GAMMA-RAY BURSTS HAVE MILLISECOND VARIABILITY

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ABSTRACT

We have performed searches for isolated flares and for steady flickering in the initial ~1 s of gamma-ray burst light curves on the microsecond to millisecond timescales. Two bursts among our sample of 20 revealed four isolated flares with timescales from 256 to 2048 μs. A wavelet analysis for our sample showed low-level flickering for all bursts on timescales from 256 μs to 33 ms, with the majority of bursts containing rise times faster than 4 ms and 30% having rise times faster than 1 ms. These results show that millisecond variability is common in classical bursts and not some exceptional activity by a possibly separate class of bursts. These fast rise times can be used to place the following severe limits on burst models. (1) The characteristic thickness of the energy generation region must be less than 1200 km along the line of sight. (2) The angular size of the gamma-ray emission region as subtended from the central source must be less than 42°. (3) The expanding ejecta must have a range of Lorentz factors along a radius line with a dispersion of less than roughly 2%. (4) Within the external shock scenario, the characteristic dimension of the impacted cloud must be smaller than 16 AU on average. (5) Within the collimated jet scenario, the collimation angle must be smaller than 42°.

Subject headings: gamma rays: bursts — methods: statistical

1. INTRODUCTION

What is the shortest timescale of intensity variations in gamma-ray bursts (GRBs)? This is an important question because this timescale can be used to place an upper limit on the size of the gamma-ray–emitting region. Historically, the rise time in the 1979 March 5 event was used to place a limit of less than 300 km (Cline et al. 1980), although we now know that this event was from a "Galactic" soft gamma repeater and hence irrelevant for cosmological GRBs. Nevertheless, the basic argument remains in force for classical GRBs, with durations less than 15 ms in the Konus catalog (Mazets et al. 1981), and it provided one of the strong reasons to consider neutron stars in burst models.

Since the launch of the Compton Gamma Ray Observatory, the Burst and Transient Source Experiment (BATSE) provides sufficient photons and time resolution to push a variability search to short timescales. Bhat et al. (1992) demonstrated that GRB 910711 has a total duration of ~8 ms, although the claimed 0.2 ms spike detected in one BATSE detector is dubious since it is only 3 σ in significance with ~100 trials and since the spike is not present in other BATSE detectors that should have seen it. Nevertheless, this event and others in the BATSE catalog with durations as short as 0.034 s (Fishman et al. 1994) show that some bursts have flares with durations as short as ~8 ms. Mitrofanov (1989) suggested that bursts were composed of microsecond flares such that dead-time and pulse pileup effects would greatly change burst demographics, but correlations between arrival times for photons in separate detectors show that this possibility is not realized (Schaefer et al. 1992). Similarly, we have shown that photon energies are uncorrelated on microsecond timescales, so burst flux can have only a small fraction of short-duration blackbody emission. Deng & Schaefer (1997) did not find any coherent periodicities from 16 μs and 33 ms in 20 of the brightest bursts. Schaefer & Walker (1998) have discussed a spike in GRB 920229 that has an e-folding rise time of 220 ± 130 μs, a decay time of 400 ± 100 μs, a significant spectral change over a time of 768 μs, and a sharp spectral continuum feature over a fractional energy range of 18%.

The above results show that rare bursts can have light-curve structure on timescales of ~8 ms or even 0.22 ms. But how exceptional are these fast-varying bursts? Are the rapid bursts a separate class whose limits cannot be applied to ordinary bursts? In addition, what is the fastest timescale for ordinary bursts? In this paper, we report on two separate searches for rapid variability in GRBs. In the first search, we tested 20 bright bursts for the presence of isolated flares on timescales from 32 to 2048 μs. In the second search, we use Haar wavelet transforms to evaluate the flickering activity in burst light curves on timescales from 2 μs to 0.13 s.

