The GRB Variability/Peak Luminosity Correlation: new results

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ABSTRACT

We report test results of the correlation between time variability and peak luminosity of Gamma-Ray Bursts (GRBs), using a larger sample (32) of GRBs with known redshift than that available to Reichart et al. (2001), and using as variability measure that introduced by these authors. The results are puzzling. Assuming an isotropic-equivalent peak luminosity, as done by Reichart et al. (2001), a correlation is still found, but it is less relevant, and inconsistent with a power law as previously reported. Assuming as peak luminosity that corrected for GRB beaming for a subset of 16 GRBs with known beaming angle, the correlation becomes little less significant.

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

1 INTRODUCTION

Despite the small number of Gamma-Ray Bursts (GRBs) with known redshift (several dozens), several correlations between intrinsic temporal or spectral parameters of the GRB prompt emission and GRB energetics have been discovered in the last seven years. Norris et al. (2000) found an anticorrelation between peak luminosity and the spectral lag (obtained by cross-correlating the time profiles of the same GRB in various energy bands), according to which more luminous bursts exhibit shorter lags. Salmonson & Galama (2002) discovered a positive correlation between the spectral lag of the gamma-ray prompt emission and the jet-break time of the afterglow decay, according to which a small break time corresponds to a small lag and consequently to a high peak luminosity of the GRB. Concerning the temporal properties of GRB time profiles, evidence has been found for a positive correlation between temporal variability of the light curves and isotropic-equivalent peak luminosity for the GRBs with known redshift (Reichart et al. 2001, hereafter R01; Fenimore & Ramirez-Ruiz 2000).

Moreover Reichart et al. (2003) have shown that the variability vs. peak luminosity correlation could also hold true for X-Ray Flashes (XRFs; see Heise et al. (2001)). As a consequence of the mentioned correlations, a correlation between time variability and spectral lag is also expected and confirmed for a large sample of BATSE bursts (Schaef er et al. 2003). The variability vs. peak luminosity correlation has been explained by several authors (e.g., Kobayashi et al. 2002, Mészáros et al. 2003) mainly within the framework of the standard fireball model, according to which internal shocks between ultra relativistic shells are responsible for the pulse-like structure of the GRB prompt emission, while the smooth afterglow emission is due to external shocks between the fireball wind and the matter surrounding the GRB progenitor (e.g., Piran 2004) for a review).

GRB variability-connected properties are thought to be more sensitive to the bulk Lorentz factor $\Gamma$ and, if the GRB emission is beamed, to the jet opening angle and/or the viewing angle (e.g., Salmonson & Galama 2003; Ioka & Nakamura 2001). Within the fireball model, there are different mechanisms that could account for different time variabilities, also giving possible explanations for XRF properties (Mészáros et al. 2002). In addition, the “cannonball model” for GRBs (Dado, Dar & De Rújula 2002) also seems to explain the variability vs. peak luminosity correlation (Palmer 2001).

From the above correlations also luminosity estimators have tentatively been derived (Reichart et al. 2001; Fenimore & Ramirez-Ruiz 2000; Schaef er et al. 2003) to investigate general properties of GRBs, such as the luminosity function and the possible link with the star formation rate. In addition, empirical redshift indicators have been proposed based on the calibration derived with the small sample of GRBs with known redshift, making use of the X- and gamma-ray observations alone (Atteia 2003; Baroy ly et al. 2003).

In this work we test the variability vs. peak luminosity correlation using the variability definition given by R01. We used a
sample of 32 GRBs with known redshift. Furthermore we studied the same correlation by replacing the isotropic-equivalent peak luminosity with that corrected for beaming for a subset of 16 GRBs with known collimation angle provided by Ghirlanda et al. (2004).

In Section 2, we discuss our sample of GRBs; in Section 3 we discuss the time variability analysis; in Section 4 we estimate the peak luminosity of the GRB in our sample and compare it with the R01 results. In Section 5 we present our results on variability/peak luminosity correlation, in Section 6 we discuss our results.

