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Testing the gamma-ray burst variability/peak luminosity correlation on a *Swift* homogeneous sample

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ABSTRACT

We test the gamma-ray burst (GRB) correlation between temporal variability and peak luminosity of the γ-ray profile on a homogeneous sample of 36 *Swift*/Burst Alert Telescope (BAT) GRBs with firm redshift determination. This is the first time that this correlation can be tested on a homogeneous data sample. The correlation is confirmed, as long as the six GRBs with low luminosity ($<5 \times 10^{50}$ erg s^{-1} in the rest-frame 100–1000 keV energy band) are ignored. We confirm that the considerable scatter of the correlation already known is not due to the combination of data from different instruments with different energy bands, but it is intrinsic to the correlation itself. Thanks to the unprecedented sensitivity of *Swift*/BAT, the variability/peak luminosity correlation is tested on low-luminosity GRBs. Our results show that these GRBs are definite outliers.

Key words: methods: data analysis – gamma-rays: bursts.

1 INTRODUCTION

A number of correlations between intrinsic properties of gamma-ray bursts (GRBs) have been discovered since it has become possible to measure their distances. In particular, correlations between properties of the γ-ray prompt emission as well as of the afterglow at different wavelengths have provided an increasing number of clues to identify the mechanisms and, ultimately, the nature of the GRB progenitors. In addition, some of these correlations have been tentatively used as luminosity estimators, with several implications on their possible usage to constrain the cosmology of the Universe (Ghirlanda et al. 2004; Firmani et al. 2005; Liang & Zhang 2005).

The increasing number of GRBs with spectroscopic redshift allows to test and better calibrate them. Recently, a crucial contribution has been supplied by the *Swift* satellite (Gehrels et al. 2004), whose average rate of 100 GRBs per year since launch (2004 November) made it possible to measure the distances of almost one-third of its sample, thus duplicating the overall number of GRBs with known redshift since 1997.

The sample of GRBs detected with the *Swift* Burst Alert Telescope (BAT; Barthelmy et al. 2005) is particularly suitable to test the correlations between intrinsic properties, with the unprecedented benefit of a homogeneous data set, apart from those requiring the peak energy measurement, made difficult by the limited energy band (15–350 keV).

Hereafter we focus on a long-standing correlation between the variability and peak luminosity of the γ-ray prompt emission (Fenimore & Ramirez-Ruiz 2000; Reichart et al. 2001). In particular, Reichart et al. (2001, hereafter R01) provided a definition of variability (hereafter denoted as $V_{\rm R}$) that turned out to correlate with the isotropic-equivalent rest-frame 100–1000 keV peak luminosity (hereafter L) for a sample of 11 GRBs with known redshift available at the time, using data from the *CGRO*/BATSE experiment (Paciesas et al. 1999).

R01 modelled the variability/peak luminosity correlation (hereafter V/L correlation) with a power law ($L \propto V_{\rm R}^m$) with $m = 3.3^{+1.1}_{-0.9}$) affected by *extrinsic* or *sample* scatter, described by $\sigma_{\log V_{\rm R}} = 0.18$. Recently, Guidorzi et al. (2005, hereafter GFM05) and Guidorzi (2005, hereafter G05) tested the V/L correlation on an extended sample of 32 GRBs with known redshift (GFM05) and on 551 BATSE GRBs, respectively. For the latters, a pseudo-redshift was derived assuming the lag–luminosity correlation (Norris, Marani & Bonnell 2000; Band, Norris & Bonnell 2004).

Both works confirmed the correlation, but with a lower slope than that derived by R01: $m = 1.3^{+0.8}_{-0.4}$ (GFM05) and $m = 0.85 \pm 0.02$ (G05). However, in either case it was pointed out that the scatter around these power laws made the description of a simple power

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law unsatisfactory. Reichart & Nysewander (2005) applied the same method as R01 to the very results obtained by GFM05, obtaining $m = 3.4^{+0.9}_{-0.6}$ and $\sigma_{\log V_{\rm R}} = 0.20 \pm 0.04$, perfectly in agreement with the original values of R01. They ascribed the disagreement to the fact that GFM05 did not deal with the sample variance properly.

More recently, Guidorzi et al. (2006) applied the D'Agostini (2005) method, accounting for the sample variance, to the data sets of both GFM05 and G05. They obtained shallower slopes than those by R01 and Reichart & Nysewander (2005) and larger scatters: in particular, for the sample of 32 GRBs with firm redshift drawn from GFM05 they obtained $m = 1.7 \pm 0.4$, $\sigma_{\log V_{\rm R}} \sim 0.34$, while for the sample of 551 GRBs with pseudo-redshifts of G05 it resulted $m = 0.88^{+0.12}_{-0.13}$, $\sigma_{\log V_{\rm R}} \sim 0.74$.

For more details on the debate concerning the methods to be used, we refer the reader to the original papers by Reichart & Nysewander (2005) and Guidorzi et al. (2006).

Li & Paczyński (2006, hereafter LP06) have recently provided a slightly modified definition of variability, hereafter denoted as $V_{\rm LP}$, which they found to correlate more tightly with L than $V_{\rm R}$, without any extrinsic scatter in addition to the uncertainties affecting the single values of the single GRBs. $V_{\rm LP}$ differs from $V_{\rm R}$ mainly in the choice of the smoothing filter determining the reference light curve with respect to which the variance is evaluated. LP06 chose the Savitzky–Golay filter instead of a simple boxcar used by R01. As a result, $V_{\rm LP}$ selects only the high frequencies, whereas only in the $V_{\rm R}$ calculation the lower frequency variance can give a contribution.

The variability of the γ-ray prompt emission light curves is supposed to be produced above the photospheric radius of the fireball, above which radiation becomes optically thin. The interpretations proposed of the V/L correlation mainly invoke the presence of a jet, whose angle θ, that is, either the opening angle or the viewing angle (e.g. see Ioka & Nakamura 2001) for some jet patterns, is strongly connected with the observed peak luminosity L as well as with the Lorentz factor Γ of the expanding shell(s). The result would be a strong dependence of both $L(\theta)$ and $\Gamma(\theta)$ on θ. For instance, Kobayashi, Ryde & MacFadyen (2002) reproduced the observed correlation through numerical simulations, assuming $\Gamma \propto \theta^{-q}$ and a log-uniform distribution in the time delay between next shells, from 1 ms to 1 s. A value of $q = 2$ seems to account well for the results by Guidorzi et al. (2006) as well as the anticorrelation between break time and peak luminosity (Salmonson & Galama 2002). Similar results have been found by Mészáros et al. (2002) and Ramirez-Ruiz & Lloyd-Ronning (2002) under slightly different assumptions.

The new piece of information from this analysis is given by the presence of low-luminosity high-variability GRBs.