2. ISOLATED FLARES

One of the possible modes by which bursts can display rapid variability is to have isolated flares. These might occur on any timescale and might be most prominent in either hard or soft photons. Giles (1997) offers a reliable and efficient algorithm for searching a light curve for significant peaks. In essence, his algorithm calculates a running mean and then seeks a significant deviation above this mean. This algorithm searches through light curves that are successively binned by factors of 2, so that we have tested light curves with bin sizes of 32, 64, 256, 512, 1024, and 2048 μs. Our threshold is set such that a flare would have to be more
significant than 5 \( \sigma \) after accounting for all the trials in a single burst. We have modified this algorithm by reducing the size of the window used in the running average so as to minimize the effect of curvature on the overall shape of the light curve.

This isolated flare search was performed on BATSE time-tagged event (TTE) data, which is ideal for rapid variability searches. The TTE data records the arrival time (within a 2 \( \mu \)s time bin) and energy (within four discriminator channels) of each photon. The energy boundaries of channels 1–4 are roughly 25–50, 50–100, 100–300, and greater than 300 keV. The onboard memory records only up to 32,768 photons around the time of the BATSE trigger. Typically, this quota of photons is used up in 1 or 2 s, which can only cover the leading portion of a long-duration burst. For short bursts, the entire episode might be in the TTE data, along with substantial times of only background emission after the burst. The time-tagged events are continuously written into a rotating memory, so TTE data is usually available for a fraction of a second before the BATSE triggers. For times before the trigger, photons from all eight BATSE modules are recorded, although we have used photons only from triggered detectors. The pulse pileup time is 0.25 \( \mu \)s, and the dead time is 0.13 \( \mu \)s.

Our isolated flare search was performed on 20 of the brightest BATSE bursts (see Table 1). These were chosen for the number of burst photons recorded in the short time interval during which TTE data is available, so the selection biases of our sample from the entire BATSE catalog may be complex. Our set of bursts is a mixture of short intense bursts with fast variability completely covered by the TTE data and the brightest bursts of ordinary duration with high numbers of burst photons during the TTE data. The columns of Table 1 give the GRB name, the BATSE burst trigger number, the peak flux from 50 to 300 keV over a 64 ms time bin, the T90 burst duration, the duration of the TTE data, and \( \langle C_{32}\rangle \), the average count rate in 32 \( \mu \)s time bins over the entire time span with TTE data. We performed the tests on three separate light-curve sets, with channels 1 + 2 + 3 + 4, channels 1 + 2, and channels 3 + 4.

Our search found only four significant flares in two bursts among our sample of 20 bright GRB light curves. These bursts are GRB 930131 (the "Superbowl Burst," with \( T_{90} = 19.2 \) s and a complex initial spike of high intensity) and GRB 920229 (with \( T_{90} = 0.19 \) s).

Our first burst with flares is the extremely bright GRB 930131. This burst has an initial spike (with duration \( \sim 1 \) s) composed of two main peaks (each with duration \( \sim 0.1 \) s) for which the first main peak has two flares (of total durations \( \sim 0.004 \) and \( \sim 0.01 \) s) visible only at the highest energies. There is substantial instrumental dead time at times of peak intensity, and this will slightly reduce the relative amplitude of short-duration flares. In channels 3 + 4, the light curve triggered on the 2048 \( \mu \)s timescale for each of the two flares on the first main peak. The fast variations in this flare are primarily in channel 4, while channels 1 and 2 have no corresponding variations (see Fig. 1c of Kouveliotou et al. 1994). The spectra of these flares are exceptionally hard.

Our second burst with flares is GRB 920229. This short burst has a 0.19 s duration, consisting of a smooth time-symmetric pulse followed by a spike with duration of roughly 0.003 s. Within the spike, on the 256 \( \mu \)s timescale, our flare search triggered on a flare near the end (at our usual 5 \( \sigma \) threshold) as well as a flare near the beginning (although only at the 3 \( \sigma \) confidence level after allowing for all the trials associated with our search for this one burst). The e-folding rise time of this spike is 220 \( \pm 130 \) \( \mu \)s, and the e-folding fall time is 400 \( \pm 100 \) \( \mu \)s, while the spectrum significantly softens over a 768 \( \mu \)s time interval during the spike’s fall. The background-subtracted count rates for the entire burst for channels 1, 2, 3, and 4 are 730, 1630, 2490, and 120 photons, which demonstrates a sharp spectral break around the energy boundary between channels 3 and 4. Detailed spectroscopy shows the spectrum has a peak \( \nu F_\nu \) at 200 keV with no significant flux above 239 keV, for a