2 THE GRB SAMPLE

2.1 GRBs with known redshift

The sample of 32 GRBs with known redshift includes 16 GRBs detected by the Gamma-Ray Burst Monitor (GRBM) Feroci et al. (1997, 1998) on board the BeppoSAX satellite (Boella et al. 1997) during the period 1997–2002, two by the BATSE experiment (Paciesas et al. 1999) aboard the Compton Gamma-Ray Observatory (CGRO), six by the FREGATE instrument aboard HETE-II (Atteia et al. 2003), one by Konus/WIND (Aptekar et al. 1995), one by Ulysses (Hurley et al. 1997) and six by BAT/Swift (Gehrels 2004). Eight of the 16 GRBs detected with the BeppoSAX GRBM were also detected with BATSE. We used public archives for GRB data obtained with BATSE1, HETE-II2, Konus/WIND3, and BAT/Swift4. Table 1 reports the list of the GRBs in our sample with mentioned the spacecraft that detected it. When the same GRB has been detected by more than one instrument, we first checked the consistency of the results derived from different data sets and then concentrated on the instrument which had the best SNR.

The time binning of the GRB light curves in our sample, which was used to derive the time variability, was the following: 7.8125 ms for the GRBM data, 64 ms for BATSE, 164 ms for HETE-II, 64 ms for Konus/WIND, 31.25 ms for Ulysses. In the case of BAT/Swift we made use of the event files and extracted the mask-tagged light curves with a binning time of 8 ms. Given the case of BATSE (970828 and 000131) the usual 4-channel 64-ms light curves are not available. Thus we made use of the 16-channel MER spectra acquired along either entire GRB with an integration time of 64 ms. Therefore we rebinned the energy-channel MER data both spectrally and temporally in order to reproduce as much as possible the 4-channel scheme of BATSE 64-ms light profiles. As we discuss below, we relied on coarse time resolution light curves only when the overall duration of the GRB was very long compared to the binning time.

In general the data available cover the entire time profile of the GRBs in our sample. However there are some exceptions. In the case of the GRBM events, given that the high-resolution data cover 8 s before the trigger time and 98 s after it, in the case of the longest events (990506 and 010222, $T_{90} = 129$ s and $T_{90} = 97$ s, respectively), it is not true. In these cases, the measure of time variability was obtained summing the variability in the part covered by the 7.8125-ms bins with that in the part covered by 1-s ratemeters (the tail of the burst).

For each GRB detected with the GRBM, we considered the light curves of the two most illuminated units and checking whether the best signal-to-noise ratio (SNR) was obtained from a single unit or by summing the two units.

We found that for the 11 GRBs detected by GRBM and Wide Field Cameras (WFCs) Jager et al. (1997), the best signal is obtained from a single GRBM unit (that with the larger area exposed to the GRB). For the five bursts detected with the GRBM but not with the WFCs the best signal was obtained by summing the two most illuminated units: units 1 and 4 (980703), 3 and 4 (990506, 020405), and 2 and 4 (991216, 010921). In principle the operation of adding the counts of different units is questionable because of dead time, as it will be discussed in Section 3. In practice, for the above cases we made sure that the results were consistent with those obtained when considering only the most illuminated unit for each GRB. This has been found to be no longer true, i.e. the correction for dead time becomes not negligible, when considering very small smoothing time-scales (Rossi et al., in preparation).

As far as the 8 bursts detected with both GRBM and BATSE (970508, 971214, 980425, 980703, 990123, 990506, 990510, 991216) are concerned, we used the BeppoSAX data for 971214, 980703, 990123, 990506, and 991216, for which the higher time resolution of the GRBM turned out to be essential for a better variability estimate, while for the remaining 3 GRBs (970508, 980425, and 990510) we used the BATSE data given the better SNR, after verifying the mutual consistency of the GRBM and BATSE variability results.
3 VARIABILITY MEASURE