In this paper, we test the V/L correlation on a homogeneous sample of 41 GRBs detected with *Swift*/BAT using fully homogeneous data. We considered two different definitions of variability: that by R01 and that by LP06. In Section 2 we describe the data sample and the selections we made. Sections 3 and 4 report how peak luminosity and variability have been calculated. Results are reported in Section 5 and discussed in Section 6.

2 THE GRB SAMPLE

The sample includes 51 long ($T_{90} > 2$ s) GRBs with spectroscopic redshift detected by *Swift*/BAT (Gehrels et al. 2004) between the launch (2004 November 20) and 2006 October. Out of this sample we selected only those bursts whose γ-ray profile is entirely covered by BAT during the burst mode (Barthelmy et al. 2005). No further selection was made on the sample, in order to avoid any arbitrary bias in the results. This requirement resulted in the rejection of 10 GRBs. In fact, in these cases the observation of *Swift*/BAT switched from burst mode to the survey mode before the end of the prompt emission. The light curve results with a truncated profile. This is the case of GRB 050318, whose light curve stops about 32 s after the trigger, as well as of GRB 050820A, GRB 050904 and GRB 060218. For GRB 060124 only the precursor was recorded in event mode, while the main event was observed in survey mode. For GRB 060906 the light curve is incomplete at the beginning, because the trigger probably missed the true onset of the burst. No burst mode event file is available for GRB 060505, as BAT observed it only in survey mode. We chose not to make use of the background-subtracted light curves acquired during the survey mode to keep the sample as homogeneous as possible. GRB 050408 was detected by XRT and UVOT, but not by BAT, although the light curve of its prompt emission is available from other instruments (*HETE-2*/*FREGATE*; Atteia et al. 2003). Nevertheless, we did not consider it in this work because we focused on BAT data for the reasons reported above. In the case of GRB 050802 and GRB 051227A the problem is in the redshift determination. For the former only a tentative redshift exists (Cummings et al. 2005), which is at odds with the interpretation of the *Swift*/UVOT results (McGowan et al. 2005). For GRB 051227A there is a redshift determination of the putative host galaxy (Foley et al. 2005a), but it is still unclear if this is the real host galaxy.

After this selection the sample has shrunk to 41 long GRBs, entirely covered by BAT and processed through the same procedure. Therefore, this work investigates the V/L relation based on a completely homogeneous sample.

The BAT event files were retrieved from the *Swift* public archive[1] and analysed through the standard BAT analysis software distributed within FTOOLS v6.1. For each GRB we extracted mask-tagged light curves for a number of different binning times in the total nominal energy band (15–350 keV),[2] through the tool BATMASKWTEVT adopting the ground-refined coordinates provided by the BAT team for each burst. These curves are therefore already background subtracted according to the coded-mask technique (Barthelmy et al. 2005, and references therein). For each burst the BAT detector quality map was obtained by processing the next earlier enable/disable map of the detectors, telling which detectors were disabled in flight because too noisy. We also applied the energy calibration to the event file making use of the closest-in-time gain/offset file through the tool BATECONVERT, as suggested by the BAT team.[3] Finally, these light curves are expressed as count rates with uncertainties: the rates are background-subtracted counts per second per fully illuminated detector for an equivalent on-axis source, as the default corrections are applied: NDETS, PCODE, MASKWT, FLATFIELD.

We also studied the behaviour of the background fluctuations in burstless regions of the light curves and we found that the mask-tagged rates, r_i, fluctuate compatibly with a white noise with σ_{r_i} (r_i and σ_{r_i} are the rate and its uncertainty of the ith bin, respectively; see Appendix A). We concluded that an upper limit of ∼2–4 per cent (4–6 per cent) at 90 per cent (99 per cent) confidence level can be derived in the presence of a possible extra variance (of instrumental origin, for instance) in addition to that due to the Poisson counting

[1] http://swift.gsfc.nasa.gov/docs/swift/archive/

[2] The effective band is 15–150 keV, because photons with energy above 150 keV become transparent to the coded mask and are treated as background by the mask-weighting technique (e.g. Sakamoto et al. 2006).

[3] http://swift.gsfc.nasa.gov/docs/swift/analysis/threads

statistics, implicitly assumed during the light-curve extraction with the tool BATBINEVT.

We found that it is not correct to perform the same analysis on BAT light curves with raw counts (i.e. not masked). In fact, we found that the GRB profile itself can be dramatically contaminated by other sources and by background variations, with time, due to the slewing of the spacecraft during the prompt emission, for most GRBs. Furthermore, we found that BAT light curves with raw counts are severely affected by extra variance, which is comparable with the Poisson variance due to the counting statistics, in agreement with previous results (LP06). Therefore, we conclude that the BAT light curves of most GRBs with raw counts, not masked, are not suitable for temporal variability studies.

3 PEAK LUMINOSITY

For each GRB we extracted the mask-tagged light curve with a binning time of 50 ms in the 15–350 keV energy band. We determined the 1-s time interval with the highest total counts and assumed this as the time interval corresponding to the 1-s peak count rate.

We extracted the mask-weighted spectrum in this time interval using the tool BATBINEVT. We applied all the corrections required: we updated it through BATUPDATEPHAKW and generated the detector response matrix using BATDRMGEN. Then we used BATPHASYSERR in order to account for the BAT systematics as a function of energy. Finally, we grouped the energy channels of the spectrum by imposing a 5σ (or 3σ when the signal-to-noise ratio was too low) threshold on each grouped channel. We fitted the resulting photon spectrum, $\Phi(E)$ (ph cm^{-2} s^{-1} keV^{-1}), with a power law with pegged normalization (pegpwrlw model under XSPEC v.12), except for GRB 050525A and GRB 060927 where a cut-off power law was used, in the rest-frame energy band 100–1000 keV. The choice of the energy band is connected with the original definition by R01 (see their equation 9) also used by GFM05 (their equation 7).

Therefore the GRBs rest-frame 100–1000 keV isotropic-equivalent peak luminosities were computed using

$$L = 4\pi D_{\rm L}^2(z) \int_{100/(1+z)}^{1000/(1+z)} E\,\Phi(E)\,{\rm d}E, \qquad (1)$$

where $D_{\rm L}(z)$ is the luminosity distance at redshift z, E is energy expressed in keV. Finally, we derived the uncertainty on the peak luminosity by propagating that of the measured flux.

