed. In §4 some discussion and conclusions are given.

2. Extrapolations to Short Duration

To explore possibilities on how many short duration GRBs could exist and go undetected by BATSE, we first focus on how BATSE's internal trigger creates a practical

relation between peak flux and duration. Figure 1 shows a plot of duration versus peak flux for BATSE 3B GRBs. Only those bursts with listed T_{50} and T_{90} durations, and peak fluxes on all three trigger time scales (64, 256, and 1024 ms) are plotted: 807 in all. This sample was chosen because it is relatively well understood and could be tested for a variety of potentially confounding internal correlations. BATSE altered its triggering criteria immediately following the conclusion of 3B catalog data collection, so even though more BATSE GRBs exist at the time of this writing, to use them may incorporate bias.

On the x-axis an estimate of duration was plotted: T_{50} from the BATSE 3B catalog, the time between when 25% and 75% of the total GRB fluence was measured. This duration measure is known to be biased in the sense that low peak flux GRBs have at least slightly shorter BATSE T_{50}s, on the average, than if they had higher peak flux (Bonnell et al. 1996; Koshut et al. 1996), even though T_{50} is designed to be independent of peak flux (Kouveliotou et al. 1993; Lee & Petrosian 1996).

On the y-axis an estimate of true peak flux was plotted. Specifically, the published BATSE peak flux estimate on the 64 ms time scale was used. A dotted line at 64 ms is drawn in vertically on Figure 1 to indicate BATSE's minimum trigger time scale.

The solid line drawn on Figure 1 is a rough indicator of detection limits, with the region below delineated by hashed lines running from the lower left to the upper right. This region, labeled "BATSE Untriggered", is generally invisible to BATSE's onboard trigger criteria. There is at least a 70 % chance that a GRB in this region would go untriggered by BATSE, according to exposure versus peak flux table published with the BATSE 1B catalog (Fishman et al. 1994a). At 64 ms, this solid line lies at a peak flux level of about 1 photon cm^{-2} sec^{-1}.

At durations shorter than 64 ms, the solid line rises toward higher peak fluxes, indicating BATSE's insensitivity to shorter bursts. The approximate detection threshold is

estimated from trigger criteria to be

$$P(t < 64 \text{ ms}) \sim P(64 \text{ ms}) \frac{64 \text{ ms}}{t_{dur}(\text{ms})}, \tag{1}$$

where t_{dur} is a duration estimate of the GRB. This insensitivity is caused solely by BATSE's 64 ms trigger criteria.

Even if a trigger bin size below 64 ms could somehow be enabled, BATSE's background would then limit the minimum measurable peak flux at a given t_{dur}. The decreased sensitivity is a direct result of the decreased number of counts available for these GRBs, given that trigger depends on some measured σ over background, and that σ scales as the square root of the background level. For a constant σ trigger,

$$P(t < 64 \text{ ms}) \sim P(64 \text{ ms}) \left(\frac{64 \text{ ms}}{t_{dur}(\text{ms})} \right)^{1/2}. \tag{2}$$

This background limit is shown by the dashed line in Figure 1.

Although equations 1 and 2 have similar terms, they demonstrate different things. Equation 1 shows how high the peak flux of a spike GRB must be to satisfy a constant trigger bin size. Equation 3, on the other hand, shows how high the peak flux of a spike GRB must be to satisfy a trigger bin size equal to the GRB duration, the "best case" for detectability.

BATSE's finite size also limits the duration of GRBs it can detect above any given peak flux. Assuming a negligible background, the limiting peak flux is

$$P_{lim} \sim \frac{N}{A \; t_{dur}}, \tag{3}$$

where P_{lim} is the limiting peak flux a detector or cross-sectional area A can measure, and N is the number of photons needed for a significant detection. For BATSE in Figure 1, we assume $N \sim 10$ and $A \sim 10^4$ cm^2. This detector-size limit is shown by the dotted line in Figure 1.

Figure 2 shows a histogram of durations for BATSE 3B GRBs. Only those GRBs in the BATSE 3B with listed T_{50}s, and peak flux on the 64 ms scale above 2 photons cm^{-2} sec^{-1} are plotted in the unfilled histogram region: 295 GRBs in all. BATSE is expected to be about 98 percent complete to this peak flux level (Fishman et al. 1994a). All rates plotted in Figure 2 are normalized to the BATSE measured rate for GRBs with T_{50} durations between 8.192 and 16.384 seconds and peak fluxes above 2 photons cm^{-2} sec^{-1}. Bursts with these durations have the highest rate recorded by BATSE.