We adopted the variability measure given by R01, slightly modified for two corrections which could affect the result: the instrument dead time, and a small non-Poisson noise present in the GRBM background data. The variability measure used by R01 was defined as a properly normalized mean square deviation of the intrinsic light curve of a GRB in a given energy band from a smoothed one. For a discrete light curve made of N bins, the variability measure, according to R01, is given by:

\[ V_{f,P} = \frac{\sum_{i=1}^{N} |S(C_f, N_i) - S(C_i, N_f)|^2}{\sum_{i=1}^{N} |S(C_i, N_i) - B_i|^2}, \]

where as intrinsic light curve we mean the GRB light curve in the source-frame, \( N_f \) is the number of data bins corresponding to the smoothing time scale \( T_f \) defined by R01 as the shortest cumulative time interval during which a fraction \( f \) of the total counts above background has been collected, \( C_f \) and \( B_i \) are the original GRB (source plus background) and background counts in the bins \( j \) and \( i \), respectively, in the observer frame, the index \( P \) means that the
variability measure is inclusive of the Poisson noise. \( S_t(C_j, N_z) \) is roughly the mean counts on \( N_z \) bins \((z = z + f)\) centred around the \( t\)-th bin:

\[
S_t(C_j, N_z) = \frac{1}{N_z} \left[ \sum_{j=1-n_x}^{i+n_x} C_j + \left( N_z - \frac{1}{2} - n_x \right) C_{i+n_x+1} \right].
\]  

(2)

\( N_z \) is the number of bins in the observer-frame, which corresponds to 1 bin in the source-frame. Assuming as time duration of 1 bin in the source-frame the shortest binning \( \Delta t \) of the data (e.g., in the case of the BeppoSAX GRBM, \( \Delta t = 7.8125\) ms), in the observer-frame the number of bins, depending on the GRB redshift \( z \), for relativistic time dilation and narrowing of the light curve at high energies \( \text{Frontera \\& Fuligni 1979} \), is given by \( N_z = (1 + z)^3 \) with \( \beta \approx 0.6 \). Thus \( N_z \) can take values other than integers and \( n_x \) is the truncated integer value of \((N_z - 1) / 2 \).

R01 found that the best luminosity estimator is obtained when using \( f = 0.45 \); for this reason, we fixed \( f = 0.45 \).

The variability \( V_{x,P} \) can also be written as follows:

\[
V_{x,P} = \frac{\sum_{i=1}^{N} \left( \sum_{j=1}^{N} a_{ij} C_j \right)^2}{\sum_{i=1}^{N} \left( \sum_{j=1}^{N} b_{ij} C_j - B_i \right)^2}
\]

(3)

where the coefficients \( a_{ij} \) and \( b_{ij} \), for each GRB, are computed by comparing eq. 3 with eq. 2 through eq. 2.

Following R01, after subtraction of the Poisson variance the variability measure is given by:

\[
V_f = \frac{\sum_{i=1}^{N} \left( \sum_{j=1}^{N} a_{ij} C_j \right)^2 - \sum_{i=1}^{N} \sum_{j=1}^{N} a_{ij}^2 C_j \right]}{\sum_{i=1}^{N} \left( \sum_{j=1}^{N} b_{ij} C_j - B_i \right)^2 - \sum_{j=1}^{N} \sum_{j=1}^{N} b_{ij}^2 C_j}
\]

(4)

which is the expression used by R01 to evaluate the variability of the GRBs in their sample. We slightly modified the above expression by taking also into account the dead time, which is known to affect the Poisson variance of a stationary process \( \text{Müller 1973, Libert 1978} \). In the case of a stationary Poisson process with measured mean \( \mu \), the variance of its counts in the time bin \( \Delta t \), which is given by \( \mu \Delta t \) in absence of dead time, becomes \( \mu \Delta t (1 - \mu / \tau) \) in the asymptotic limit \( \tau / \Delta t \ll 1 \), where \( \tau \) is the dead time.

In the case of the BeppoSAX GRBM \( \tau = 4\mu s \), \( \tau / \Delta t \approx 5 \times 10^{-4} \) for the shortest bin duration \( \Delta t = 7.8125\) ms. In the same limit \( \tau / \Delta t \ll 1 \), the same correction factor \((1 - \mu / \tau)^2 \) applies to the white noise level of the power spectral density (PSD) estimate \( \text{Frontera \\& Fuligni 1972, van der Klis 1989} \). It is shown \( \text{Frontera \\& Fuligni 1972} \) that the same correction factor holds when the process is non-stationary, like GRBs or flares. Potentially our variability calculations could be sensitive to dead time, especially for those GRBs with huge peak count rates, like in the case of 990123 (~16,000 cts/s with GRBM), for which, around the peak, the true variability is ~ 0.9 times the measured counts.

