QUIESCENT TIMES IN GAMMA-RAY BURSTS: HINTS OF A DORMANT INNER ENGINE

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Received 2006 September 28; accepted 2007 May 4

ABSTRACT

We perform a statistical analysis of the temporal structure of long gamma-ray bursts (GRBs). We consider a sample of bursts in which a long quiescent time is present. By comparing the prequiescent with the postquiescent emission we show that they display similar temporal structures, hardness ratios, and emitted powers, but, on average, the postquiescent emission is roughly twice as long as the prequiescent emission. We then analyze a sample of long and bright GRBs (long and faint GRBs are not included) and find that the average duration of the quiescent times is comparable to the average duration of the emission periods. This leads us to suggest an interpretation of quiescent times as due to dormancy periods of the inner engine. The interpretation of quiescent times as instead caused by stochastic modulations of a continuous wind is less plausible due to the larger energy requirements that it imposes on the inner engine. Interestingly, before and after a dormancy period the inner engine produces similar emissions.

Subject headings: dense matter — gamma rays: bursts

Online material: color figure

1. INTRODUCTION

The time structure of gamma-ray bursts (GRBs) is usually complex and often displays several short pulses separated by time intervals lasting from fractions of a second to several tens of seconds. The analysis of the light curves can provide hints on the activity of the inner engine, although the relation between the observed signal and the physics of the inner engine is not yet completely understood.

A previous statistical analysis (Nakar & Piran 2002b) showed that there are three timescales in the GRB light curves: the shortest one is the variability scale determining the pulses’ durations and the intervals between pulses; the largest one describes the total duration of the bursts; and finally, an intermediate timescale is associated with long periods within the bursts having no activity, the so-called quiescent times. The origin of these periods of quiescence is still unclear.

Here we show, through a statistical analysis, that if a quiescent time longer than a few tens of seconds is present in the light curve then the prequiescent and the postquiescent emissions (pre-QE and post-QE, respectively) have similar variability scales, but, on average, the post-QE is longer and only marginally softer than the pre-QE. The similarities between the first and the second emission periods strongly suggest that both emissions are produced by the same mechanism. Moreover, we show that the average durations of pre-QE and of post-QE, separately, are compatible with the theoretical durations predicted by various inner engine models.

2. DATA ANALYSIS

We have performed a statistical analysis of the time intervals $\Delta t$ between adjacent peaks using the peak-finding algorithm of Li & Fenimore (1996) and borrowing from Nakar & Piran (2002a) the definition of active periods separated by quiescent times (QTs). In Figure 1 we show an example of a burst where these quantities are illustrated. We have applied this analysis to all the light curves of the BATSE catalog.

In a first investigation we have merged all the bursts of the catalog into one sample from which we compute the cumulative probability $c(\Delta t)$ of finding time intervals $\Delta t$ which are not QTs; i.e., we compute the distribution of the time intervals within each active period. In Figure 2a, we show that $c(\Delta t)$ is well described by a lognormal distribution. In Figure 2b, the histogram of QTs is displayed together with a lognormal distribution. As already observed by previous authors (Nakar & Piran 2002b), there is an evident deviation of the data points from the lognormal distribution for time intervals longer than a few seconds, indicating an excess of long $\Delta t$. In Figure 2c we show a power-law fit of the tail of the QTs’ distribution, which displays very good agreement with the data, as already observed by Quilligan et al. (2002). The physical interpretation of this distribution is discussed below. Finally, in Figure 2d we show a correlation function, indicating the probability of finding at least two QTs longer than $\Delta T$ in the same GRB. As shown in the figure this probability rapidly decreases and essentially vanishes for $\Delta T > 40$ s.