### Table 1

**Bursts Analyzed**

| GRB    | Trigger | \( P_{64} \) (photons s\(^{-1}\)) | \( T_{90} \) (s) | TTE Duration (s) | \( \langle C_{32}\rangle \) |
|--------|---------|-------------------------------|----------------|----------------|----------------|
| 910503 | 143     | 52                            | 50.8           | 0.89           | 0.98           |
| 910609 | 298     | 56                            | 0.45           | 1.10           | 0.69           |
| 910627 | 451     | 17                            | 15.2           | 1.50           | 0.55           |
| 910718 | 551     | 5.6                           | 0.25           | 0.94           | 0.71           |
| 911109 | 1025    | 18                            | 2.62           | 1.34           | 0.59           |
| 911202 | 1141    | 9.3                           | 20.1           | 1.50           | 0.54           |
| 920229 | 1453    | 12                            | 0.19           | 1.42           | 0.61           |
| 920622B| 1664    | 10.5                          | 3.52           | 1.78           | 0.46           |
| 920718 | 1709    | 14                            | 3.46           | 0.85           | 0.99           |
| 920720 | 1711    | 22                            | 5.95           | 0.73           | 1.11           |
| 921022 | 1997    | 40                            | 60.2           | 0.78           | 0.91           |
| 930131 | 2151    | 168                           | 19.2           | 0.078          | 10.97          |
| 93056   | 2329    | 43                            | 22.1           | 1.49           | 0.55           |
| 930706 | 2431    | 44                            | 2.78           | 0.54           | 1.61           |
| 930905 | 2514    | 28                            | 0.20           | 0.66           | 1.35           |
| 930922 | 2537    | 27                            | 4.80           | 0.56           | 1.43           |
| 931031 | 2611    | 35                            | 12.2           | 0.65           | 1.27           |
| 950211 | 3412    | 55                            | 0.068          | 1.17           | 0.80           |
| 950325B| 3480    | 22                            | 9.1            | 0.43           | 2.07           |
| 950503 | 3537    | ...                           | \( \sim 10 \) | 0.40           | 2.22           |
sharpness of $\Delta E/E = 18\%$. These observations are presented in detail in Schaefer & Walker (1998).

This systematic study of 20 bright bursts shows that isolated flares of large amplitude are not common on the 2 ms timescale or faster.

### 3. Flickering

Another possible mode by which bursts can display rapid variability is to have many small-amplitude flares flickering quietly. This would just be an extension of the flickering seen on longer timescales as part of the multiple pulses forming the overall shape of many light curves. What is the shortest timescale on which bursts flicker? Short-duration flickers must fall below the thresholds already established by our isolated flare search, and this implies that the flickers are either isolated and of low relative amplitude or crowded together so that many flickers are bright at any one time.

If the low-amplitude flares recur repeatedly, then there should be statistical evidence for the burst showing fluctuations above that expected from Poisson noise alone. One means to test for frequent low-level fluctuations is a wavelet analysis. Wavelets are a set of mathematical functions that form an orthonormal basis that can readily describe short-duration events (Scargle 1997; Daubechies 1992). Wavelets have already been used for analysis of GRBs on long timescales by Norris et al. (1994) and Kolaczyk (1997).