In addition, we corrected for a slight (a few percent) non-Poisson noise found in the GRBM high-resolution data. This noise increases the Poisson variance by a factor \( r_{np} \), which ranges from 1.027 to 1.049, depending on the detection unit, for the GRBM data after November 1996.

Taking into account both dead time and non-Poisson noise,

5 During the first months of BeppoSAX operation the non-Poisson noise of the GRBM was much higher, due to the too low energy threshold (around 20 keV) set at the beginning of the mission \( \text{Feroci et al. 1997} \).

The right terms to be subtracted in the numerator and denominator of eq. 8 become \( \sum_{j=1}^{N} a_{ij}^2 C_j r_j \) and \( \sum_{j=1}^{N} b_{ij}^2 C_j r_j \), respectively (see, for comparison, eq. 5), where

\[
r_j = r_{np} \left( 1 - C_j \frac{\tau}{\Delta t} \right)^2
\]

(5)

As a consequence, the expression we used to estimate the net GRB time variability is given by:

\[
V_f = \frac{\sum_{i=1}^{N} \left( \sum_{j=1}^{N} a_{ij} C_j \right)^2 - \sum_{i=1}^{N} \sum_{j=1}^{N} a_{ij}^2 C_j r_j \right]}{\sum_{i=1}^{N} \left( \sum_{j=1}^{N} b_{ij} C_j - B_i \right)^2 - \sum_{j=1}^{N} \sum_{j=1}^{N} b_{ij}^2 C_j}
\]

(6)

We used as statistical uncertainty \( \sigma_{V_f} \) on the variability measure that given by R01 (eq. 8) properly modified to take into account the correction factor \( r_j \).

We found that the variability measure is not sensitive to dead time corrections for long GRBs, in which \( T_f = 0.45 \) is much longer than the bin time, while it is significantly modified for relatively short GRBs exhibiting sharp intense pulses.

### 3.1 Variability dependence on binning time

In order to understand how time binning affects the GRB variability, for the brightest GRBs, detected with either GRBM or BATSE we evaluated the variability measure (eq. 5) as a function of the binning time of the data. The result is that the variability is better estimated for very short time durations of the data bins with respect to the smoothing time-scale \( T_s = T_f = 0.45 \). More specifically, it results that the variability significantly decreases for few \( 0.01 < \Delta t / T_s < 0.01 \), and becomes unreliable when this ratio becomes still higher, i.e. for \( \Delta t / T_s > \text{few 0.1} \).

On the other side, the bin time should be long enough to collect a good number of photons (typically at least 20 per bin on average) to ensure the Gaussian limit and take over the effects of statistical fluctuations. Thus we rejected those GRBs whose data sets do not match the above requirements.

Figures 1 and 2 show the illustrative cases of 991216 and 970228, respectively. We calculated \( V_f = 0.45 \) using both GRBM and BATSE subset with \( \Delta t > 0.45 \) ms.
and BATSE (KONUS) data sets as a function of the binning time \(\Delta t\) for 991216 (970228). For both GRBs, the variability seems to approach an asymptotic value for decreasing values of binning time. In the case of 991216, it appears that the original binning time of BATSE, 64 ms, is a little too coarse since its correspondent value of \(V_f=0.45\) is significantly lower: we assume as asymptotic value the measure obtained with the smallest binning time of GRBM data and get \(V_f=0.45 = 0.193 \pm 0.002\), while the BATSE measure is \(0.170 \pm 0.003\), i.e. \(\sim 6\sigma\) apart. Differently, in the case of 970228 the KONUS measure with the smallest binning time of 64 ms yields a measure of \(V_f=0.45\) which is apparently consistent with the GRBM one (Fig. 2). In the case of 991216 it is worth noting that the measure of \(V_f=0.45\) turns out to be significantly underestimated with respect to the asymptotic value as far as we assume binning times at least a few \(10^{-2}\) times as high as the smoothing time-scale.

In general, we noticed that for all the GRBs for which \(V_f=0.45\) approaches an asymptotic value for small binning times, different measures of \(V_f=0.45\) are still consistent with that, provided that the ratio between binning time and smoothing time-scale is not too high (\(\Delta t/T_s < \text{few} \times 10^{-2}\)).