We must make a technical remark. In our analysis we have considered two possible values for $\sigma$, the parameter used to discriminate signal from noise. A standard choice is $\sigma = (\text{background})^{1/2}$. Using that definition we can reproduce the results of Nakar & Piran (2002b) on the cumulative distribution of $\Delta t$. Instead, the results presented in our figures have been obtained using another definition: $\sigma = (\text{max})^{1/2}$, where “max” is the maximum number of counts in the light curve. The reason for this choice is that we want to study the main events of a GRB light curve (those having a large luminosity) and not the faint microstructures (e.g., precursors, which we would exclude from our sample). It is important to remark that using this larger value of $\sigma$ we can recover the main results of Nakar & Piran, but the distinction between (1) time intervals which are not QTs and (2) QTs is now even more clear on a statistical basis: the former are perfectly interpreted by a lognormal distribution, while long QTs are very well fitted by a power law, as discussed above.
Active periods begin (finding algorithm of Li & Fenimore (1996): indicating with extracted by taking as initial and final bins those with counts above 2 is first determined using a linear fit and then subtracted from the data. The signal is periods are defined as periods in which bins with counts exceeding 4 drops below 2 candidate peak and with 

\[ \frac{C_p}{C_0} \]

\[ \frac{N_{\text{var}}}{N_{\text{var}}} = 5 \] in our analysis. The true peaks are indicated by the black circles.

We can now define a subsample of the BATSE catalog composed of all the bursts having a QT longer than 40 s.\(^5\) In Figure 2a

\[ \chi^2 \] test provides a significance of 28% for Fig. 3a and of 34% for Fig. 3b that the two data sets are drawn from the same distribution function.\(^6\) Let us remind the reader that within the internal-external shocks model (Piran 2005; Zhang & Meszaros 2004), external shocks produce emissions lacking the short timescale variability produced by internal shocks (Sari & Piran 1997). The result of Figure 3 rules out a scenario in which post-QE is dominated by external shocks and pre-QE by internal shocks. This in turn excludes the possibility of associating the QTs with the time needed by the jet to reach and interact with the interstellar medium. Clearly enough, the statistical analysis we present does not rule out the existence of specific GRBs we also show the distribution of \( \Delta t \) within the subsample. The distributions of the full BATSE catalog and of the subsample are essentially equal. This indicates that the subsample is not composed of bursts having an anomalously large redshift because in that case all timescales within the subsample would be homogeneously dilated.

In our analysis we concentrate on the subsample. From the result of Figure 2d, the bursts of the subsample contain only one long QT, and it is therefore possible to divide each burst into a pre-QE and a post-QE of which we compare the temporal and spectral structure.

In Figure 3 we display the cumulative distributions \( c_1(\Delta t) \) and \( c_2(\Delta t) \) within each of the two emission periods. In Fig. 3a we display only \( \Delta t \) which are not QTs (same as in Fig. 2a), while in Fig. 3b QTs are included. In both cases the two distributions are very similar. The \( \chi^2 \) test provides a significance of 28% for Fig. 3a and of 34% for Fig. 3b that the two data sets are drawn from the same distribution function.\(^6\)

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**Fig. 1.—**Light curve of a typical GRB: time profile of BATSE burst 5486 in the energy range 55 keV < \( E < 320 \) keV. For each light curve, the background is first determined using a linear fit and then subtracted from the data. The signal is extracted by taking as initial and final bins those with counts above 2. The active periods are defined as periods in which bins with counts exceeding 4 drops below 2. Within each active period we search for peaks using the peak-finding algorithm of Li & Fenimore (1996): indicating with \( C_i \) the counts of a candidate peak and with \( C_l \) and \( C_r \) the counts in the bins to the left and to the right of the candidate, a “true” peak must satisfy the relation \( C_l - C_{i-1} \geq N_{\text{var}} C_i^{1/2} \), where \( N_{\text{var}} = 5 \) in our analysis. The true peaks are indicated by the black circles.