Concerning the six BAT GRBs shared with the sample of GFM05, we compared the two sets of peak luminosities: these GRBs are 050315, 050319, 050401, 050505, 050525A and 050603. They are consistent with those of GFM05, apart from two cases. For 050401 our L_{50} measure, where $L_{50} = L/(10^{50}$ erg s$^{-1})$, is 1405 ± 165, while GFM05 reported 740 ± 100. For 050603, we obtained $L_{50} = 2706 \pm 1470$ to be compared with GFM05's 1200 ± 300. The reason in either case resides in a slightly different choice of the 1-s time interval around the peak. GFM05 determined this from the 40–350 keV light curve to match the 40–700 keV of the *BeppoSAX*/GRBM, while we used the 15–350 keV. The choices of the 1-s time interval turned out to differ by 1–2 s in either case. This, combined with the fact that both of these GRBs exhibit a sharp peak, turned into the discrepancies provided above. We note that in both cases they still lie in the $V_{\rm R}$–L region with high $V_{\rm R}$ and high L, consistently with the *V/L* correlation.

4 VARIABILITY

4.1 R01 definition

The main difference between our data set and those used by R01 and GFM05 is that our light curves are expressed in background-subtracted rates and not in counts. This fact is due to the way BAT, which is a coded mask, has been conceived. Hereafter we assumed a Poissonian variance for the statistical fluctuations of the light curves, as we proved in Appendix A. The formula we used to compute the variability, according to the R01 definition, is basically the same as those of R01 and GFM05, with no extra-Poissonian noise term, given that our rates are already background subtracted.

$$V_{\rm R} = \frac{\sum_{i=1}^{N}\left[\left(\sum_{j=1}^{N} a_{ij} r_j\right)^2 - \sum_{j=1}^{N} a_{ij}^2\,\sigma_{r_j}^2\right]}{\sum_{i=1}^{N}\left[\left(\sum_{j=1}^{N} b_{ij} r_j\right)^2 - \sum_{j=1}^{N} b_{ij}^2\,\sigma_{r_j}^2\right]}, \qquad (2)$$

where a_{ij} and b_{ij} are the same coefficients as those introduced by R01 in their equations (6)–(7). The differences between our formula, equation (7) of R01 and equation (4) of GFM05, are the replacement of the counts C_j with the rates r_j in the first terms of both numerator and denominator, where the original C_j represented the GRB signal, and the replacement of the counts C_j with the statistical noise variances $\sigma_{r_j}^2$ affecting the rates r_j in the terms to be subtracted, where the original counts C_j represented the noise. The sum, $j = 1, \ldots, N$, runs over the N bins encompassing the GRB time profile. The background term B_j in the original formulae of R01 has been set to zero, as it has already been removed during the extraction of the light curves.

For each GRB we estimated the smoothing time-scale $T_f(f = 0.45)$, defined by R01 as the shortest cumulative time interval during which a fraction f of the total counts above background has been collected. For each GRB we calculated T_f and the corresponding variability $V_{\rm R}$ as a function of the binning time. We chose the values obtained with the binning time Δt that fulfilled the requirements reported by GFM05 concerning the ratio $\Delta t/T_f$. On one side, when this ratio is too small, the light curve is dominated by statistical fluctuations, while, on the other side, when the binning is too coarse the variability is underestimated. A detailed description of these criteria is provided by GFM05.

4.2 LP06 definition

Concerning the definition of variability given by LP06, hereafter denoted by $V_{\rm LP}$, we point out a number of different choices with respect to the their analysis. First, we estimated $V_{\rm LP}$ from the background-subtracted mask-tagged light curves, while LP06 used the raw-count light curves of the seven *Swift*/BAT GRBs of their sample (Li, private communication). We assumed no extra-Poissonian variance to be subtracted, unlike LP06. We adapted equations (1)–(3) of LP06 accordingly and obtained the following:

$$V_{\rm LP} = \frac{\sum_{i=1}^{N}\left[W\,(r_i - y_i)^2 - \sigma_{r_i}^2\right]}{(N-1)\,r_{\rm max}^2}, \qquad (3)$$

where y_i is the value for the ith bin of the reference light curve obtained with the Savitzky–Golay filter with a smoothing window of $T_f(f = 0.45)$. W is the same weight as that used by LP06 and accounts for the fact that the set of y_i is not completely statistically independent from r_i. As for the determination of the peak count rate, $r_{\rm max}$, we searched the light curve of the same GRB a number of times, each time increasing the binning time, until we found the peak 5σ higher than the contiguous bins. This turned out to be very accurate, particularly for weak GRBs. In order to comply with the procedure of LP06, N corresponds to the total number of bins encompassing the time interval which defines the T_{90}, that is, from 5 to 95 per cent of the total fluence. The values of T_{90} have been calculated using the FTOOL BATTBLOCKS. Values of $V_{\rm LP}$ have been derived from the 64-ms light curves.

5 RESULTS

Table 1 reports the results of $V_{\rm R}$, $V_{\rm LP}$, L and $T_{f=0.45}$ obtained for the sample of 41 GRBs.

5.1 R01 definition

Significant values of $V_{\rm R}$ have been obtained for 36 GRBs shown in Fig. 1 (circles). In the remaining five cases this was not possible for different reasons. For GRB 050814 and GRB 050824 we could not find any binning matching the requirements mentioned above. While for GRB 050126, GRB 050908 and GRB 060512 $V_{\rm R}$ turned out to be consistent with zero within uncertainties. Fig. 1 also shows the sample of 26 GRBs of GFM05 (squares): the underluminous GRB 980425, which belongs to the GFM05 sample, is not shown because of scale compression reasons; moreover, its uncertainty on $V_{\rm R}$ is relatively large.

We do not show the values GFM05 estimated for six *Swift*/BAT bursts in common with our sample. Except for the case of GRB 050319, our values of $V_{\rm R}$ for the other five GRBs are broadly consistent with those of GFM05, some differences being due to a different energy band choice (see above). In general, we note that our T_f are systematically somewhat higher than those of GFM05: this is so because we included low-energy bands, in which GRBs are known to last longer. In addition, we know that in some cases $V_{\rm R}$ has a strong dependence on the energy band (GFM05), although the definition of $V_{\rm R}$ by R01 was originally thought to account for the narrowing of pulses at higher energies (Fenimore et al. 1995; Norris et al. 1996). In the case of GRB 050319 we measured $V_{\rm R} = 0.285 \pm 0.044$, while GFM05 obtained $V_{\rm R} = 0.06 \pm 0.03$. The inconsistency is due to the fact that the original event file, available at the time and used by GFM05 to extract the light curve, was missing the first sequence of impulses well before the trigger time. Therefore, we consider the value reported in this paper as the correct one.

We tested the existence of the *V*/*L* correlation over a number of different GRB data sets. Our sample of 36 BAT GRBs shows no significant correlation according to Pearson's, Spearman's and Kendall's coefficients, whose corresponding no-correlation probabilities are 72, 51 and 37 per cent, respectively. However, from Fig. 1 we note that in the region of high $V_{\rm R}$ and low L, rather unexplored by previous data sets (R01, GFM05), there are six GRBs: 050223, 050416A, 050803, 051016B, 060614, 060729. If one selects the BAT GRBs from our sample with $L_{50} > 5$, the resulting sample of 30 GRBs shows a significant improvement of the *V*/*L* correlation: the probability of no correlation becomes 16, 5.1 and 3.1 per cent, respectively. Likewise, if we merge the two samples (GFM05's and ours) we obtain similar results: when the seven bursts with $L_{50} < 5$ are taken out from the total sample of 62 GRBs, the correlation becomes significant with a no-correlation probability of $\sim 2 \times 10^{-4}$ according to the non-parametric tests.