In particular, we have used the simple Haar wavelet, which is an antisymmetric function consisting of one bin negative and the next bin positive with all other bins being zero. For a given bin size, the wavelet activity is defined as the average of the squares of the products of the Haar wavelet and the light curve for all relative offsets. To be quantitative, the Haar wavelet activity is equal to $\langle (C_i - C_{i+1})^2\rangle$, where $C_i$ is the counts in the $i$th time bin of the light curve and the angular brackets indicate an average over all values of $i$. As such, the activity is a measure of the rise and fall times present in the light curve. For normal Poisson variations alone, the expected activity level is $2\langle C_i \rangle$. In practice, the observed value is slightly different because of dead-time effects and the overall modulation of the light curve on long timescales. The rms scatter of the Poisson activity is $(8/N)^{0.5} \langle C_i \rangle$, where $N$ is the number of time bins in the light curve. Our normalized activity is the ratio between the observed activity and that expected for Poisson variations alone.

The normalized activity is calculated for light curves with bin sizes varying by factors of 2 from 32 $\mu$s to 0.131 s. In general, this number is around unity for short bin sizes, and it starts to rise significantly for some timescale that we identify as the shortest timescale of variability. From studies of simulated data, we find that the overall envelope of variability on long timescales does not produce activity on short timescales. The existence of this shortest timescale of variability implies neither that all variations are on that timescale nor that the fast variations have high amplitude. Rather, there appears to be a continuum of variations ranging from large-amplitude pulses of long duration to smaller pulses of short duration.

From studies of background data and of simulated data, we find that the normalized activity varies with a 1 $\sigma$ scatter from 0.7% to 3.0% for $\langle C_{32} \rangle$ values from 0.5 to 2.0. That is, for both background and simulated data, we find no significant deviations from $A_{\text{norm}} = 1$ on any timescale. This allows us to place a confidence limit on the shortest timescale of variability as the bin size in which the normalized activity is $3 \sigma$ above the Poisson level ($\tau_{\text{min}}$). Such timescales for each burst are tabulated in Table 2.

For GRB 930131 and GRB 920229, we recover the fast variations in the flares as $\tau_{\text{min}}$. We find no significant correlation between $\tau_{\text{min}}$ and either $T_{\text{obs}}$ or $\langle C_{32} \rangle$. These facts indicate that the normalized activity is indeed a measure of the shortest timescale of variability that is independent of brightness and duration.

From above, our definition of the normalized activity is

$$A_{\text{norm}} = \langle (C_i - C_{i+1})^2 \rangle / [(8/N)^{0.5} \langle C_i \rangle].$$

The average counts in a time bin of duration $D$, $\langle C_i \rangle$, can be found by scaling from the average counts in a 32 $\mu$s time bin, $\langle C_{32} \rangle$:

$$\langle C_i \rangle = \langle C_{32} \rangle \times (D/32 \mu s).$$

The values of $\langle C_{32} \rangle$ are tabulated in Table 1 and apply to the entire time interval with TTE data. This average count rate over the entire time interval (even with mixing of background, bright, and faint time intervals) is relevant for activity spectra derived for the same time interval. In the case that the variations in the light curve are due to flickering superposed on normal Poisson fluctuations,

$$A_{\text{norm}} = (V_f + V_p)/V_p.$$  

Here, $V_f$ is the variance of the light curve due to flickering, with

$$V_f = \sigma_f^2,$$

where $\sigma_f$ is the rms amplitude of flickering in counts within a bin. $V_p$ is the variance due to Poisson noise, with

$$V_p = \langle C_i \rangle.$$

These equations can be used to quantify the rms amplitude of flickering, $\sigma_f$.

Figure 1 displays the normalized activities as a function of bin size for five bursts. These five bursts were chosen for this figure since they display the range of behavior spanned by our complete sample. In these bursts and in all our 20