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**Fig. 2.—**Analysis of time intervals between peaks. (a) Cumulative distribution of time intervals \( \Delta t \) that are not QTs (black triangles) compared with its best-fit lognormal distribution (solid line). The data come from the full BATSE sample after eliminating bursts displaying data gaps. The gray squares correspond to the cumulative distribution of \( \Delta t \) taken from the subsample of bursts containing a QT longer than 40 s (see text). (b) Histogram of the QTs and its lognormal fit (dashed line). (c) Histogram of QTs and power-law fit of its tail (dashed line). The fit is based only on QTs longer than 40 s. (d) Frequency of bursts containing at least two QTs longer than \( \Delta T \). Hereafter all temporal quantities are expressed in seconds. [See the electronic edition of the Journal for a color version of this figure.]
in which the second episode is indeed associated with external shocks. For instance, GRB 960530 and GRB 980125 are examples of bursts in which post-QE has a smoother morphology and a softer spectral evolution than pre-QE (Hakkila & Giblin 2004).

We now perform a statistical analysis of the durations $D_1$ and $D_2$ of the two emission periods. As shown in Figure 4a, the two data sets are well fitted by two lognormal distributions (the Kolmogorov-Smirnov test provides a significance of $\approx 90\%$). The two distributions have different mean values ($D_{1\text{ave}} \approx 21$ s, $D_{2\text{ave}} \approx 41$ s) and almost identical standard deviations ($\sigma_1 = 36$ s, $\sigma_2 = 33$ s). We now address the following question: is the longer duration of post-QE a manifestation of a progressive increase in the active periods’ durations during the burst? To answer this question we have repeated the previous analysis by dividing pre-QE and post-QE each in two parts, using the longest QT within each emission as a divider. The distributions of the duration of all parts are shown in Figure 4b. The durations of the two parts within each emission period share the same distribution (the $\chi^2$ test provides significances larger than 50% in both cases) but, in agreement with the previous findings, the average durations of the two parts of post-QE are longer than the two parts of pre-QE. Therefore, the longer duration of post-QE cannot be attributed to a continuous modification of the emission but is a specific feature of the second part of the GRB.

It is interesting to study the dependence of our results on the QTs’ minimal duration, which characterizes the sample. Our previous sample was defined by considering only GRBs containing at least one QT longer that 40 s. We now analyze another sample composed of bursts in which only one QT longer than 10 s is present (bursts having more than one QT longer than 10 s are excluded from this new sample). This sample contains 80 bursts, and the results on the durations of pre-QE and post-QE are shown in Figure 5. Interestingly, in this new sample the average duration of pre-QE and post-QE, $D_{1\text{ave}} \approx 13$ s and $D_{2\text{ave}} \approx 12$ s, are the essentially the same. If instead we extract from this new sample a subsample containing bursts having one QT longer than 40 s we obtain qualitatively the same result of Figure 4 with post-QE on average lasting longer than pre-QE ($D_{1\text{ave}} \approx 8$ s, $D_{2\text{ave}} \approx 15$ s). It seems therefore that when a long QT is present a new timescale appears, which allows for different average durations for pre-QE and post-QE.

To estimate the emitted energy during pre-QE and post-QE we have analyzed the hardness ratios, defined as the ratios between the photon counts in two BATSE channels (the second and the third in our case). The average hardness of post-QE turns out to be only marginally smaller ($\approx 20\%$) than the average hardness of pre-QE. Since, as shown above, the average durations of pre-QE and of post-QE are described by the relation $D_{2\text{ave}} \approx 2D_{1\text{ave}}$, the total energy emitted during post-QE is also about a factor of 2 larger than that emitted during pre-QE. This is also evident from the result of Figure 6, where the distributions of the powers emitted during pre-QE and post-QE are displayed, showing that the average powers of the two emissions are essentially the same.

It is interesting to compare our result on the durations with the correlation between the duration of QT and of post-QE found by Ramirez-Ruiz & Merloni (2001). By computing the average duration of QT and of post-QE in our subsample (which is not the same as that analyzed by those authors) we obtain the following result: post-QE $\approx 41$ s and QT $\approx 80$ s. Therefore, in our sample and using the Nakar & Piran algorithm we cannot confirm the...
correlation found by Ramirez-Ruiz & Merloni (2001). Indeed, if that correlation were present the average durations of QT and of post-QE would be comparable, since the correlation law suggested by those authors is a straight line with a slope of the order of 1. Actually, in our sample the statistical correlation between the durations of QT and of post-QE is very small, $r \approx 0.13$. Similar considerations also hold for the sample with one QT longer than 10 s: the average duration of the QT, 36 s, is longer than the average duration of post-QE (12 s as indicated above).

