BROADBAND TURBULENT SPECTRA IN GAMMA-RAY BURST LIGHT CURVES

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ABSTRACT

Broadband power density spectra offer a window to understanding turbulent behavior in the emission mechanism and, at the highest frequencies, in the putative inner engines powering long gamma-ray bursts (GRBs). We describe a chirp search method alongside Fourier analysis for signal detection in the Poisson noise-dominated, 2 kHz sampled, BeppoSAX light curves. An efficient numerical implementation is described in $O(Nn \log n)$ operations, where $N$ is the number of chirp templates and $n$ is the length of the light-curve time series, suited for embarrassingly parallel processing. For the detection of individual chirps over a 1 s duration, the method is one order of magnitude more sensitive in signal-to-noise ratio than Fourier analysis. The Fourier–chirp spectra of GRB 010408 and GRB 970816 show a continuation of the spectral slope with up to 1 kHz of turbulence identified in low-frequency Fourier analysis. The same continuation is observed in an average spectrum of 42 bright, long GRBs. An outlook on a similar analysis of upcoming gravitational wave data is included.

Key words: gamma-ray burst: general – methods: data analysis – stars: black holes – stars: neutron – turbulence

Online-only material: color figures

1. INTRODUCTION

The prompt gamma-ray burst (GRB) emission in long GRBs is believed to be produced in dissipative fronts downstream of ultra-relativistic outflows originating in a long-lived inner engine, which may harbor a rapidly rotating (proto-)neutron star (PNS) or a black hole-accretion disk system (BHS; e.g., Piran 1999, 2004). These outflows may be modulated by the evolution and time variability of the inner engine with a possible imprint on the observed gamma-ray light curves. For stellar mass inner engines, these modulations may extend to relatively high frequencies of up to a few kHz in the comoving frame of reference. Therefore, the 1 kHz window, offered by the 2 kHz BeppoSAX light curves (Frontera et al., 2009), provides a broadband window to the dissipative emission process as well as to the inner engines of long GRBs.

A detailed exploration of high-frequency gamma-ray light curves may, hereby, provide valuable priors to more direct probes of the inner engines by the upcoming gravitational wave detectors LIGO–VIRGO, KAGRA, and the Einstein Telescope (Barish & Weiss, 1999; Arcese et al., 2004; Kuroda & LCGT Collaboration, 2010; Hild et al., 2008). For instance, a recent extraction of normalized light curves from the BATSE catalog of long GRBs shows evidence of rapidly spinning black holes losing angular momentum against surrounding high density matter, expected to form in core collapse of massive stars (van Putten, 2012). The results point to the possible emission of gravitational waves contemporaneous with the gamma-ray emission of long GRBs produced by forced turbulence in an inner disk or torus.

Given the limited collector area of the BeppoSAX satellite, the high-frequency light curves of GRBs are typically Poisson noise dominated, flattening their Fourier spectra above tens of Hz at most. Low-frequency Fourier analysis reveals a Kolmogorov spectrum in GRB light curves (Beloborodov et al., 1998, 2000; Guidorzi et al., 2012; Dichiara et al., 2013a, 2013b), which is expected to continue smoothly to high frequencies. A broadband turbulent spectrum from the gamma-ray emission process may, hereby, present a new baseline in searches for high-frequency modulations by the central PNS or BHS.

Here, we describe a method for high-frequency analysis of long GRBs, which aims at the detection of turbulence in the gamma-ray emission region and possible imprints by a time-evolving inner engine. To ensure maximal sensitivity, our method uses matched filtering, using chirps whose frequencies gradually increase or decrease with time. Our motivation to use chirp templates is twofold. First, turbulence produces phase-coherent intermittencies on short to intermediate time scales, which covers an extended bandwidth in frequency space. To search for turbulence in a Poisson noise dominated signal, we set aside Fourier analysis, since it focuses on phase coherence across a relatively narrow bandwidth. Enhanced sensitivity is expected with chirps, whose frequency drifts represent phase coherence across a finite bandwidth. Second, turbulent excitations in the inner disk or torus may give rise to chirps on intermediate time scales due to the expansion of the innermost stable circular orbit during black hole spin-down (van Putten, 2008). Through either a collimating disk or torus winds, this behavior may be imprinted on the dissipative fronts downstream of the ultra-relativistic outflow producing the observed gamma-ray emission.