| GRB      | $\tau_{\text{min}}$ (ms) | $\tau_{\text{peak}}$ | $A_{\text{norm}}$ (33 ms) |
|----------|--------------------------|-----------------------|--------------------------|
| 910503   | 2.0                      | ...                   | 3.5                      |
| 910609   | 1.0                      | ...                   | 20                       |
| 910627   | 33                       | ...                   | 1.4                      |
| 910718   | 1.0                      | ...                   | 65                       |
| 911109   | 16                       | ...                   | 2.6                      |
| 911202   | 33                       | ...                   | 1.14                     |
| 920229   | 0.26                     | ...                   | 65                       |
| 920622B  | 4.1                      | ...                   | 3.7                      |
| 920718   | 33                       | ...                   | 1.8                      |
| 920720   | 4.1                      | ...                   | 4.2                      |
| 921022   | 0.51                     | 33                    | 477                      |
| 930131   | 1.0                      | ...                   | ...                      |
| 930506   | 8.2                      | 8.2                   | 1.17                     |
| 930706   | 4.1                      | 66                    | 8.9                      |
| 930905   | 1.0                      | 16                    | 20                       |
| 930922   | 4.1                      | ...                   | 34                       |
| 931031   | 16                       | 66                    | 10.3                     |
| 950211   | 4.1                      | 66                    | 330                      |
| 950325B  | 8.2                      | ...                   | 9.4                      |
| 950503   | 2.0                      | 33                    | 110                      |
FIG. 1.—Normalized wavelet activity for five bursts. On each timescale, the observed wavelet activity is divided by the expected activity from normal Poisson fluctuations to obtain the normalized activity. For each of the five sample bursts, the normalized activity is close to unity for timescales less than some \( \tau_{\text{min}} \) value and then starts rising fast for timescales longer than \( \tau_{\text{min}} \). The \( \tau_{\text{min}} \) values occur when the activity has risen 3 \( \sigma \) above the Poisson level and represent primarily the rise times in the light curves. The observed times of fastest variations range from 256 to 33 ms, with the majority of bursts showing activity on the 4 ms timescale. The upward-pointing triangles are for GRB 930131, squares for GRB 920229, diamonds for GRB 930905, circles for GRB 910503, and downward-pointing triangles for GRB 910627. These results show that millisecond variability is a common property of bursts and thus provide general constraints applicable to burst models.

bright bursts, the normalized activity is around unity for timescales less than \( \tau_{\text{min}} \) and then rises sharply above \( \tau_{\text{min}} \). Table 2 lists the observed values of \( A_{\text{norm}} \) for the 33 ms light curve to illustrate values at some constant timescale.

In some cases, the activity does not rise monotonically with timescale, for example, the peak at 0.016 s for GRB 930905 in Figure 1. The timescale of these local maxima in normalized activity is \( T_{\text{peak}} \), as tabulated in Table 2. From our sample, we find significant peaks for seven bursts, with \( T_{\text{peak}} \) ranging from 8.2 ms up to our highest observable value of 66 ms. While it is possible that these peaks arise from flickers that have a characteristic rise time, we believe that the peaks are caused by single flares of large amplitude that contribute much activity on the timescale of their rise time. Indeed, with one exception (GRB 930506, for which the peak has a small \( A_{\text{norm}} = 1.24 \)), the \( T_{\text{peak}} \) values can be linked to a single specific rise with the same timescale.

4. INTERPRETATION OF WAVELET ACTIVITY

Our observed wavelet activity needs to be interpreted in terms of the corresponding variations in the light curve. To aid in this analysis, we have employed both analytic calculations and simulations.

An important question is whether wavelet activity is produced on short timescales because of the overall shape of the burst or because of edge effects in the data stream. We find no edge effects either analytically or from direct simulation or from analysis of background data. The presence of a linear slope in the light-curve shape does (from either a changing background or a brightening burst) contribute a term that increases as the cube of the timescale. This conclusion also holds for sawtooth-shaped modulation as well as for triangle-shaped flares, as long as the timescales are shorter than the rise times. This shows that the wavelet activity falls off very rapidly as the timescale is decreased to below that for which there is significant change in flux from bin to bin. As this conclusion is supported by direct simulation, we conclude that wavelet activity on short timescales is caused by light-curve variations on the same timescale.

Another important question is the amplitude and frequency of the flickering. Unfortunately, for modest flicker fractions, there is a degeneracy between the flare amplitude and frequency. That is, when the individual flares are not distinguished, the wavelet activity for frequent low-amplitude flares and for infrequent moderate-amplitude flares is identical. The wavelet activity can constrain only the product of the flare frequency and the square of the amplitude. Thus, flickering with unit amplitude and frequency cannot be distinguished from flickering with 10 times the amplitude and a 100 times lower frequency. However, the total flux in the flickers varies only as the product of the amplitude and frequency, so the fraction of the observed flux in the flickers will vary. Perhaps the Bayesian block method of Scargle, Norris, & Bonnell (1998) may break this degeneracy.