3. DISCUSSION

3.1. Dormant Engine Scenario versus Wind Modulation Model

As observed by Ramirez-Ruiz et al. (2001), within the internal shocks model it is possible to explain the QTs either as a turnover of the inner engine (IE) or as a modulation of a continuous relativistic wind emitted by the IE (wind modulation model [WMM]). Both hypotheses are consistent with the result of Figure 3.

The main difference between the WMM and the dormant engine scenario is that in the WMM the inner engine has to provide a constant power during the whole duration of the burst. In our subsample, we have several bursts whose total duration (including the QT) approaches 300 s. These durations have to be corrected by taking into account the average redshift of the BATSE catalog, $z_{\text{ave}} \approx 2$ (Piran 1999), but even after this re-normalization, durations of 100 s or more are not too rare.

Let us explicitly discuss an example of a bright and long burst, GRB 7301 of the BATSE catalog (see Fig. 8). In that burst a large QT is present lasting $\sim 100$ s followed by a post-QE of $\sim 70$ s and with a pre-QE of $\sim 40$ s. Within the WMM, this would imply an emission of energy during the QT comparable to the sum of the energies emitted in the pre-QE and post-QE.

Obviously, the previous remark would be meaningless if the example we are providing were not typical of the time structure of long GRBs. Instead, by checking all the GRBs of the “current catalog” of BATSE having $T_{90} > 100$ s and peak photon flux in the 256 ms channel $>5$ photons s$^{-1}$ cm$^{-2}$, we can come to the following conclusion: all the light curves of this subsample can be interpreted within the dormant engine model by rescaling the total duration by a factor of $1/(z + 1) = 1/3$ and by splitting the burst into two emission episodes, separated by a dormancy period corresponding to a chosen QT. The average durations are $\sim 53$ s for the pre-QE, $\sim 67$ s for the post-QE, and $\sim 57$ s for the QT. In Figures 7 and 8 we show all the GRBs of this sample and we indicate the longest QT. Clearly enough, there are bursts in which it is not unambiguous to decide which QT should be interpreted as the dormancy period, because more than one QT is present. In the figures we indicate the only two cases (out of 15 GRBs analyzed) in which we suggest a dormancy period that is different from the longest QT. In both of those cases the suggested dormancy period corresponds to the second longest QT present in the burst. This rather small ambiguity can easily be explained by noticing that a small fraction of long QTs can be generated by stochastic fluctuations (described by the tail of the lognormal distribution) and not by a dormancy period. As discussed above, the association of a QT with a dormancy period is totally unambiguous for bursts in which QT longer than $\sim 40$ s is present. In conclusion, our analysis of the long and bright GRBs indicates that within the WMM the inner engine should on average emit the same amount of energy during the QT as emitted during pre-QE or post-QE, because the corresponding average durations are comparable. Instead, in the dormant inner engine scenario the total energy budget is smaller, making this scenario more plausible.

Let us now briefly discuss long and faint GRBs, which are not included in our analysis. For instance, the last light curve presented in Figure 8 (GRB 6454) corresponds to a faint burst which does not belong to the subsample discussed in this section (GRBs of high luminosity). It is interesting to note that in this burst the pre-QE and post-QE are so long that after dividing their durations by a redshift factor of 3, the energy requirement would be large even assuming a dormant engine scenario. In any case, the faintness of this burst is probably due to the extreme distance of the source, and a larger redshift correction should then be applied. Similar considerations are also valid for other superlong bursts presented in Tikhomirova...
Very recently Swift detected a burst, XRF 060218 (Liang et al. 2006), in which a prompt emission exists in the 0.3–150 keV band with a duration of the order of 2000 s. This burst, related to long and faint GRBs, is extremely near, since it has a low redshift, and therefore its long duration cannot be attributed to time dilation effects. Due to its very low luminosity, roughly 5 orders of magnitude lower than that of typical GRBs, this burst belongs presumably to a subclass of very faint GRBs (which we are not considering in our analysis) for which, up to now, there is not a unique interpretation. A possible explanation of these very long and faint emissions can be provided within magnetar models (Usov 1994), as suggested by Toma et al. (2007) in the specific