Our final set of variability measures include only those GRBs for which the three following requirements have been fulfilled with a single binning time: 1) smallness of ratio \(\Delta t/T_s\), 2) asymptotic behaviour of \(V_f=0.45\) as a function of binning time \(\Delta t\) for small \(\Delta t\), 3) Gaussian limit of at least 20 counts per bin on average.

Following this guideline, we discarded the HETE-II bursts 021211 and 050408, for which \(\Delta t/T_s\) is around 0.2 and 0.08, respectively. In the case of the couple of GRBs above considered, we infer that GRBM data turned out to be essential in estimating the variability of 991216, since BATSE data alone, although consistent with GRBM data for comparable binning times, do not seem to approach an asymptotic value of \(V_f=0.45\), while GRBM data do. On the other side, in the case of 970228 KONUS data exhibit an asymptotic trend towards small binning times; together with the fulfillment of the other two requirements, KONUS time resolution is acceptable and yields a variability measure which is consistent with the GRBM within errors.

### 4 PEAK LUMINOSITY ESTIMATE

The GRBs peak luminosities were estimated using the definition of luminosity distance in the source-frame 100–1000 keV energy band:

\[
L = 4\pi D_L^2 \left( \frac{1000}{1+z} \right) \int_{100/(1+z)}^{1000} E \Phi(E) dE
\]

where \(\Phi(E)\) is the measured spectrum (ph cm\(^{-2}\)s\(^{-1}\)keV\(^{-1}\)) around the peak time, \(D_L(z)\) is the luminosity distance at redshift \(z\), \(E\) is energy expressed in keV. By replacing \(E' = E(1+z)\) we get:

\[
L = \frac{4\pi D_L^2(z)}{(1+z)^2} \int_{100}^{1000} E' \Phi \left( \frac{E'}{1+z} \right) dE'
\]

Formally, eq. (8) is the same as eq. 9 of R01; there \(D(z)\) is the co-moving distance, which is equal to \(D(z) = D_L/(1+z)\) if we consider a flat Universe. However, unlike R01 who used as \(\Phi(E)\) the best-fitting Band model (Band et al. 1993) to the average GRB count spectrum normalised to the peak count rate, we used for the GRBM data the best-fitting power-law spectrum (\(\Phi(E) = N E^{-\alpha}\)) to the GRB peak count rate spectrum obtained from the 1-s ratemeters available in two channels (40–700 keV and > 100 keV). When the 225-channel time-averaged spectrum was not available, we added a conservative 10% systematics to the peak luminosity uncertainties. Thus, for the GRBM bursts, eq. (8) becomes:

\[
L = 4\pi D_L^2(z) (1+z)^{-\alpha-2} F_p
\]

where \(F_p = \int_{100}^{1000} N E'^{\alpha-1} dE'\) is the 100–1000 keV peak flux measured in the observer frame (erg cm\(^{-2}\)s\(^{-1}\)). In the case of GRBs with sharp peaks of < 1 s duration (e.g. GRB000214), the peak luminosity obtained from 1-s ratemeters was further corrected.
by the ratio between the actual peak value and that derived from 1-s rameters.

For the GRBs in our sample not detected with the GRBM, we used the best-fitting parameters of $\Phi(E)$ available from the literature. The best-fitting spectral parameters for HETE-II bursts were taken from Sakamoto et al. (2004), except for the recent 041006 for which we used the best-fitting cutoff power-law parameters published by HETE-II team on the HETE web page ($E_\text{bd}=100.2$ keV, $\alpha=1.367$). For the Ulysses GRB000911 we made use of the best-fitting parameters published by Price et al. (2002a), while for the Konus burst 991208 we used the parameter values given by R01. For the BATSE GRB000131 we fitted the peak energy spectrum from MER data in the range 30–1000 keV with the Band function ($\alpha=-0.56$, $\beta=-2.17$, $E_\text{bd}=153$ keV, $\chi^2/\text{dof}=1.0$). Likewise, for the BATSE GRB970828 the peak energy spectrum was fitted with the Band function ($\alpha=-0.65$, $\beta=-2.56$, $E_\text{bd}=260$ keV, $\chi^2/\text{dof}=1.1$). For BAT/Swift we extracted from the event file the 1-s 80-channel spectrum around the peak; for all the 6 BAT/Swift GRBs considered, the peak spectrum was fitted with a simple power law in the 15-350 keV range, apart from a couple of them (050525 and 050603) for which only the cut-off power-law model yields a good fit. We then used eq. (7) to evaluate the peak luminosity.