Superimposed on BATSE's 3B detections at short durations is a cross-hatched histogram. This region represents an upper limit on the rate that GRBs might have been measured, were BATSE's sensitivity level somehow held constant below 64 ms. More precisely, GRBs falling in this region fall below a 1-σ upper limit estimate of how many short GRBs would have been measured to a peak flux limit on 64-ms where BATSE is about 98 % complete. The 1-σ lower limit was near zero for most of these short time bins, so it is also possible that very few GRBs occur in this region.

This extrapolation to short GRBs were computed as follows. Candidate rate levels were assumed for GRBs with durations between 1 ms and 64 ms, from which a virtual catalog of GRBs was created. Each duration bin was confined to the measured, differential, BATSE 3B log N - log P distribution. This virtual GRB catalog was then subjected to trigger thresholds similar to BATSE (Nemiroff et al. 1996). Specifically, GRBs with peak flux falling below equation (1) were cut, leaving a duration histogram that was compared to a 1-σ upper limit on the base BATSE 3B histogram (unhatched region) of Figure 2. The candidate rate levels were iterated until a satisfactory match was found. The virtual GRB catalog was made much larger than the actual GRB catalog to minimize numerical error. Between 1 μs and 1 ms, extrapolation of the bright portion of the GRB log N - log P indicates that as duration drops by a factor of 2, the acceptable 1-σ rate should increase by

a factor of roughly $2^{1.5}$.

3. The Abundance and Utility of GRB Spikes

Inspection of the hatched short duration part of the Figure 2 histogram indicates that a significant rate of short GRBs might exist but go undetected by BATSE. In fact, to a given peak flux level, there may be more GRBs that occur between 1 and 2 ms than between 8.192 and 16.384 seconds. The limit on the rate of microsecond spikes is even less well constrained, and could even be an order of magnitude greater. Alternatively, these "spike" GRBs might not exist at all: both are acceptable to within 1-σ errors. Were spike GRBs to exist, however, they would not be recoverable by analysis on existing BATSE archival data because the highest time resolution, continuously recorded BATSE data type has 1.024 sec bins ("DISCLA" data).

Currently there are claims that a non-negligible fraction of our Galaxy is composed of compact objects on the order of a fraction of a solar mass (see, for example, Alcock et al 1996). Also, a non- negligible fraction of the baryon content of our universe, on order $\Omega \sim 0.01$, might exist in a stellar or stellar remnant form (see, for example, Carr 1994, and references therein). If so, a sufficiently tuned GRB detector might resolve these microlenses temporally. The precise relation for a single standard compact gravitational microlens is (Mao 1992; Nemiroff et al. 1993; Krauss and Small 1991)

$$\Delta t = \frac{R_S(1+z_L)}{c}\left(\frac{f-1}{\sqrt{f}} - \ln f\right), \tag{4}$$

where Δt is the time delay between the two bright images, R_S is the Schwarzschild radius of the lens ($R_S \sim 3$ km $M/M_\odot$), z_L is the redshift of the lens, f is the dynamic range between images ($f > 1$), and c is the speed of light. For $f = 6.85$, the dynamic range when a lens is displaced one Einstein ring from the source, $z_L = 0.5$ and lens mass of 0.5 $M_\odot$, the resulting

time delay between images is $\Delta t \sim 2.3$ microseconds. Significantly more disparate images would bring significantly longer time delays.

How often would microlensing occur? For sources at cosmological redshift near unity, the expected microlensing rate is on order $\Omega_{lens}/8$ for an $\Omega = 1$ universe (see, for example, Nemiroff 1989). For GRBs at a canonical cosmological redshift of unity and the known star field estimate of Ω_{stars} of 0.002 (Carr 1994), roughly one in 4000 GRBs would be expected to undergo detectable microlensing. For MACHOs of 0.5 $M_{\odot}$ composing half of galaxy halos (see, for example, Alcock et al. 1996), the universal density would be quite uncertain owing to our lack of knowledge on the true extent of spiral galaxies. However, were $\Omega_{MACHO} \sim 0.1$, this would result in one in 110 GRBs undergoing detectable microlensing. From this one can see that even a null result in a microlensing search in short GRBs could indicate the extent to which MACHOs populate galactic halos.

Even higher microlensing rates would be expected for even less popular cosmological scenarios, possibly involving a cosmological constant and/or a significantly higher Ω_{lens}. Of course, the probability of any specific GRB undergoing microlensing is a strong function of the GRB redshift and the detectable dynamic range, although *not* a function of lens mass (Nemiroff 1989).