For the five bursts illustrated in Figure 1, we have constructed detailed model simulations of the light curves and then tested these models against the observed wavelet activity.

GRB 910503 is one of the brightest BATSE bursts, with its light curve consisting of two ∼10 s episodes. The TTE data covers only the first rise, and this rise is approximately linear with no apparent individual flares. Simulations that include only the linear rise account well for the wavelet activity for timescales of 16 ms or longer. However, the wavelet activity from 2 to 8 ms is greatly and significantly above that expected from the combination of the roughly linear rise and normal Poisson variations. The activity in the 2–8 ms range must come from flickering where individual flares are of sufficiently low amplitude to have not been identified in our search for isolated flares. Thus, we have run simulations that include the long-term rise plus randomly placed square-wave flickers. One model that closely matches the observed wavelet activity includes flares that occur with a frequency of 100 Hz, a duration of 4096 \( \mu s \), and a flare amplitude of roughly 0.1 counts per 32 \( \mu s \) bin (for the flares comprising 3.5% of the observed flux). Note that the match between this model and the observed wavelet activity is good to within the random variations inherent in our simulations. Alternatively, a trade-off between the flare frequency and amplitude can yield the same wavelet activity. Thus, the wavelet activity is also reproduced in a model with flares of duration 4096 \( \mu s \), frequency 10,000 Hz, and flare amplitude 0.01 counts per 32 \( \mu s \) bin (for the flares comprising a third of the observed flux). The flare amplitude cannot be greater than ∼0.3 counts per 32 \( \mu s \) bin, or the individual flares would be identified. Within a model of uniform flare durations, the durations cannot be greatly longer or shorter than 4 ms to account for the excess wavelet activity from 2 to 8 ms. With such durations, the rise times must be comparable to our measured \( \tau_{\text{min}} \). Perhaps more realistic models would allow for differently shaped flares and some distribution in durations. In summary, GRB 910503 must have flickering with characteristic rise timescales of roughly 2 ms superposed on the smooth rise in the light curve.

GRB 910627 consists of two peaks, with the TTE data covering the rise and one-half of the fall of the first peak. We have simulated the overall light-curve shape as a linear rise and a linear decline of the appropriate slopes. This model produces wavelet activity in close agreement with obser-
vations, that is, where the $A_{\text{norm}}$ value rises above unity only for the 33 ms timescale. We find no need to invoke any short-duration flickering to account for the observed wavelet activity.

GRB 920229 is a short burst with a smooth light curve plus an extremely short duration spike at the end. We have modeled this burst as the positive portion of a cosine shape plus two superposed triangular flares (with durations of 1600 and 320 $\mu$s and amplitudes of 7 and 5 counts per 32 $\mu$s bin). The background was modeled as a constant 0.3 counts per 32 $\mu$s bin, and this is important since the TTE data includes a time interval roughly 1.2 s long with no burst flux. This model was able to completely account for the observed wavelet activity. That is, the significant activity on timescales of 256 $\mu$s is fully accounted for by the observed structure in the final spike, with no room for any short-duration flickering.

GRB 930131 (the “Superbowl Burst”) is the most intense classical GRB detected with BATSE, and this is shown by the very short duration of the TTE data. The overall shape of the light curve during this interval is reasonably well modeled as a constant (11 counts per 32 $\mu$s bin) plus a sine wave (with a period of 30 ms and a full amplitude of 6 counts per 32 $\mu$s bin) plus a triangular flare (with a full duration of 6.4 ms and an amplitude of 3 counts per 32 $\mu$s bin). This model reproduces well the overall shape of the light curve, but it does not reproduce the wavelet activity on timescales from 1 to 8 ms. This fast activity can be modeled as flickers producing fluctuations above the normal Poisson level. In particular, a model with square-wave flares of duration 4096 $\mu$s, amplitude 2 counts per 32 $\mu$s bin, and frequency 300 Hz can reproduce the observed activity spectrum (for ~30% of the observed flux residing in the flickers). Again, there will be a trade-off between flare amplitude and frequency, with complications from alternate flare shapes and duration distributions. However, the wavelet activity on timescales from 1 to 8 ms requires short-duration flickering to be present in the light curve of GRB 930131.