Finally, we calculated $V_{\rm R}$ in the 25–350 keV energy band, that is, ignoring the lowest energy channel 15–25 keV, of the six low-luminosity outliers. The aim was to establish the importance of the low-energy channel contribution to the resulting $V_{\rm R}$, especially when compared with the results of GFM05, whose low-energy threshold was 40 keV. We found that in all cases $V_{\rm R}$ resulted systematically higher, although still compatible within uncertainties. The only case in which $V_{\rm R}$ in the 25–350 keV was significantly higher than for the whole band was 060614 due to its small statistical uncertainty. This corroborates the nature of outliers of the six GRBs considered: we can rule out that their high values of $V_{\rm R}$ are due to the presence of the low-energy photons not considered by previous data sets.

5.2 LP06 definition

Significant values of $V_{\rm LP}$ have been obtained only for 10 GRBs shown in Fig. 2. In the remaining 31 cases the resulting variability is consistent with zero within uncertainties (see Table 1).

Despite the small number of GRBs with significant $V_{\rm LP}$, the correlation appears to be significant within 1–2 per cent according to the non-parametric tests: 1.1 per cent (Spearman) and 1.6 per cent (Kendall). See Table 2 for further details. Fig. 2 shows these 10 BAT GRBs as well as the sample of 22 GRBs of LP06. Shaded areas show the 1 and 2σ regions around the best-fitting power law obtained by LP06 using the FITEXY routine, with a slope of $m = 3.25 \pm 0.26$ and a χ^2/d.o.f. = 1.93 (20 d.o.f.). If we ignore GRB 060614, which clearly lies far away from any power-law correlation between $V_{\rm LP}$ and L, and use the same routine as LP06, we obtain a best-fitting value of the slope of $m = 2.3 \pm 0.17$ and χ^2/d.o.f. = 8.5 (7 d.o.f.). The χ^2 is clearly too high and therefore, although the correlation appears to be real, the description in terms of a power law with no sample scatter, as the usage of the routine FITEXY assumes, is not acceptable. We note that this conclusion also holds for the very same result of LP06, whose χ^2 has a null hypothesis probability of 0.75 per cent.

6 DISCUSSION

Interestingly, if one ignores the six GRBs from our sample of *Swift*/BAT with low L, specifically $L_{50} < 5$, the remaining homogeneous sample of 30 BAT GRBs, for which we could derive a reliable estimate of $V_{\rm R}$ in the 15–350 keV energy band, is fully consistent in the $V_{\rm R}$–L plot with those from previous detectors, thus confirming the existence of the $V_{\rm R}/L$ correlation. This is remarkable, given that BAT is a different kind of γ-ray detector and has a different energy band from that of the *BeppoSAX*/GRBM, 40–700 keV, whose data mainly comprise the sample of 32 GRBs of GFM05. Another important confirmation provided by this BAT sample is that the scatter of the correlation originally found by R01 and GFM05, despite their alternative descriptions of it, is not due to the combination of data from different instruments with different effective areas, response functions, statistical noises and energy bands, but it is intrinsic to the correlation. In fact, for the first time our data set represents a homogeneous sample of 36 GRBs with measured redshift acquired with the very same detector and with the very same kind of data for each GRB.

What is new with this BAT sample is the presence of six (out of 36) low-luminosity GRBs ($L_{50} < 5$). If one ignores GRB 980425, a peculiar underluminous and very nearby burst, from the sample of GFM05 and R01 it turns out that none of the previous GRBs has $L_{50} < 5$. This is not surprising, given the unprecedented sensitivity of BAT. Therefore these six BAT GRBs allow us to test, for the first time, whether the correlation holds for low-luminosity GRBs. Fig. 1 clearly shows that none of them lies where one might have expected

Table 1. Variability, according to both definitions considered in the text (Sections 5.1 and 5.2), and peak luminosity for a homogeneous sample of 41 *Swift*/BAT GRBs.