GRBs of all durations undergo gravitational microlensing, but detector size, background, and long duration bin sizes have made this effect, so far, undetectable. Bursts at or below a μs in duration would likely show microlensing with an easily discerned double peaked light curve signature. Longer duration bursts with significant temporal variability at or below a μs might also show detectable microlensing, although it might not appear so obvious to the untrained observer. For this reason, we refer sometimes to "GRB spikes" instead of "spike GRBs" so as to more clearly incorporate the possibility that longer duration GRBs might have internal spikes that could show micolensing. In an informal

search through BATSE TTE data, the shortest significant fluctuation we were able to find was on the order of 100 μs. Indeed, Schaefer et al. (1993) have shown that bright BATSE GRBs are not, in general, a superposition of bright microsecond flares (Mitrofanov 1989).

As an aside, we note that these results might have some bearing on past and future time dilation estimates for GRBs. First, one must be very careful about including short bursts of low peak flux. For GRBs with T_{50}s below about 2 seconds, BATSE trigger limits create an artificial dearth of low peak flux GRBs. Were this unaccounted for, one's analysis might be skewed by a false dim/long association (for more discussion see Lee & Petrosian 1996). We note that the Norris collaboration searching for time dilation (see, for example, Norris et al. 1994 & Norris et al. 1995) routinely exclude bursts this short in their time dilation analysis.

4. Discussion and Conclusions

Several assumptions went into the above extrapolated rate estimates. One was that the log N - log P distribution for GRBs in not a strong function of duration. A popular special case of this occurs when instantaneous GRB peak flux is a true standard candle. Were fluence a better GRB standard candle, however, shorter GRBs (at a given peak flux) would be increasingly nearby, and hence at decreasing probability of undergoing detectable microlensing.

Another implicit assumption is that the correct GRB physical model does not prohibit GRB spikes. Given the abundance of suggested physical models (see, for example, Nemiroff 1994), we know of no fundamental reason why GRB spikes should not exist. Even were GRB time scales somehow related to the light crossing time of a neutron star, on order 100 μs, the resulting emission might result from the collision of relativistic shells with γ factors

in the hundreds, perhaps providing the needed time structure. If spike or short GRBs never occurred, this would be interesting by itself, as it could be used to place a lower limit on the size of the emitting region and hence give a clue to the emission mechanism behind GRBs.

Spike GRBs are even predicted for some models, including small evaporating black holes (Cline et al. 1997). In this case, lack of detection limits the cosmological density of these objects (Fichtel et al. 1994).

Inspection of Figure 2 indicates that some short GRBs with durations below 64 ms may be theoretically detectable by BATSE at a rate exceeding that in the 3B catalog, although not recoverable from existing archival data. Toward this end, BATSE's single sweep pulsar data type can be programmed to run for approximately (t_{bin}/ 32 ms) fraction of the time (Meegan 1996). Such a program would also better determine the rate of relatively dim Terrestrial Gamma Flashes, events typically having durations near 10 ms (Fishman et al. 1994b; Nemiroff, Bonnell & Norris 1997).

Future GRB detectors may be designed to explore this important spike regime. Specific attributes desirable in future detectors are larger area, smaller time bin sizes, sensitivity to photons of lower energy, and faster triggers. Inverting and augmenting Eq. 3 we see that

$$A \sim \left(\frac{N}{1 \text{ photon}}\right) \left(\frac{1 \text{ ph cm}^{-2} \text{ sec}^{-1}}{P_{lim}}\right) \left(\frac{1 \text{ sec}}{t_{dur}}\right) \left(\frac{E}{50 \text{ KeV}}\right)^2, \quad (5)$$

where E is the lowest energy the detector can efficiently measure. The later term derives from a canonical estimate for the spectrum of GRBs which yields significantly more photons at lower energies. To detect 10 photons from a GRB of duration 1 μs at the BATSE minimum peak flux of 1 photon cm^{-2} sec^{-1} above 50 KeV, the detector area must be on order 10^7 cm^2, or about 36 meters in diameter. Although this is prohibitively large, detectors sensitive to lower energy photons are more reasonably sized, with a 5 KeV detector sensitive to GRB spikes at 3.6 meters in diameter, and a 1 KeV detector sensitive to GRB spikes can be less than one meter in diameter. Such detectors must be properly

shielded to reduce the background. Were GRB spikes intrinsically longer at lower energies, even these numbers might be optimistic. At higher energies, we note that EGRET was used to search for GRB spikes at 250 MeV at a level of about 10^{-3} photons cm^{-2} sec^{-1}, without success (Fichtel et al. 1994).