GRB 930905 has a duration of roughly 0.25 s with two structured peaks. We have modeled the overall shape of this light curve as eight segments with linear rises or falls. The last segment consists of the flat time interval with only background flux. We find that the wavelet activity is reproduced well with this model. In particular, the decline of the wavelet activity from 16 to 33 ms corresponds to the duration of the minimum between the two light-curve peaks, such that this “negative” flare is smeared out on a timescale of 33 ms. For this burst, short-duration flickering is not needed to explain the activity on the 1 ms timescale.

The fast timescale variations in burst light curves can be explained by a combination of short-duration flares (as in GRB 920229), the overall shape of the light curve (as in GRB 910627 and GRB 930905), and rapid low-amplitude flickers (as in GRB 910503 and GRB 930131). Other bursts with millisecond flickers include GRB 910609, GRB 910718, and GRB 921022. All bursts in our sample display significant wavelet activity on timescales of 33 ms or faster.

While our isolated flare search measured durations, our wavelet activity search measured rise and fall times. For several reasons we believe that our $t_{\text{min}}$ values are essentially rise times. First, the $T_{\text{peak}}$ values for six bursts have been identified with particular rises. Second, the $t_{\text{min}}$ values for GRB 920229 and GRB 930131 correspond to specific rises in the light curve that are more than 2 times faster than any significant fall. Third, in general, bursts always display a substantially faster rise than fall (Barat et al. 1984; Nemiroff et al. 1994).

Among our sample of 20 bright bursts, the range of $t_{\text{min}}$ is from 256 $\mu$s to 33 ms, with a median value of 4 ms, and 30% with activity at 1 ms or faster. Thus, we conclude that the first second or so of most burst light curves contain rises with a timescale of order 1 ms.

5. IMPLICATIONS

We have shown that the majority of our sample of 20 GRBs has flickering with rise times faster than 4 ms, while individual flares can vary with rise times as fast as 220 $\mu$s. Thus, millisecond variability is common in bursts and is not just a rare phenomenon restricted to some special and possibly distinct class.

The rise and fall times measured by the wavelet activity can be used to place constraints on GRB models. Based on the recent discoveries of low-energy counterparts (Costa et al. 1997; van Paradijs et al. 1997; Frail et al. 1997; Metzger et al. 1997) and detailed successful models (Mészáros & Rees 1997), bursts are now generally thought to be relativistically expanding fireballs at cosmological distances. With the severe energy requirements for some bursts with measured distances (e.g., GRB 990123), a popular model consists of the energy being sent out in a narrow jet. The Lorentz factor of the expansion $\Gamma$ is generally thought to be from 100 to 1000 so as to explain the GeV photons seen in some bursts (Harding & Baring 1994). The collimation of the radiation emitted by the jet is likely to be narrower than the jet opening angle, so an observer on Earth would not see any consequences of the jet in the burst light curve. Within this basic scheme, pulse durations and fall times can limit fireball properties (Fenimore, Madras, & Nayakshin 1996, hereafter FMN), as can the rise times. The model constraints will depend on the particular scenario invoked, but some general arguments can use the rise times to constrain fireball properties independent of the specific scenario.

The first constraint is that the size of the central engine is limited to $c t_{\text{min}}$. Within fireball models, the initial uncollimated flow will result in a density gradient at the front edge of the expanding shell with a width equal to the light travel time across the emission region. For external shock scenarios, the fuzziness of the shell will result in emission starting to rise when the leading edge first hits the stationary cloud while the peak comes later when the bulk of the shell hits the cloud. For internal shock scenarios, the constraints will only be stricter since the outer shell is also moving. Thus, the energy generation volume must have a typical thickness of smaller than 1200 km for the majority of bursts. A narrowly collimated jet scenario might be able to substantially violate this limit.