Our peak luminosity estimates are reported in Tables 1.

For the common sample of GRBs, our estimates of the peak luminosity are fully consistent with those obtained by R01 (see Fig. 3).

5 RESULTS

5.1 GRBs with known redshift

First of all we evaluated the time variability of the GRBs (13) common to our sample and to that by R01, in order to test the mutual consistency of our results with those obtained by R01.

5.1.1 Variability

Figure 4 compares the two time variability estimates. As can be seen, the results are well consistent with each other, except for three cases (970228, 991216, and 000131).

For each of these GRBs we investigated the reason of the discrepant measure of $V_{f=0.45}$ first of all by trying to reproduce the results by R01 using KONUS data alone for 970228 and BATSE data alone for the other two.

5.1.2 GRB 970228

In order to reproduce R01’s results for 970228 we used the same data set, i.e. the light curve by KONUS. The only difference is that we used public data that include a single light curve in the 50–200 keV energy band, while R01 used three different energy bands: 10–45 keV, 45–190 keV and 190–770 keV. R01 report the smoothing time-scale for each of the three energy channels and only the global variability measure derived from merging the three different measures according to the procedure described therein. Our measure of the smoothing time-scale is $2.82 \pm 0.32$ s to be compared with that obtained by R01 for the same energy channel, i.e. $2.891$ s (no error is reported), thus consistent. Our variability measure with KONUS data is $0.19 \pm 0.04$ to be compared with R01’s one, $0.08 \pm 0.05$. The measure obtained with GRBM data, $0.22 \pm 0.02$, well agrees with our KONUS measure (see Fig. 3), but does not with R01 KONUS one. The measure reported by R01 was derived from the three energy channels; this might partially explain the difference. However, we notice that our KONUS measure is $2.2\pm 0.8$ apart from the R01 value of $0.08$. We are led to think of two potential sources of discrepancy between our measure and R01’s. First, the overall time interval containing the GRB might be different; second, the extrinsic scatter that R01 find on the global measure of $V_{f=0.45}$ is a little underestimated with respect to what we find comparing a single KONUS channel with the R01 global measure. We address the reader to the R01 paper for a definition of the extrinsic scatter of variability due to the different energy channels derived for each GRB. Since we neither have the same KONUS data as R01, nor we know the overall time interval adopted by R01, we cannot establish conclusively the reason for the discrepancy for this GRB. However, concerning the first possibility, we tentatively adopted other time intervals trying to match the variability measure reported by R01. We find a variability measure of $0.08 \pm 0.03$ for a time interval including the first sharp pulse and lasting about 40 s until the first pulse following a quiescent interval from the very first pulse. It must be pointed out that our true measure was performed on a 80-s long interval, since there is evidence for emission. This could be a hint for the possible explanation of the discrepancy.

5.1.3 GRB 991216

For this GRB we adopted the measure obtained with GRBM data and we already discussed the reasons in Sec. 5.1. Here we try to reproduce the R01 results using the same BATSE data and then compare our variability measures on each energy channel with the merged value derived by R01. In Figure 5 we show the variability published by R01 for a common sample of 13 GRBs. The dashed line shows the equation corresponding to equality. See text.
smoothing time-scale values and those obtained by R01. Therefore we are led to conclude that our variability measures should match consequently. On this basis, from Fig. 5 we notice that the extrinsic scatter by R01, whose 1-σ region is displayed through dashed lines, seems to be little underestimated. In fact, the channel 1 measure is 2.6-σ below and the channel 3 is 3-σ above. In addition to this, we remind that for this particular GRB exhibiting sharp pulses we know from GRBM data that a time binning of 64 ms is too coarse (see Fig. 1 and discussion in Sec. 3.1). We therefore conclude that the effect of a higher scatter of variability at different energy channels than that estimated by R01, combined with the fact the for this GRB a binning time of 64 ms seems inadequate, account for the discrepancy between our measure of variability for 991216 and that published by R01.