The computational effort of our method is $O(Nn \log n)$ operations, consistent with the fast Fourier transform (FFT), where $n$ denotes the number of samples in the data time series and $N$ denotes the number of chirp templates. This limit appears to be competitive to other approaches (O’Toole et al., 2010; Fish et al., 2011).

To illustrate our method, we report on spectra of bright 2 kHz sampled light curves of long GRBs in the BeppoSAX catalog (Frontera et al., 2009).

The chirp templates are described in Section 2 and an efficient numerical implementation of the matched filtering algorithm is given in Section 3. Chirp detection sensitivity is analyzed in Section 4. We apply the method to extract broadband spectra from a sample of BeppoSAX light curves in Sections 5 and 6,
derive a continuation of Fourier spectra. An outlook on further applications is briefly described in Section 7.

2. CHIRP TEMPLATES

Chirps are transients described by a base frequency and a frequency rate of change. They are different from quasi-periodic oscillations (QPOs), which persist for periods of time coherently across a finite frequency bandwidth. Here, of particular interest are chirps with an exponential change in frequency as a function of time. They can be extracted by time slicing a single long duration chirp into subintervals of duration, $T/a$, where $T/\tau$ is a dimensionless scale to parameterize the time scale, $\tau$, of change in chirp frequency.

The choice of $\tau$ is used to search for phase coherence over a time scale, $\tau$, such that $\Delta t \ll \tau \ll T$, where $\Delta t$ denotes the sampling time interval or the bin size of integration of the data. Accordingly, we consider $N = T/\tau$ time intervals

$$t_k < t < t_{k+1}, \quad t_k = \frac{k T}{N} \quad (k = 0, 1, \ldots, N - 1)$$

in our time slicing procedure. Figure 1 illustrates slicing of a model chirp with $T = 8$ s into $N = 8$ one second chirp templates

$$z_k(t'), \quad 0 \leq t' \leq \tau, \quad t' = t - t_k,$$

where $k = 0, 1, \ldots, N - 1$.

In steady state, the statistical properties of, e.g., a velocity field in turbulent motion, are the same when the time series is viewed forward and backward in time, whereby the probabilities for detecting positive and negative chirps are similar for intermediate durations, $\tau$. We shall therefore employ difference chirps, obtained as the difference of chirps considered forward and backward in time. If $x_k(t')$ is a chirp template extracted from Equation (5), we consider

$$x_k(t') = z_k(t') - z_k(\tau - t') \quad (0 \leq t' \leq \tau).$$

In using Equation (4), we save a factor of two in computational cost, allowing for detections of positive or negative chirps in one calculation. Because the cross-correlation between chirps forward and backward in time is small, Equation (4) can be used efficiently with a negligible loss in sensitivity over two runs performing matched filtering, enabling searches for positive and negative chirps in one computational run.

3. EFFICIENT MATCHED FILTERING

To develop a search with maximal sensitivity to features with frequencies changing in time, we set out to employ matched filtering. Matched filtering obtains the highest possible sensitivity for phase-coherent features, upon sufficiently including many templates to cover the full range of possible signals and their phase-coherent behavior. For this reason, efficient numerical implementation of method matched filtering is important.

For a time series, $y(t)$, and chirp template, $x(t)$, let $\hat{x}(t) = x(t) - \mu_x$ and $\hat{y}(t) = y(t) - \mu_y$ by subtracting the respective mean values $\mu_x$ and $\mu_y$, and consider their cross-correlation

$$\rho(t) = \int_{-\infty}^{\infty} \hat{x}(s)\hat{y}(t + s)ds.$$  (5)

Using the Fourier transform, $F(k)$, of a function, $f(t)$,

$$F(k) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} f(t)e^{-ikt}dt,$$  (6)

$$f(t) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} F(k)e^{ikt}dk,$$  (7)

$\rho(t)$ is efficiently calculated as the inverse Fourier transform of the product $X^*(k)Y(k)$ of the complex conjugate $X^*(k)$ of the transform of $\hat{x}(t)$ and $Y(k)$ of $\hat{y}(t)$.