In sum, were cosmological gamma-ray bursts (GRBs) with duration or variability of the order of a microsecond to exist ("GRB spikes"), they would time-resolve intervening stars as cosmic microlenses. Given the BATSE 3B catalog and standard canonical assumptions, we find to one-sigma accuracy that the rate of GRBs with durations at and below 1-ms could be higher than for GRBs of any other duration, or could be zero. For Omega of unity, MACHOs comprising one tenth of the critical density would be expected to detectably microlens roughly one in 200 GRB spikes. From the known star field, however, only one in 7500 GRB spikes would undergo detectable microlensing. Although present spacecraft detectors are too small to measure a significant GRB spike rate, future detectors optimized for size, energy, and memory might constrain or detect an abundance of baryons, stars, and MACHOs in the universe.

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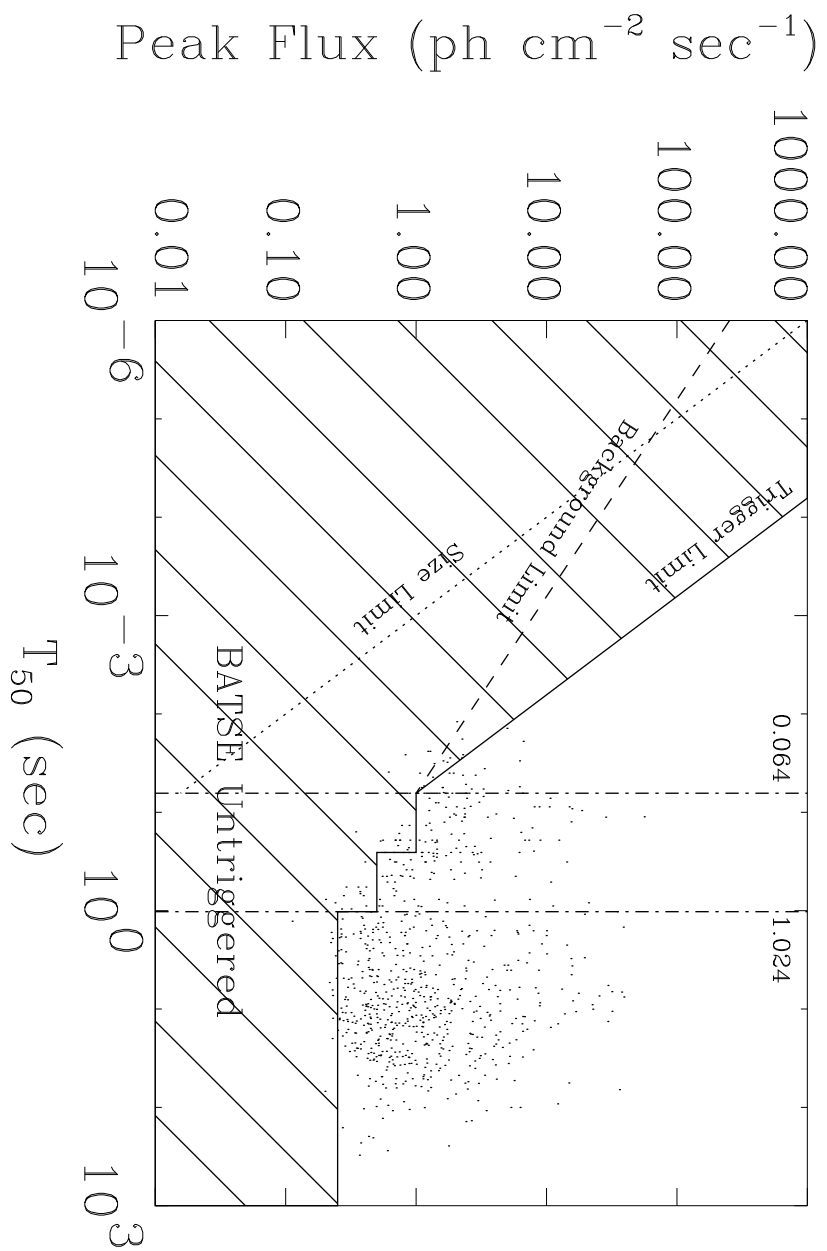
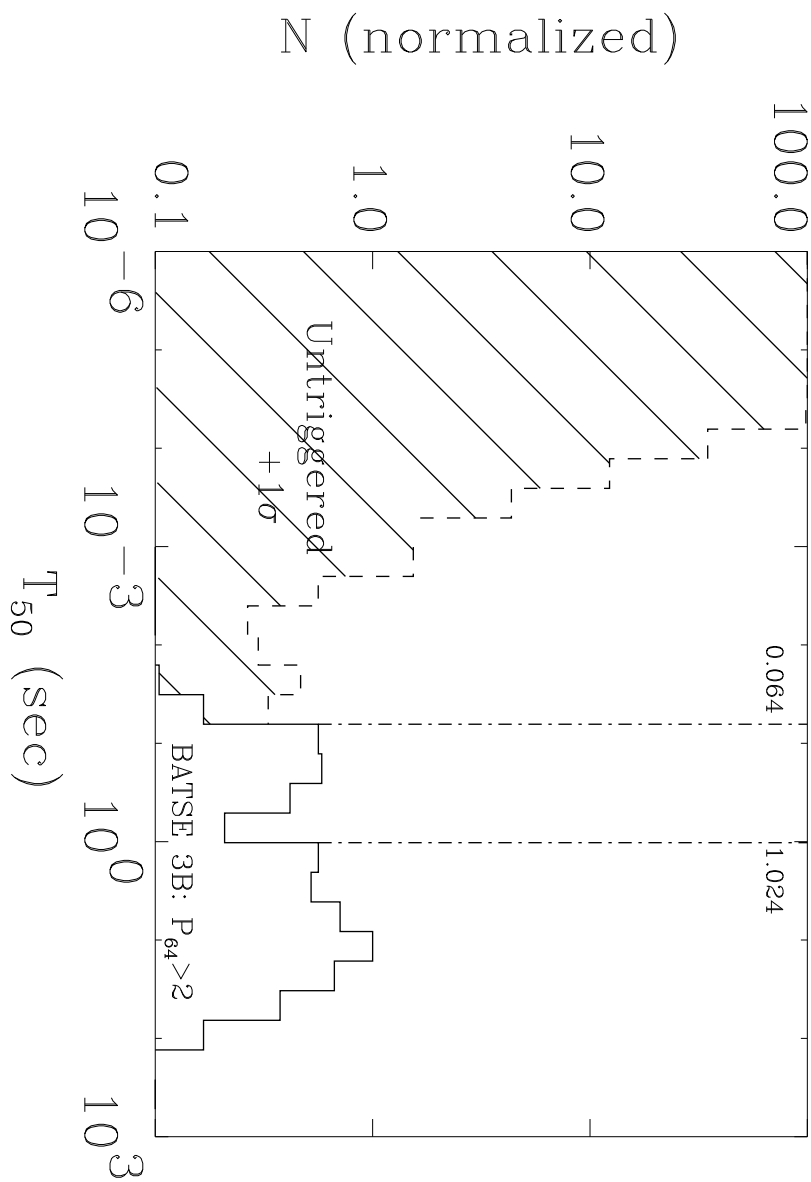