![Image of long and bright bursts: GRBs of the “current catalog” of BATSE, having $T_{90} > 100$ s and peak photon flux in the 256 ms channel > 5 photons s$^{-1}$ cm$^{-2}$. The dashed lines indicate the fit of the background and the 2 and 5 $\sigma$ levels used to define the active periods. Dark gray circles and light gray circles mark the initial and the final points of each active period, respectively. Black arrows indicate the longest QT. Gray arrows indicate the suggested dormancy period when it does not coincide with the longest QT (two cases only).](image-url)

7 When using the algorithm of Nakar & Piran (2002a), some faint components of the light curves are not considered parts of the signal because their count number is smaller than 4–5 $\sigma$ and therefore cannot be considered active periods. This reflects the estimated duration of the bursts. In particular there are bursts whose $T_{90}$ durations exceed 100 s, while their durations based on the active periods are shorter, and therefore these bursts are excluded from our sample. This selection criterion clearly depends on the value of $\sigma$. We have performed our analysis using for $\sigma$ both choices described in §2. In Figs. 6 and 7 we show the results obtained using $\sigma = (\text{background})^{1/2}$, which is the most conservative choice (in this case the excluded GRBs are 1157, 1886, 3458, 3930, and 7527). If we instead used the larger value for $\sigma$, more components of the light curves would be excluded, and our conclusions would be even stronger.

& Stern (2005; GRB 6454 is one of the bursts discussed in that paper).
case of XRF 060218. An interpretation of the long and relatively weak tail present in several GRBs has been proposed in Drago et al. (2007) within the quark deconfinement model.

As we return to the discussion of our results, we note another problem with the WMM: its prediction that the emitted power during post-QE is larger than during pre-QE. This prediction is based again on the existence of a continuous emission of shells also during the QT (Ramirez-Ruiz et al. 2001). The analysis displayed in Figure 6 does not support this prediction.

It is also worth recalling that, on average, post-QE lasts roughly twice as long as pre-QE. While it is probably possible to fix the parameters of the WMM in order to satisfy that constraint, no reason is provided within the WMM model to explain that feature in terms of the activity of the inner engine or of the dynamics of the jet formation. On the contrary, models of a dormant inner engine can associate the durations of the emission periods with the durations of physical phenomena taking place within the IE. This point is discussed in §§ 3.2.

We conclude that long QTs most probably correspond to periods of inactivity of the IE. On the other hand, it is possible that the WMM is responsible for short QTs occurring within the two emission periods, as suggested by Figure 4b, where it is shown that the durations of the two parts of a single emission period have the same distribution. This possibility is also supported by the result of Figure 5 indicating that a relatively short QT does not separate the burst into a pre-QE and a post-QE having different

Fig. 8.—Same as Fig. 7, but here the suggested dormancy period always coincides with the longest QT. We also display a faint burst, 6454 (which does not satisfy the limit on the peak photon flux), whose very long duration could be due to a large redshift.
average durations. Finally, while our subsample is composed of GRBs having QTs longer than 40 s, it is surely possible that in many cases the IE switches off for a much shorter time. Unfortunately, in those cases it is not trivial to distinguish between QTs generated by the switch-off and QTs generated by the WMM, as it also results from the previous discussion of Figures 7 and 8 concerning the cases in which the suggested dormancy period differs from the longest quiescent time.