In matched filtering, the potential significance of a chirp is identified by the normalized cross-correlation $\hat{\rho}(t)$ of $\hat{x}$ and $\hat{y}(t)$ (i.e., the Pearson coefficient):

$$\hat{x}(t) = \frac{x(t)}{||x||}, \quad \hat{y}(t) = \frac{y(t)}{||y||},$$

where $||f(t)|| = \left(\int_{-\infty}^{\infty} f^2(t)dt\right)^{1/2}$ is the $L^2$ norm of $f(t)$.

For a discrete series of samples at $t = t_i$ ($i = 1, \ldots, n$), consider $Y = \{\hat{y}_i\}_{i=1}^{n}$ and $X = \{\hat{x}_i\}_{i=1}^{m}$ ($1 \leq m \leq n$), where $N = n/m$ denotes the number of slices illustrated in Figure 1. Since Equation (5) is bilinear, the sample correlation
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coefficient (SCC) \( \rho_1 = \rho(t_1) \) obtained from \( Y \) and \( X \) is readily calculated by the FFT in \( O(n \log n) \) operations. However, the normalized SCC, \( \hat{\rho}_i \), obtained from \( \hat{Y} = \{ \hat{y}_i \}_{i=1}^n / \| \hat{y} \| \) and \( \hat{X} = \{ \hat{x}_j \}_{j=1}^m / \| \hat{x} \| \) (1 \( \leq m \leq n \) ) is nonlinear in \( Y \) and \( X \) due to normalizations \( \| f \| = (\sum f^2) / 2 \). Direct evaluation of these nonlinear expressions is prohibitively expensive when the number of chirps is large.

To be precise, consider the Pearson coefficient between \( Y \) given by a section \( y_{il} = y_{il} \) (1 \( \leq l \leq m \), \( 1 \leq m \leq n - m \)), of the time series \( \{ y_{il} \}_{i=1}^n \) and a template, \( X \),

\[ \hat{\rho}_i = \sum_{j=1}^m \hat{x}_j \hat{y}_{ij} \quad (i = 1, 2, \ldots, n - m) \quad (9) \]

where

\[ \hat{x}_j = \hat{x}_j / \sqrt{\sum_{i=1}^m \hat{x}_i^2}, \quad \hat{x}_l = x_l - m^{-1} \sum_{j=1}^m x_j, \]
\[ \hat{y}_{ij} = \hat{y}_{ij} / \sqrt{\sum_{i=1}^m \hat{y}_{ij}^2}, \quad \hat{y}_{il} = y_l - m^{-1} \sum_{j=1}^m y_{lj}. \quad (10) \]

Exact normalization in Equation (9) ensures that it will be the cosine between \( Y \) and \( X \), satisfying \(-1 \leq \hat{\rho}_i \leq 1\).

The unnormalized cross-correlation

\[ \rho_i = \sum_{j=1}^m \hat{x}_j \hat{y}_{ij} \quad (i = 1, 2, \ldots, n - m) \quad (11) \]

can be evaluated in \( O(n \log n) \) operations using the FFT, which is cost effective compared to Equation (9) when \( m > \log n \). We now consider \( \rho_i \) block wise over data slices of duration \( \tau \), i.e., the discretized intervals

\[ km < i < (k + 1)m \quad (k = 0, 1, \ldots, N - 1). \quad (12) \]

Normalizing \( \rho_i \) as an array over each slice requires \( N \) normalizations,

\[ C_k = \sqrt{\sum_{j=1}^{k+1} \rho_j^2} \quad (k = 0, 1, \ldots, N - 1). \quad (13) \]

The \( C_k \) defines a staircase as a function of \( k \), where \( k, m \leq i \leq (k + 1)m \), giving a block wise normalized SCC:

\[ \hat{\rho}_i = \rho_i / C_k. \quad (14) \]

Block wise normalization is particularly opportune when \( y_i \) shows variations in dispersion no faster than the intermediate time scale, \( \tau \). If so, our block normalized SCC applies to the operational cost of FFT, which is below the cost of true SCC’s in Equation (9) whenever \( m > \log n \).