GRB	z	$T_{f=0.45}$ (s)	V_R	Peak luminosity L^a (10^{50} erg s^{-1})	V_{LP}	References for z
050126	1.29	12.29	$-0.005^{+0.041}_{-0.040}$	14.73 ± 8.53	-0.0506 ± 0.0893	Berger, Cenko & Kulkarni (2005a)
050223	0.5915	9.73	$0.084^{+0.053}_{-0.053}$	1.47 ± 0.65	-0.0986 ± 0.0805	Berger & Shin (2006)
050315	1.949	24.96	$0.081^{+0.012}_{-0.012}$	29.44 ± 4.97	-0.0026 ± 0.0063	Kelson & Berger (2005)
050319	3.24	12.54	$0.285^{+0.044}_{-0.044}$	90.91 ± 14.00	0.0046 ± 0.0034	Fynbo et al. (2005c)
050401	2.9	4.80	$0.175^{+0.020}_{-0.021}$	1405.1 ± 165.3	0.0176 ± 0.0035	Fynbo et al. (2005a)
050416A	0.6535	1.47	$0.185^{+0.092}_{-0.092}$	0.85 ± 0.25	-0.0083 ± 0.0064	Cenko et al. (2005)
050505	4.27	10.50	$0.175^{+0.036}_{-0.036}$	369.00 ± 42.00	-0.0060 ± 0.0163	Berger et al. (2005b)
050525A	0.606	2.62	$0.096^{+0.005}_{-0.004}$	57.11 ± 15.30	0.0022 ± 0.0002	Foley et al. (2005b)
050603	2.821	2.43	$0.286^{+0.031}_{-0.030}$	2706.5 ± 1470.0	0.0090 ± 0.0014	Berger & Becker (2005)
050730	3.967	54.72	$0.063^{+0.024}_{-0.024}$	87.14 ± 19.24	-0.0404 ± 0.0284	Chen et al. (2005)
050803	0.422	20.48	$0.094^{+0.029}_{-0.029}$	1.91 ± 0.56	-0.0007 ± 0.0072	Bloom et al. (2005)
050814	5.3	54	–	196.78 ± 64.28	-0.0118 ± 0.0083	Jakobsson et al. (2006a)
050824	0.83	12	–	0.202 ± 0.0145	-0.3938 ± 0.2506	Fynbo et al. (2005b)
050908	3.35	6.40	$-0.012^{+0.032}_{-0.032}$	73.00 ± 15.00	-0.0373 ± 0.0324	Fugazza et al. (2005)
050922C	2.198	1.34	$0.026^{+0.005}_{-0.005}$	443.05 ± 21.10	0.0055 ± 0.0018	Jakobsson et al. (2005)
051016B	0.9364	3.26	$0.272^{+0.094}_{-0.086}$	4.85 ± 1.19	-0.0092 ± 0.0055	Soderberg, Berger & Ofek (2005)
051109A	2.346	9.79	$0.154^{+0.076}_{-0.069}$	274.18 ± 44.50	-0.0167 ± 0.0123	Quimby et al. (2005)
051111	1.55	11.20	$0.026^{+0.005}_{-0.006}$	103.88 ± 12.18	-0.0009 ± 0.0022	Hill et al. (2005)
060115	3.53	27.65	$0.120^{+0.031}_{-0.024}$	115.56 ± 17.22	-0.0140 ± 0.0089	Piranomonte et al. (2006)
060206	4.048	3.84	$0.054^{+0.022}_{-0.022}$	444.52 ± 20.18	-0.0038 ± 0.0022	Fynbo et al. (2006b)
060210	3.91	40.77	$0.203^{+0.021}_{-0.022}$	542.42 ± 40.56	0.0038 ± 0.0025	Cucchiara, Fox & Berger (2006a)
060223A	4.41	6.72	$0.106^{+0.037}_{-0.036}$	244.49 ± 24.72	-0.0174 ± 0.0148	Berger et al. (2006)
060418	1.49	16.70	$0.184^{+0.009}_{-0.009}$	131.65 ± 9.89	0.0053 ± 0.0006	Dupree et al. (2006)
060502A	1.51	9.22	$0.006^{+0.006}_{-0.005}$	87.44 ± 15.11	-0.0130 ± 0.0075	Cucchiara et al. (2006b)
060510B	4.9	92.16	$0.105^{+0.014}_{-0.015}$	143.84 ± 22.46	0.0013 ± 0.0220	Price (2006)
060512	0.4428	3.46	$0.058^{+0.077}_{-0.080}$	0.15 ± 0.10	-0.2220 ± 0.0842	Bloom et al. (2006)
060522	5.11	22.08	$0.083^{+0.049}_{-0.051}$	90.26 ± 25.11	-0.0197 ± 0.0166	Cenko et al. (2006)
060526	3.21	17.02	$0.298^{+0.047}_{-0.044}$	189.93 ± 20.05	0.0003 ± 0.0011	Berger & Gladders (2006)
060604	2.68	8.96	$0.189^{+0.131}_{-0.130}$	17.42 ± 5.46	-0.9493 ± 0.5234	Castro-Tirado et al. (2006)
060605	3.7	19.01	$0.097^{+0.061}_{-0.062}$	99.03 ± 20.89	-0.0657 ± 0.0259	Still et al. (2006)
060607	3.082	22.08	$0.171^{+0.018}_{-0.022}$	164.79 ± 16.27	-0.0010 ± 0.0016	Ledoux et al. (2006)
060614	0.125	24.90	$0.274^{+0.010}_{-0.010}$	0.80 ± 0.11	0.0049 ± 0.0006	Fugazza et al. (2006b)
060707	3.43	20.35	$0.096^{+0.044}_{-0.046}$	98.96 ± 21.02	-0.0029 ± 0.0297	Jakobsson et al. (2006d)
060714	2.71	22.40	$0.180^{+0.021}_{-0.021}$	88.78 ± 10.53	-0.0021 ± 0.0079	Jakobsson et al. (2006e)
060729	0.54	26.62	$0.165^{+0.064}_{-0.064}$	0.49 ± 0.35	-0.0036 ± 0.0309	Thoene et al. (2006)
060904B	0.703	6.91	$0.109^{+0.027}_{-0.035}$	17.16 ± 3.05	0.0003 ± 0.0008	Fugazza et al. (2006a)
060908	2.43	5.76	$0.106^{+0.011}_{-0.014}$	280.00 ± 24.00	0.0021 ± 0.0036	Rol et al. (2006)
060912A	0.937	1.28	$0.025^{+0.012}_{-0.009}$	46.20 ± 4.00	-0.0011 ± 0.0015	Jakobsson et al. (2006c)
060926	3.208	3.07	$0.059^{+0.034}_{-0.033}$	55.00 ± 9.00	0.0122 ± 0.0182	D'Elia et al. (2006)
060927	5.6	3.84	$0.155^{+0.022}_{-0.021}$	984.00 ± 590.00	0.0125 ± 0.0023	Fynbo et al. (2006a)
061007	1.262	17.54	$0.123^{+0.002}_{-0.002}$	675.16 ± 28.51s	0.0117 ± 0.0005	Jakobsson et al. (2006b)

[a]Isotropic-equivalent peak luminosity in 10^{50} erg s^{-1} in the rest-frame 100–1000 keV band, for peak fluxes measured on a 1-s time-scale, $H_0 = 65$ kms^{-1} Mpc^{-1}, $\Omega_m = 0.3$ and $\Omega_\Lambda = 0.7$.

from the correlation. Instead, they exhibit relatively high values of V_R. This is proven by the correlation coefficients, in particular the non-parametric Spearman's r_s and Kendall's τ, according to which the correlation is significant (5.1 and 3.1 per cent, respectively) or not, depending on whether these six low-luminosity GRBs are excluded or not. This is confirmed by merging our sample of BAT with that of GFM05: the correlation is significant, provided that low-luminosity bursts are excluded (see Table 2).