Fig. 1.— A plot of peak flux versus duration for BATSE 3B GRBs. GRBs occurring in the hatched region with lines running from the lower left to the upper right would not, in general, trigger BATSE. GRBs below the dashed line would be hidden below BATSE's background, and GRBs below the dotted line would deposit less than 10 photons on BATSE.

Fig. 2.— A duration histogram. The unhatched region results from GRBs in the BATSE 3B catalog. Burst rate is normalized to the BATSE bin covering durations between 8.192 and 16.384 seconds. Bursts occurring in the hatched region with lines running from the lower left to the upper right are one-sigma upper limits on the rate for GRBs with peak flux greater than 2 photons per square centimeter per second. Note that within one sigma upper limits, the rate of GRBs with durations below 1 microsecond may exceed the GRB rate at 10 seconds.


Peak Flux (ph cm^{-2} sec^{-1})
1000.00
100.00
10.00
1.00
0.10
0.01
10^{-6}
10^{-3}
10^{0}
10^{3}
T_{50} (sec)
Trigger Limit
Background Limit
Size Limit
BATSE Untriggered
0.064
1.024


N (normalized)
100.0
10.0
1.0
0.1
10^{-6}
10^{-3}
10^{0}
10^{3}
T_{50} (sec)
Untriggered
+1σ
BATSE 3B: P_{64}>2
0.064
1.024