When \( m \) is relatively large, e.g., \( 2^p \) with \( p \geq 8 \), \( \hat{\rho}_i \) typically shows a near-Gaussian distribution by the central limit theorem. In what follows, we shall use a further normalization by the variance of the cross-correlations (Equation (11)) in each time slice, i.e.,

\[ R_i = \rho_i / \sigma_k, \quad \sigma_k = C_k / \sqrt{m - 1}. \quad (15) \]

\( R_i \) hereby differs from \( \hat{\rho}_i \) only by a constant factor \( \sqrt{m - 1} \), whose probability density function (PDF) approaches a truncated Gaussian of unit variance. The truncation is a function of both the total number of trials \( n-m \) and the potential for a chirp being present in the data.

Figure 2 illustrates the numerical implementation.

4. CHIRP DETECTION SENSITIVITY

We consider quantifying the sensitivity of matched filtering relative to that obtained by Fourier analysis. To this end, we perform the injection experiment

\[ y(t) = y_0(t) + \alpha y_1(t) \quad (16) \]

on the BeppoSAX light curve \( y_0(t) \) of GRB 010408 by the light curve \( y_1(t) \) of a chirp for various amplitudes \( 0.01 \leq \alpha \leq 1 \).

A chirp search by matched filtering obtains the time series \( R_i \) following Equation (15). We consider detection by

\[ R = \max_{i=1,\ldots,n} |R_i| \quad (17) \]

in light of the approximately Gaussian PDF of the \( R_i \), truncated by the finite number of \( n-m \) trials in each template search.

To compare Equation (17) with Fourier analysis, we calculate the spectrum by the Welch method (Welch 1967; Cooley et al. 1970; Press et al. 2002) using a partition in \( Q = 10 \) sub-windows of length \( n/Q \) with a \( \Delta f = 1 \) Hz frequency resolution. The spectrum is calculated as an average over \( 2Q \) periodograms from intervals of length \( n/Q \) with 50% overlap. Each periodogram is obtained with a Welch window, i.e., as the Fourier transform of \( u(t) \) by FFT, where \( t = 4u(1 - u) \), where \( u = t_1/0.8 \) with \( t_1 = t/1(1) \). By construction of the Welch method, fluctuations in the resulting power spectrum are approximately Gaussian, as a \( \chi^2 \) distribution from averaging \( 2Q \) periodograms.

For each \( \alpha \) detection is expressed, similarly to Equation (17), by peak values

\[ H = \max_{k=1,\ldots,n/Q} H_k \quad (18) \]
relative to the asymptotically flat Poisson dominated spectrum in terms of

\[ H_k = \frac{|c_k| - s_0}{\sigma_0}, \]  

(19)

where \( s_0 \) and \( \sigma_0 \) denote the mean and standard deviation of the \(|c_k|\) in the Poisson dominated tail of the Fourier spectrum.

As a control, consider a chirp search in random data. In this event, \( R \) and \( H \) have expectation values of \( R_0 \) and \( H_0 \), respectively, that derive from the expectation value \( x_0 \) of the truncation in the distribution of \( n - m \) trials of a variable \( x \) taken from a Gaussian distribution with unit variance. Here, \( x_0 \) satisfies

\[ N \text{erfc}(x_0/\sqrt{2}) \simeq 1, \]

(20)

with \( N = (n - m) \) for \( R_0 \) and \( N = n/Q \) for \( H_0 \), where \( \text{erfc}(x) = 2/\sqrt{\pi} \int_x^{\infty} e^{-s^2} ds \) denotes the complementary error function.

Figure 3 shows \( R_0 \) and \( H_0 \) distributions numerically computed from \( M = 10^5 \) maxima in trial samples of size \( N \) from a Gaussian distribution with unit variance. Their mean, \( \mu \), is determined by \( N \) according to Equation (20) and the resulting distributions have positive skewness. The distribution shown are truncated themselves, according to Equation (20), upon substituting \( MN \) for \( N \).

Figures 4 and 5 show the results of our injection experiment for various values of \( \alpha \) obtained in Fourier analysis and, respectively, matched filtering.