5.1.4 GRB 000131

For this GRB we made use of BATSE data while R01 used KONUS data. Unfortunately the public KONUS data of this GRB do not cover the whole profile, so we are bound to use BATSE data alone and compare our variability measures with the R01 value. Figure 6 displays the variability as a function of the BATSE energy channel and dashed lines show the R01 estimate. The reasons of the discrepancy, which is apparent from Fig. 6 are due to the different smoothing time-scales: by comparing our set of four values with the three ones corresponding to the three lower KONUS channels (the light curve of channel 4 cannot be used according to R01), our values are systematically greater than R01’s. If we adopt the same time-scales obtained by R01 we get variability measures which are consistent within the scatter with the R01 value. Thus, the two sets of variability measures are consistent within errors for each single BAT channels.

5.1.6 Variability/Peak Luminosity

Figure 8 and Table 1 show the $V_{f=0.45}$ vs. Peak Luminosity for the entire sample of 32 GRBs with known redshift. Dashed lines show the best-fitting power-law relationship found by R01 along with the ±1σ width, according to which $L \propto V_{f=0.45}^{m}$, where $m = 3.3^{+1.1}_{-0.9}$. Apparently, from Fig. 8 the correlation between the GRB variabil-

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Figure 8. $V_f=0.45$ vs. Peak Luminosity for GRBs with known redshift. Dashed lines mark the best-fitting power-law relationship found by R01 (central line) and ±1σ widths.

Table 2. Correlation Coefficients for GRBs with known redshift. We also report among brackets the mode values obtained from simulations.

<table>
<thead>
<tr>
<th>Kind</th>
<th>Coefficient</th>
<th>Probability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pearson’s $r$</td>
<td>0.514 (0.412)</td>
<td>0.0026 (0.019)</td>
</tr>
<tr>
<td>Spearman’s $r_s$</td>
<td>0.625 (0.612)</td>
<td>0.0001 (0.0002)</td>
</tr>
<tr>
<td>Kendall’s $\tau$</td>
<td>0.446 (0.436)</td>
<td>0.0003 (0.0005)</td>
</tr>
</tbody>
</table>

Table 3. Best-fitting power-law parameters of the $L$ vs. $V_f=0.45$ correlation for GRBs with known redshift.

<table>
<thead>
<tr>
<th>Method</th>
<th>$m$</th>
<th>$q$</th>
<th>$\chi^2$/dof</th>
</tr>
</thead>
<tbody>
<tr>
<td>Least-square fit</td>
<td>$1.30^{+0.84}_{-0.43}$</td>
<td>$3.36^{+0.89}_{-0.43}$</td>
<td>1167/30</td>
</tr>
<tr>
<td>Least-absolute-deviation fit</td>
<td>$1.16^{+0.65}_{-0.17}$</td>
<td>$3.32^{+0.49}_{-0.15}$</td>
<td>1145/30</td>
</tr>
</tbody>
</table>

where the peak luminosity is $L = L_{50} \times 10^{50}$ erg cm$^{-2}$ s$^{-1}$, independently of the method used for the fit (usual least-square fit or minimization of absolute deviations, see Press et al. 1993), we find unsatisfactory results ($\chi^2 > 1000$, 30 dof, in either cases). Just to compare our best-fitting power-law model results with those obtained by R01, in Table 3 we report the best-fitting parameters of the power-law for the two fit methods above mentioned. In Fig. 8 we report the 1σ contour plot of the best-fitting parameters $m$ and $q$. As can be seen, the two parameters are highly correlated.

We also evaluated the statistical uncertainty in the log $L_{50}$ as a function of $V_f=0.45$, taking into account the correlation between the two parameters. In Fig. 8 the point corresponding to GRB 980425 is out of the plot window to avoid scale compression, but its variability is affected by a large uncertainty ($0.049^{+0.045}_{-0.048}$) (see Table 1).