The second constraint is on the physical dimension in the direction perpendicular to the expansion of the shell. The arrival time for photons from a single shell will be the travel time of the shell to the radius of impact plus the travel time of the gamma ray to Earth. As the shell expands at very close to light speed, the delay is purely geometrical, with photons from off-axis regions being delayed compared with photons from on-axis regions. The observed delay depends only on the radius of the shell at the time of impact with the cloud ($R$) and the angular radius of the gamma-ray emission.
region as subtended from the burst site \((\Delta \Theta)\). At a typical off-axis angle such as \(\Gamma^{-1}\), the rise time will be close to \(R(c\Gamma)^{-1}\Delta \Theta\). The shell has been expanding for at least the time from the start of the burst until the time of the rise \((T_{\text{rise}})\), so \(R > 2c\Gamma^2 T_{\text{rise}}\) (FMN). Then, \(\Delta \Theta < \tau_{\text{rise}}/(2\Gamma T_{\text{rise}})\).

For the bursts in our sample, with \(\tau_{\text{rise}} \sim 4\) ms, \(T_{\text{rise}} > 0.1\) s, and \(\Gamma > 100\), we find that \(\Delta \Theta < 0.0002\) radians or \(<42^\prime\). Because of self-shadowing, Earth can see only a "cap" of the shell, which subtends an angle \(\Theta_{\text{cap}} = \Gamma^{-1}\), so the individual emission region associated with the rises subtends only a small region of the cap (\(\sim 42^\prime\)). This is in contrast to the total fraction of the shell that becomes active, \(\sim 5 \times 10^{-3}\) (Fenimore et al. 1998). This demonstrates that either the shell or the impacted cloud is very fragmented, and this could be realized by a narrow jet hitting a large cloud.

The third constraint is on the velocity dispersion within a single individual emitting region. Based on the precedent of supernova shells, we expect there should be a substantial range of velocities within a shell, with the fast-moving material sorting itself to the front and the slow-moving ejecta in the rear. For the external shock scenario, the flare will start to brighten when the leading edge hits the cloud and will peak when the bulk of the shell hits the cloud, resulting in a measurable rise time. Let \(\Gamma\) be the Lorentz factor for the densest layer of the shell, with \(\Delta \Gamma\) the difference in Lorentz factor between the densest layer and the leading edge of the shell. To account for the observed rise time, the fractional dispersion in Lorentz factors \((\Delta \Gamma/\Gamma)\) within an emitting region must be less than \(\tau_{\text{rise}}/2T_{\text{rise}}\). For the majority of bursts, the \(\Gamma\) dispersion is \(\sim 2\%\) for the emitting regions. In contrast, the range of \(\Gamma\) associated with the different emitting regions can have a large dispersion, more than a factor of 2 (see Fenimore et al. 1998).

The fourth constraint is on the size scale of the impacted cloud along the line of sight within the external shock scenario. For a thin shell, the gamma radiation will start when the shell sweeps across the inner boundary of the cloud, while the peak flux will be produced when the shell sweeps across the center (or densest region) of the cloud. The characteristic dimension for the structure of the cloud must be smaller than \(2\Gamma c \tau_{\text{rise}}\) since the shock is moving at near light speed (FMN). For the average rise time of 4 ms and \(\Gamma < 1000\), the typical cloud size must be smaller than 16 AU.

The main conclusion of this work is that the majority of GRBs contain flares or flickers with rise times faster than 4 ms in the first \(\sim 1\) s of their light curves, and this places severe limits on burst scenarios. In particular, the size of the central engine region must be typically smaller than 1200 km. The individual gamma-ray–emitting region must be quite small (subtending only about \(42^\prime\)). There can be only a small dispersion of \(\Gamma (\Delta \Gamma/\Gamma)\) less than \(\sim 2\%\) factors within the individual emitting regions.

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