Applied to \( R_3 \), Equation (20) implies a base level \( R_0 \simeq 4 \) when \( n = 2^{14} \) when sampling over the first 8 s of the 2 kHz light curves in the BeppoSAX catalog. Under the null hypothesis with no signal present, \( R \) has a probability of occurrence \( P \simeq (n - m) \text{erfc}(R/\sqrt{2}) \). An excess \( R > R_0 \) is either a false positive with \( P < 1 \), or denotes the presence of a signal. For \( m = 2048 (\tau = 1 \text{ s}) \), a 3\( \sigma \) detection corresponds to \( R_3 = 5.24 \), indicated by the dot-dashed line in Figure 5. \( H \) is obtained similarly from \( H_k \), giving a 3\( \sigma \) threshold \( H_3 = 4.79 \).

For a 3\( \sigma \) detection, the critical value \( \alpha_3 = 0.027 \) for matched filtering is a factor of 5.3 smaller than \( \alpha_3 = 0.14 \) for Fourier analysis using the Welch method. An additional moving average of the Fourier spectrum shows some improvement in its sensitivity, leaving a gain by matched filtering by about one order of magnitude in the S/N = \( \sigma^2 \) (right).

(A color version of this figure is available in the online journal.)
the constant background value of $R_0$, set by the number of trials $n-m$. Upon subtracting $R_0$, we thus obtain a detection method with a linear response to small amplitude signals. In general, $R_0$ is a function of frequency, which poses the question on devising a suitable control.

We express the spectra in terms of a strain $h = h(f)$ given by the square root of the PDS,

$$h(f) = \frac{R(f) - R_0(f)}{R_0(f)\sqrt{B(f)}}, \quad h_k = \frac{|c_k| - s_0}{\sigma_0\sqrt{B_0}}. \quad (21)$$

Here, $R_0(f)$ denotes the results of chirp analysis of control light curves and $B(f) = \kappa(\tau)f^{1/2}$ is the bandwidth of a chirp templates at about the frequency $f$, where $\kappa(\tau)$ is a coefficient that depends on the choice of chirp duration. The $h_k$ are calculated from the Fourier coefficients $|c_k|$, that have a noise dominated high-frequency tail with standard deviation, $\sigma_0$, and mean, $s_0$.

A chirp search is not a linear transform in the sense of Fourier analysis. A chirp search seeks a best-fit chirp to the data, by varying frequency and frequency rate of change. Different chirp templates are hereby linearly dependent at high resolutions with finite cross-correlations, as opposed to working with basis functions that satisfy exact linear independence. However, this distinction is immaterial in calculating spectra.

For Gaussian additive noise, such as in the high-frequency, shot-noise dominated region of strain amplitude noise in gravitational wave detectors, light curves obtained by time randomization or produced by a random number generator will be effective as a control $R_0$. By whitening in Equation (15), these two alternatives essentially give the same results.

For the Poisson noise in the 2 kHz BeppoSAX light curves, whose average photon counts are of the order of unity per 0.5 ms bin, we propose as a control, $R_0$, a synthetic Poisson noise light curve that shares the smoothed light curve as the original. A control of this type accurately captures the secular variation of the variance in the noise with (smoothed) amplitude, illustrated in Figure 6.

5. FOURIER–CHIRP SPECTRA

We observe that $R(\alpha)$ scales linearly with $\alpha$ across an appreciable range beyond $\alpha_c \approx 0.015$, below which it assumes

![Figure 6](image1)

**Figure 6.** Left: top panel (A) shows a synthetic fast rise and exponential decay Poisson noise light curve (FRED) with a smoothed light curve following a 2 Hz filter, and derived light curves with (B) Gaussian additive noise and (C) Gaussian noise, whose variance tracks the amplitude of the smoothed light curve. Right: the $R$ distribution is shown for the different noise types added to the smoothed light curve, each with positive skewness as in Figure 3, obtained here by matched filtering over $N = 160,000$ chirp templates with log-uniform distribution in frequency and frequency rate of change. The distribution of $R$ in panel (A) shows a pronounced excess to that in panel (B). Essentially, the same $R$ distribution results from panel (C). Therefore, the excess is due to the Poisson correlation between variance and average, here a moving average defined by the smoothed light curve.