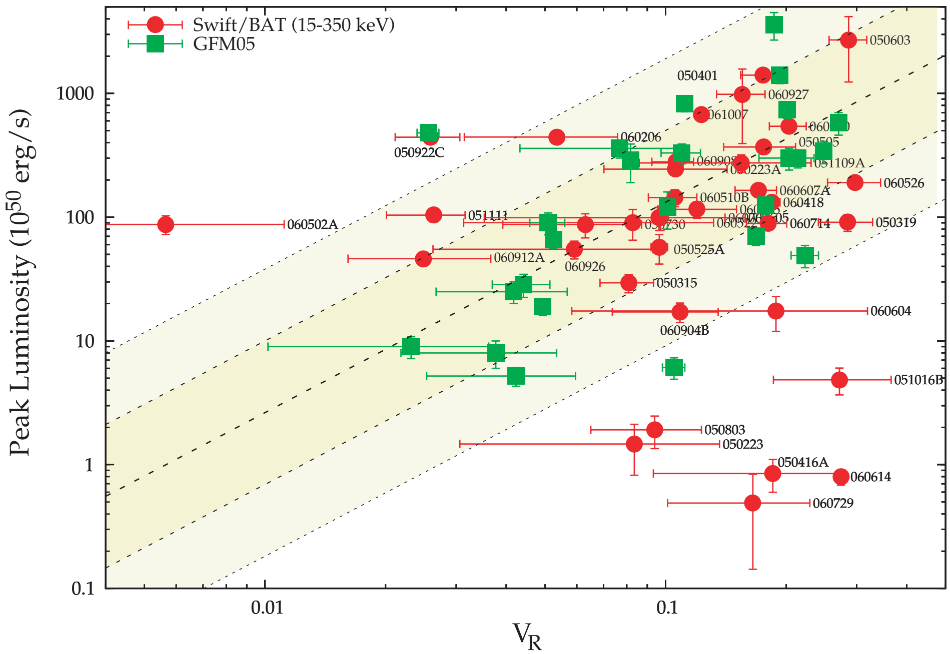

Figure 1. Variability V_R versus peak luminosity L for a sample of 36 long bursts detected by *Swift*/BAT (circles) according to the definition of variability by R01. For comparison we show 25 GRBs (squares) from GFM05. The shaded areas show the 1 and 2σ regions around the best-fitting power law obtained by Guidorzi et al. (2006) with the D'Agostini method, with a slope of 1.7.

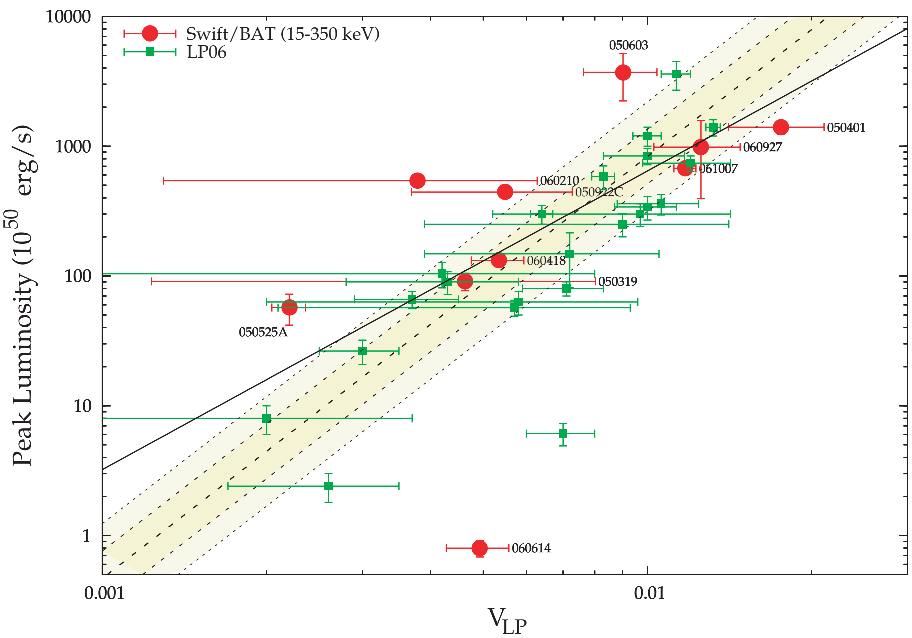

Figure 2. Variability V_{LP} versus peak luminosity L for a sample of 10 long bursts detected by *Swift*/BAT (circles) according to the definition of variability by LP06. For comparison we show 22 GRBs with significant V_{LP} (squares) from LP06. The shaded areas show the 1 and 2σ regions around the best-fitting power law obtained by LP06, with a slope of 3.25. Solid line shows the best-fitting power law obtained with all of the 10 BAT bursts shown here, but GRB 060614; its slope is 2.3 (see Section 5.2).

Guidorzi et al. (2007) have investigated the nature of the six BAT GRB outliers of the V/L correlation and found strong evidence that they are also outliers of the anticorrelation, discovered by Norris et al. (2000), between the rest-frame temporal lag and the peak luminosity. In particular, they found that these GRBs are characterized by a small or negligible time lags and a relatively low luminosity. We refer the reader to the paper by Guidorzi et al. (2007) for more details.

Concerning the definition of variability, V_{LP}, given by LP06, we found that this still correlates with L, although our results differ from those by LP06 (see Fig. 2 and Table 2). In particular, we find the description of the correlation in terms of a power law with no

Table 2. Correlation coefficients for different sets of GRBs.

Set of GRB[a]	Coefficient (probability)		
	Pearson's r	Spearman's r_s	Kendall's τ
36 GRBs (V_R versus L_{50})	−0.062 (0.719)	0.115 (0.506)	0.105 (0.369)
30 GRBs (V_R versus $L_{50} > 5$)	0.261 (0.163)	0.359 (0.051)	0.278 (0.031)
62 GRBs[b] (V_R versus L_{50})	0.190 (0.139)	0.315 (0.013)	0.231 (0.008)
55 GRBs[b] (V_R versus $L_{50} > 5$)	0.418 (1.5×10^{-3})	0.476 (2.4×10^{-4})	0.342 (2.3×10^{-4})
10 GRBs (V_{LP} versus L_{50})	0.536 (0.111)	0.758 (0.011)	0.600 (0.016)

[a] $L_{50} = L/(10^{50}\ \mathrm{erg\ s^{-1}})$. [b]This sample resulted from the merging of our sample with that of GFM05.

extrinsic scatter inadequate, given the high values of χ^2/d.o.f. yielded by both samples, ours and that of LP06. Regarding our sample of 41 BAT GRBs, we find that, unlike the definition of V_R by R01, the smoothing filter adopted by LP06 in their definition of V_{LP} cuts off the low-frequency variability of GRBs. This results in a selection of a smaller sample of GRBs with significant (high-frequency) variability: 10 versus the 36 obtained for the R01 definition. We note that GRB 060614 confirms its nature of outlier of the correlation, no matter which choice of the definition of variability we adopt (Fig. 2).

In general, from Table 2 we note that the Pearson linear correlation coefficient r is systematically less significant than the other two. This supports the finding that the correlation shows a clear scatter around the best-fitting power law. Therefore this scatter must be taken into account properly (e.g. with the D'Agostini method), when fitting the data (see D'Agostini 2005; Guidorzi et al. 2006).

6.1 Low-luminosity GRBs and the Amati correlation

We tested if the six low-luminosity GRBs are also outliers of the $E_{p,i}$–E_{iso} (Amati et al. 2002) (E_{iso} is the isotropic energy released in the 1–10^4 keV rest-frame band) as well as of the $E_{p,i}$–L (Yonetoku et al. 2004; Ghirlanda et al. 2005) correlations. $E_{p,i} = E_p(1 + z)$ is the intrinsic peak energy of the total spectrum of a burst, where E_p is the peak of the $\nu F(\nu)$ spectrum in the observer frame. A correlation between temporal variability and $E_{p,i}$ was originally found by Lloyd-Ronning & Ramirez-Ruiz (2002) for a number of bursts with pseudo-redshift derived assuming the variability/peak luminosity correlation. Taking into account that $E_{p,i}$ also correlates with E_{iso} and with L (isotropic peak luminosity), we test whether the breaking of the V/L correlation in the case of these six bursts is explained by anomalous values of $E_{p,i}$.