5.2 Luminosity correction for GRB beaming

For the GRBs with known redshift, we also investigated the correlation between variability $V_f=0.45$ and peak luminosity after correcting the luminosity values given in Table 1 for the GRB beaming an-
Figure 10. Top Panel: Beaming-corrected rest-frame Peak Luminosity $L_{p,\gamma}$ vs. Variability for a subset of 16 GRBs with known redshift and beaming angle (Ghirlanda et al. 2004). Also shown are two lower limits (971214 and 011121) and three upper limits (000131, 000911 and 010921). Bottom Panel: $L_p$, isotropic-equivalent Peak Luminosity vs. Variability for the same 16 GRBs.
Figure 9. Contour plot of the 1σ region of the two best-fitting parameters $m$ and $q$ (least-square fit) in the case of $V_{f=0.45}$.$L$.

Table 4. Correlation Coefficients for 16 GRBs with known redshift and beaming angle: $V$ vs. beaming-corrected $L_{p,γ}$ (first two columns) and $V$ vs. isotropic-equivalent $L_p$ (last two columns).

<table>
<thead>
<tr>
<th>Kind</th>
<th>$V$ vs. $L_{p,γ}$</th>
<th>$V$ vs. $L_p$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pearson’s $r$</td>
<td>0.664</td>
<td>0.005</td>
</tr>
<tr>
<td>Spearman’s $r_s$</td>
<td>0.653</td>
<td>0.006</td>
</tr>
<tr>
<td>Kendall’s $τ$</td>
<td>0.467</td>
<td>0.012</td>
</tr>
</tbody>
</table>

6 For a couple of them, i.e. 041006 and 050525, the values derived by the same authors are taken from the following web site: http://www.merate.mi.astro.it/~ghirlanda/deep/blink.htm

larger sample (32 events) of GRBs is used. In this case the correlation between $V_{f=0.45}$ and $L$ is confirmed (significance $≤3×10^{-4}$ according to non-parametric tests), but the data points are spread out in only two regions of the parameter space, with a bad description of the data points ($χ^2 > 1000$, 30 dof) with a power-law function, which was the best-fitting function found by R01. If, in spite of that, this function is used as fit model, the power-law index derived from our data ($m = 1.3_{-0.2}^{+0.3}$) is much lower than that found by R01 ($m = 3.3_{-0.2}^{+1.1}$) and inconsistent with it. The correlation becomes less significant (see the comparison between the two sets of correlation coefficients in Table 4) when we correct the isotropic-equivalent peak luminosity for the GRB beaming, in contrast with the result found by Ghirlanda et al. (2004) who find a lower spread of the Amati et al. (2002) relationship when they perform this correction.

7 CONCLUSIONS

We have tested the correlation found by R01 between peak luminosity and time variability following the same method used by R01 with a larger sample of GRBs. For 32 GRBs with known redshift we confirm the existence of a correlation between the measure of time variability defined by R01 and the isotropic-equivalent peak luminosity. However we find a much higher spread of the data points in the parameter space, with the consequence that the correlation cannot be described by a power-law function as found by R01. If, in spite of that, we fit the data with this function we find that the power-law index ($1.3_{-0.2}^{+0.3}$) is much lower and inconsistent with that found by R01 ($3.3_{-0.2}^{+1.1}$). If we correct the peak luminosity for the GRB beaming, the correlation is less significant.

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REFERENCES

Berger E., Bradley Cenko S., Steidel C., Reddy N., Fox D.B., 2005, GCN 3368
Berger E. & Becker G., 2005, GCN 3520

On the GRB Variability-Peak Luminosity Correlation

Djorgovski S.G. et al., 2001b, GCN 1108
Donaghy T.Q. et al., 2005, GCN 3128
Frontera F. et al., 1997, A&AS, 122, 357
Fugazza D. et al., 2004, GCN 2782
Fynbo J.P.U., Hjorth J., Jensen B.L., Jakobsson P., Møller P., 2005a, GCN 3136
Fynbo J.P.U. et al., 2005b, GCN 3176
Galama T.J. et al., 1999, GCN 388
Greiner J., Günter E., Klose S., Schwarz R., 2003a, GCN 1886
Infante L., Garnavich P.M., Stanek K.Z., Wyrzykowski L., 2001, GCN 1152
Kelson D. & Berger E., 2005, GCN 3101
Müller J.W., 1973, Nucl. Instr. Meth. 112(1), 47
Müller J.W., 1974, Nucl. Instr. Meth. 117(2), 401
Vreeswijk P.M. et al., 1999, GCN 496.

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