(A color version of this figure is available in the online journal.)

where $m = 2048$, in the case at hand, for $\tau = 1$ s. The observed value $\alpha = 2.5\%$ for a $1\sigma$ excess in $R$ above background is indeed close to the anticipated value $1/\sqrt{m}$.

![Figure 7](image2)

**Figure 7.** Shown are two bright long GRBs in the BeppoSAX catalog (GRB 010408 and 970816) at 2 kHz, sampling over the first 8 s, their smoothed light curves (black) and their spectra over 1–1000 Hz in a log–log plot. Fourier analysis reveals a typical low-frequency turbulent spectrum, noise limited above tens of Hz (blue), at most, shown with asymptotic normalization, $h_0 = 1$. The spectral slope identified at low frequency in Fourier analysis (black solid lines) continues at high frequency in our matched filtered chirp search, here over 8.64 million templates (red, $h_0 = 0$).

(A color version of this figure is available in the online journal.)

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Figure 8. Shown are the smoothed light curves (sorted by $T_{90} = 3$–456 s) of an ensemble of 72 bright long GRBs in the BeppoSax catalog, sampled at 2 kHz over the first 8–10 s.

(A color version of this figure is available in the online journal.)

Figure 9. Ensemble of 72 GRBs falls into two groups according to the first zero in their autocorrelation coefficients. On average, red (42) and white (30) bursts have a first zero at 1.08 s and, respectively, 0.003 s. Their mean durations $T_{90}$, are, respectively, 48.93 s and 113.2 s.

(A color version of this figure is available in the online journal.)

Figure 10. For reference, shown are the observed durations $T_{90}$ vs. redshift of long GRBs in the Swift catalog (NASA, HEASARC, http://swift.gsfc.nasa.gov/archive/grb_table). The spread in observed $T_{90}$ durations is intrinsic, given the lack of correlation to redshift.

(A color version of this figure is available in the online journal.)

6. AVERAGE SPECTRUM OF BRIGHT GRBs

We are now in a position to apply our method to two bright long GRBs from the BeppoSAX catalog. Matched filtering calculations are performed with a log-uniform distribution in frequency and frequency rate of change over a total of 8.64 million templates with frequencies $f$ below 1 kHz from 1.28 million model parameters ($f_0$, $T$) in Equation (1). For control, we use synthetic Poisson noise light curves around smoothed light curves, following a low-pass filter at 2 Hz.

Figure 7 shows a blended Fourier–chirp spectrum up to about the maximal frequency of 1000 Hz, set by the sample rate of 2 kHz. Here, the low-frequency spectrum is computed by Fourier analysis and the high-frequency spectrum by our chirp search method. Included is a linear extrapolation of the low-frequency spectrum, to highlight a common spectral slope in the low- and high-frequency spectra, obtained independently here by two completely different methods.

We next consider a sample of 72 bright events in the BeppoSAX catalog (Figure 8). We select a subsample of 42 events with a pronounced autocorrelation in their 2 kHz light curves (“red,” Figure 9) for extracting an ensemble averaged Fourier–chirp spectrum.

The Swift catalog of long GRBs shows no correlation with redshift of the observed durations, $T_{90}$, over a broad range of redshifts with mean $z = 2.1$, shown in Figure 10. The spread in the observed durations $T_{90}$, therefore, is essentially intrinsic to the source.

We consider long GRBs to be produced by BHSs, rather than a PNS, based on van Putten et al. (2011a) and two hyper-energetic GRB supernovae with an output exceeding the maximal spin energy of the latter (van Putten 2012). In a BHS, $T_{90}$ can be identified with the lifetime of black hole spin, whereby $T_{90} \propto M$ for a black hole mass $M$ (van Putten & Ostriker 2001). The spectrum of turbulence and intermittencies in the surrounding
accretion disk or torus scales likewise with $M^{-1}$. If correlated to a collimating wind from the disk or torus, the spectra of the turbulent outflow are hereby normalized when considered as a function of frequency $(1+z)T_{90}/T_0$, where $T_0$ denotes the mean duration of the ensemble.