For two bursts, XRF 050416A (Sakamoto et al. 2006) and GRB 060614 (Amati et al. 2007) $E_{p,i}$ has already been reported elsewhere. Both GRBs are consistent with the Amati relation. In particular, XRF 050416A remarkably confirms it down to the XRFs region (Sakamoto et al. 2006). For the remaining four GRBs, the BAT photon spectrum can be fitted with a single power law $N(E) \propto E^{-\Gamma_{BAT}}$, where Γ_{BAT} is the photon index. In order to constrain E_p, we fitted the total spectrum of each burst with a cut-off power law by fixing the power-law index α to the typical value of 1.0 and letting the break energy $E_0 = E_p/(2 - \alpha)$ free to vary. We took the lower/upper limit for E_0 from the 90 per cent confidence level interval on one parameter: if the interval included or lay close to the lower (higher) boundary of the BAT passband, we assumed the upper (lower) limit on E_0. Our results are broadly in agreement with the empirical correlation found by Zhang et al. (2007) between E_p and Γ_{BAT}.

Results are reported in Table 3. All of the six bursts (or their limits) turned out to lie in the 2σ region of the Amati relation (see Amati 2006).

Table 3. Intrinsic peak energy $E_{p,i}$ of the total spectrum for the subset of six low-luminosity GRBs of our sample. Γ_{BAT} is the photon index of the total photon spectrum [$N(E) \propto E^{-\Gamma_{BAT}}$] when this is fitted with a single power law in the BAT energy band. Limits are given at 90 per cent confidence level.

GRB	Γ_{BAT}	$E_{p,i}$ (keV)	E_{iso} (10^{52} erg)
050223	1.90 ± 0.16[a]	<127	0.12 ± 0.02
050416A[b,c]	–	25.1 ± 4.2	0.12 ± 0.02
050803	1.58 ± 0.09	>103	0.20 ± 0.03
051016B	2.13 ± 0.27	<125	0.14 ± 0.04
060614[d]	–	55 ± 45	0.25 ± 0.10
060729	1.62 ± 0.18	>80	0.27 ± 0.05

[a]In agreement with Page et al. (2005); [b]from Amati (2006); [c]from Sakamoto et al. (2006); [d]from Amati et al. (2007).

We also found that the two bursts with firm $E_{p,i}$ as well as two with upper limits are consistent with the $E_{p,i}$–L correlation, while the remaining two lower limits on $E_{p,i}$ for GRB 050803 and GRB 060729 are not, as shown in Fig. 3. The better consistency with the $E_{p,i}$–E_{iso} than with the $E_{p,i}$–L correlation can be explained with the fact that $E_{p,i}$ better correlates with the time-integrated released energy, as proven also by the scatter of the correlation between L and E_{iso} (Ghirlanda et al. 2005).

We also tested whether the duration of these events correlates with their peak luminosity. To this aim, in Fig. 4 the rest-frame $T_{90,rest} = T_{90}/(1 + z)$ is plotted against L_{50} for the entire sample of 41 *Swift*/BAT GRBs considered. T_{90} is the time interval collecting from 5 to 95 per cent of the total fluence in the observer frame. For

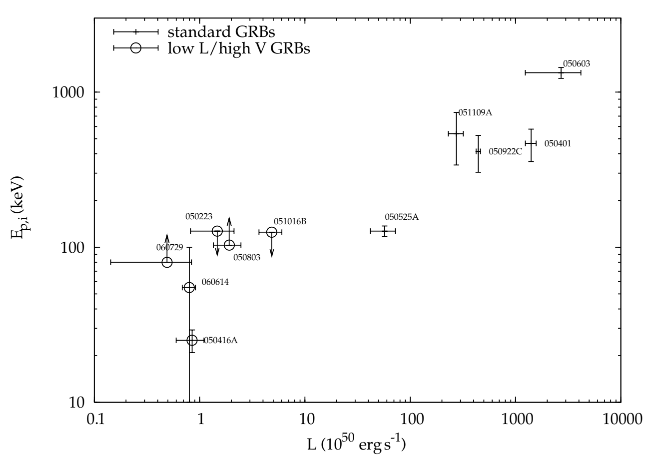

Figure 3. Peak luminosity L versus rest-frame peak energy $E_{p,i}$ of the total energy spectrum for five bursts with firm $E_{p,i}$ measurements (Amati 2006) and the six low-luminosity ($L_{50} < 5$) GRBs (empty circles) of our *Swift*/BAT sample.

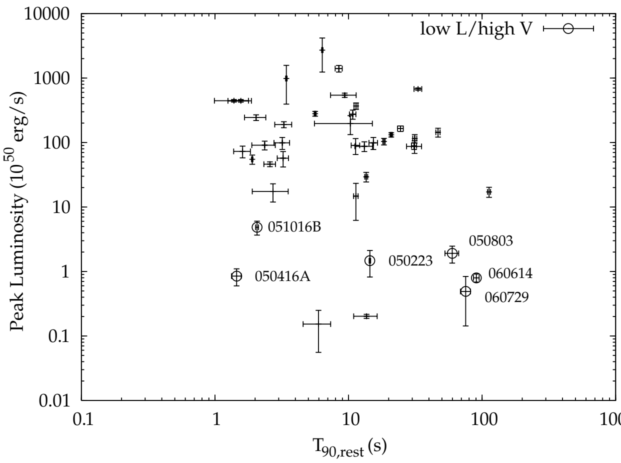

Figure 4. Rest-frame duration $T_{90,\mathrm{rest}}$ versus peak luminosity for all the 41 *Swift*/BAT bursts reported in Table 1. Empty circles show the six low-luminosity ($L_{50} < 5$) high-variability GRBs.

each burst we used the value published by the BAT team in the refined GCN circulars. Empty circles correspond to the six low-luminosity GRBs with a significant measure of variability. Apparently there is no hint for correlation and also no evidence for a different behaviour of the six low-luminosity GRBs with respect to the others. The result does not change in essence when we replace $T_{90,\mathrm{rest}}$ with T_{90}.

We conclude that the fact that the variability of these six low-luminosity high-variability GRBs does not correlate with the peak luminosity is not connected with their $E_{\mathrm{p,i}}$, which correlates with E_{iso} as almost all of the long GRBs with known redshift (Amati 2006).