3.2. Models for a Dormant Inner Engine

Let us now discuss how to generate dormancy periods using various models of the IE. Within the most popular model, the collapsar model (MacFadyen & Woosley 1999), there are two possible scenarios: a temporary interruption of the jet produced by Kelvin-Helmholtz instabilities (Woosley et al. 2003) or the fragmentation of the collapsing stellar core before its merging with the black hole (King et al. 2005). In both scenarios it is possible to produce long QTs. For instance, in the scenario proposed by King et al. (2005) the durations of the emission periods are related to the durations of the accretion disks generated by each fragment. Our result on the durations of pre-QE and of post-QE can be explained if, for example, the average mass of the second fragment is larger than that of the first fragment. A discussion of the mass distribution of the fragments can be found in Perna et al. (2006).

Another model for the IE is based on the conversion of a metastable hadronic star into a star containing quark matter (Cheng & Dai 1996; Bombaci & Datta 2000; Ouyed & Sannino 2002; Berezhiani et al. 2003; Paczynski & Haensel 2005). In the past few years the possibility of forming a diquark condensate at the center of a compact star has been widely discussed in the literature (Rajagopal & Wilczek 2001). The formation of a color superconducting quark core can increase the energy released by a significant amount (Drago et al. 2004). It has also been shown that the conversion from normal to gapped quark matter goes through a first-order transition (Ruster et al. 2006). It is therefore tempting to associate post-QE with the transition from hadronic to normal quark matter and post-QE with the formation of the superconducting phase (Drago et al. 2006). In this scenario the two-dimensional scales regulating the durations of pre-QE and post-QE are the energies released in the two transitions. Finally, let us remark that the power law fitting the long QTs’ distribution can originate from a superposition of exponential distributions with different decay times (Wheatland 2000). In the quark deconfinement model, the different decay times are associated with slightly different masses of the metastable compact star. If the interpretation based on the quark deconfinement model is correct then the GRB data analysis provides very stringent bounds on the physics of high-density matter.

A possible signature of the models in which the IE goes dormant would be the detection of external shock emissions at the end of both pre-QE and post-QE, indicating that the two emissions are physically disconnected.

4. CONCLUSIONS

In this paper we study the problem of quiescent times in long GRBs, borrowing the technique developed by Nakar & Piran. The main results obtained in our analysis are as follows:

1. The cumulative distribution of time intervals between peaks within the same active period is well fitted by a lognormal distribution, while long quiescent times are well fitted by a power-law distribution. This strengthens the conclusion of Nakar & Piran (2002b) that long quiescent times and shorter quiescent time intervals have different origins.

2. The two components of the emission, that preceding and that following the quiescent time, are statistically similar from the viewpoint of their temporal microstructure, their hardness ratio, and their emitted power. These results suggest a unique mechanism at the origin of both the prequiescent and the postquiescent emission. Interestingly, the latter emission lasts on average twice as long as the first, which provides an important constraint on the inner engine models.

3. The existence of very long quiescent times favors the dormant inner engine scenario over wind modulation models because of the larger energy requirements that the latter impose on the inner engine.

Finally, the observations collected by Swift unambiguously indicate the existence of prolonged activity of the inner engine in a relevant fraction of GRBs. In most cases the detected signal gives rise to an X-ray plateau, during which episodic X-ray flares can also be present. This late emission is typically softer than that discussed in our paper, and therefore these signals do not belong to the same class of phenomena as that we have here labeled as post-QE. It is still important to remark that in the case of XRF 060218, prolonged activity of the inner engine has been observed in the 0.3–150 keV band. However, this burst has an extremely low luminosity and is therefore rather different from the GRBs here analyzed. It is also interesting to remark that the new temporal features of GRBs discovered by Swift can find a natural interpretation in models in which the GRB is powered by a compact star, as proposed, e.g., in Drago et al. (2007).

It is a pleasure to thank Filippo Frontera, Enrico Montanari, and Rosalba Perna for many useful suggestions and for help in the data analysis.

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