Figure 11 shows the average normalized spectrum, plotted as a function of normalized frequency in the comoving frame of reference, assuming a fiducial redshift, $z = 2$, similar to that in the Swift sample shown in Figure 8. The resulting spectral slope is in excellent agreement with existing studies on BeppoSAX light curves (Figure 9 in Dichiara et al. 2013a).

We point out that chirps with $\tau = 0.5$ s ($\tau = 2$ s) show considerably more (less) scatter in the ensemble average. Our choice of $\tau = 1$ appears to provide a compromise between scatter and frequency coverage in extending the slope of the turbulent spectrum. Scatter slightly increases with chirp templates with constant amplitude, rather than slowly varying as shown in the forward and reverse time slice S5 in Figure 1.

7. CONCLUSIONS

Through Fourier analysis of long GRBs, turbulent spectra in low frequency are found to continue smoothly to high frequencies, determined here through two relatively bright GRBs obtained in a broadband chirp search by matched filtering. Matched filtering theoretically obtains the maximal sensitivity of a detection, provided that the template bank is sufficiently dense and broad enough to capture the signal of interest. To capture turbulence, we employ chirps with frequencies varying slowly in time, following exponential decay or growth. Figure 7 shows that Poisson noise is hereby effectively circumvented, upon using a control that shares the secular evolution of variance with the amplitude of Poisson noise in the 2 kHz BeppoSAX light curves.

Figure 7 shows that extraction of high-frequency spectra is quite noisy due to the strong Poisson noise in the BeppoSAX light curves in light of the small number photon counts in each 0.5 ms bin. On account of this as well as our limited chirp parameter scan, e.g., using $\tau = 1$ only, there is no conclusive evidence for the presence or absence of pronounced chirps distinct from those arising from turbulence. Extensive searches for transient chirps of different durations await future investigation.

Our extension of the turbulent spectrum in the blended Fourier–chirp spectrum can serve as a new baseline in searches for high-frequency transient features. To this end, the smoothed averaged spectrum of Figure 11 may serve as a reference in searches for bumps at high frequency, e.g., around the redshifted frequency of 1 kHz. The detection of a bump would reveal the presence of a PNS with a misaligned axis of angular momentum and magnetic field, representative of a new pulsar’s birth. The same would be absent in the case of a rapidly rotating black hole, whose magnetic moment and angular momentum are perfectly aligned by Carter’s theorem (Carter 1968). Based on the present chirp search, including over 8.64 million templates, no such bump has been found.

Figures 7 and 11 demonstrate high-frequency analysis as a new probe of the physics of the gamma-ray emission mechanism, which includes a potentially powerful window to intermittencies in the GRB inner engine, even in light of exceedingly small photon counts. The ensemble of 42 bursts used in Figure 11 represents bright events with a pronounced autocorrelation (“red” events) with mean photon counts of 1.2569 per bin in the brightest channel, selected out of an initial sample of 72 bright events in the BeppoSAX catalog. The remaining 30 (“white” events) have mean photon counts of 0.5936 per bin in the brightest channel, that lack any perceptible autocorrelation. Future gamma-ray missions with larger photon yields promise to greatly facilitate high-frequency analysis by improving S/Ns and enlarging the sample of red events with average photon counts greater than one per bin.

Chirp searches can also be applied to the strain amplitude data from upcoming advanced gravitational wave detectors, LIGO–VIRGO and KAGRA, by changing control to, e.g., time randomized data. The proposed Fourier–chirp spectra can be extracted to search for gravitational wave signatures of possibly forced turbulence (van Putten 1999) in high density matter in the inner disk or torus around black holes, long lasting up to tens of seconds and possibly accompanied by pronounced transient chirps (van Putten et al. 2011b). Given the limited sensitivity range of these detectors, of interest are LGRBs and hyper-energetic core-collapse supernovae in the local universe. Core-collapse supernovae may be found in nearby galaxies such as M51 (hosting SN1994i, SN2005cs, and SN 2011dh) and possibly M82 (Muxlow et al. 2010) with event rates over one per decade in each.

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