7 CONCLUSIONS

We tested the variability/peak luminosity (V/L) correlation with a homogeneous sample of 36 GRBs detected with *Swift*/BAT in the 15–350 keV energy band with firm redshift. We adopted two different definitions of variability: that by Reichart et al. (2001; V_{R}) and that by Li & Paczyński (2006; V_{LP}), which differs from the former for a different smoothing filter. The most interesting results have been derived with V_{R}. If we consider only the GRBs with peak luminosity L comparable with those of previous samples, that is, $L > 5 \times 10^{50}$ erg s^{-1} in the rest-frame 100–1000 keV energy band, we confirm the correlation and its intrinsic dispersion around the best-fitting power law obtained by Guidorzi et al. (2006): $m = 1.7 \pm 0.4 (L \propto V^m)$ and $\sigma_{\log L} = 0.58^{+0.15}_{-0.12}$.

Interestingly, all of the six low-luminosity GRBs detected by *Swift*/BAT turn out to be outliers to the V/L correlation, showing higher values of V_{R} than expected. This does not contradict the results from previous samples of GRBs with known redshift. Instead, we are led to conclude that the correlation does not hold any more for low-luminosity GRBs. We also find that these bursts are consistent with the $E_{\mathrm{p,i}}$–E_{iso} correlation (Amati et al. 2002) and four of them also with the $E_{\mathrm{p,i}}$–L correlation (Yonetoku et al. 2004; Ghirlanda et al. 2005).

Unlike the results obtained by LP06, we do not find evidence for a tighter correlation using V_{LP} instead of V_{R}. Rather, fewer GRBs appear to have a significant measure of V_{LP}; we ascribe this to the fact that the smoothing filter adopted by LP06 to construct the reference light curve with respect to which the variability is computed, only selects high-frequency variability.

ACKNOWLEDGMENTS

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APPENDIX A: STATISTICAL NOISE OF BAT MASK-TAGGED LIGHT CURVES

We report the analysis performed on the BAT mask-tagged light curves of the GRBs considered in this work, aimed at studying the statistical noise. As the GRB itself is characterized by intrinsic temporal variance which is unknown a priori, we limited to the pre- and post-burst regions of the light curves, where the background is supposed to be the dominant source of statistical fluctuations. In order to make sure that we excluded the entire light curve of the GRB, we binned it spanning very different integration times (from 64 ms to 32 s) and checked that no trend in the residuals was visible.

Let r_i and σ_{r_i} be the count rate and its uncertainty, respectively, of the ith bin of a 64-ms mask-tagged BAT light curve. This light curve is the result of the BAT standard pipeline already summarized in Section 2 (see also Barthelmy et al. 2005). Uncertainties $\sigma_{r_i} (i = 1, \ldots, N$, where N is the total number of bins of the selected portion of light curve) are calculated by propagation of errors, starting from the raw counts assumed to be affected by purely Poissonian noise through the FTOOL BATBINEVT.

We tested the following null hypothesis: each r_i is a single realization of a normal random variable with null expected value and σ equal to σ_{r_i}: $N(0, \sigma_{r_i})$. Little can be inferred on a random variable from a single realization. However, as long as this hypothesis is true, the various $r_i/\sigma_{r_i} (i = 1, \ldots, N)$ can be seen as different realizations of the same random variable, $r_{\rm n}$, hereafter called 'normalized rate', which has a standard normal density: $N(0, 1)$.

So we studied the observed distribution of $r_{\rm n}$ for each single light curve removed of the GRB profile. We fitted the observed distribution with a Gaussian $N(\mu, \sigma)$.

In particular, we are interested in constraining the possible presence of any additional source of statistical noise (e.g. instrumental) to the Poissonian one.

More generally, should the various r_i fluctuate more than σ_{r_i}, so that the true variance is $(1 + f_{\rm np})\,\sigma_{r_i}^2$, where $f_{\rm np}$ is the fraction of additional non-Poissonian variance, the resulting σ should be greater than unity. More precisely, we should find $\sigma^2 = (1 + f_{\rm np})$.

Therefore we fitted the observed distribution of $r_{\rm n}$ with $N(\mu, \sigma)$, first by imposing $\sigma = 1$. In every case we found acceptable χ^2 values, confirming that no evidence for additional noise has been found.

In particular, we were interested in setting a limit to $f_{\rm np}$ with a given confidence level. Following Papoulis & Pillai (2002; p. 313), in the case of unknown μ we used the sample variance s^2 defined as

$$s^2 = \frac{1}{N-1} \sum_{i=1}^{N} (r_{{\rm n},i} - \overline{r_{\rm n}})^2, \tag{A1}$$

where $r_{{\rm n},i} = r_i/\sigma_{r_i}$ is the single realization of $r_{\rm n}$ and $\overline{r_{\rm n}}$ is the mean value. The random variable $(N - 1)s^2/\sigma^2$ follows a $\chi^2(N - 1)$ distribution, so that we can constrain σ^2, that is, $(1 + f_{\rm np})$, through

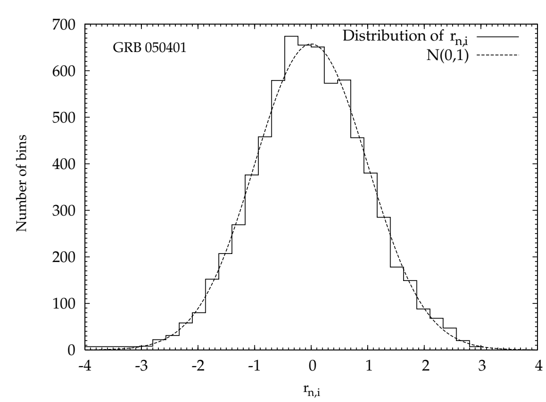

Figure A1. Distribution of the normalized rates $r_{{\rm n},i}$ in the case of GRB 050401. The total number of bins is $N = 7065$. The distribution is well fitted with $N(0, 1)$.

the following relation:

$$1 + f_{\rm np} = \sigma^2 < \frac{(N-1)\, s^2}{\chi^2_{\delta/2}(N-1)} \tag{A2}$$

at $(1-\delta)$ confidence level; $\chi^2_u(n)$ is the u percentile of the $\chi^2(n)$ distribution. In most cases N was big enough ($>10^3$) to ensure the following approximation:

$$f_{\rm np} < s^2 \left[1 + z_{1-\delta/2} \sqrt{\frac{2}{(N-1)}} \right] - 1, \tag{A3}$$

where z_u is the u percentile of the standard normal density.

We show the example of GRB 050401. The distribution of $r_{{\rm n},i}$, $N = 7065$, can be fitted with a Gaussian $N(0, 1)$, $\chi^2/{\rm d.o.f.} = 32.2/28$, as shown in Fig. A1.

The sample variance resulted $s^2 = 0.999$. The consequent upper limit on $f_{\rm np}$ turns out to be 2.7 per cent (4.3 per cent) at 90 per cent (99 per cent) confidence level.

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