Study of GRB light curve decay indices in the afterglow phase

R. Del Vecchio[1], M.G. Dainotti[2,1], M. Ostrowski[1].

(1)Astronomical Observatory, Jagiellonian University, Poland.
(2) Physics Department, Stanford University, USA.

E-mail: roberta@oa.uj.edu.pl, mdainott@stanford.edu, mio@oa.uj.edu.pl.

Abstract

We study the distribution of temporal power-law decay indices, α, in the Gamma Ray Burst (GRB) afterglow phase, fitted for 164 long GRBs with known redshifts. These indices are compared to the characteristic values of the afterglow luminosity, $\log L_a$, the time, $\log T_a^*$, and the (analogous) decay index, α_W, derived using a global light curve fitting proposed by Willingale et al. (2007). Analysis of the (α, $\log L_a$) distribution reveals only a weak correlation of these quantities. However, we discovered a significant regular trend when studying GRB α values along the $\log L_a$ versus $\log T_a^*$ (LT) distribution, with systematic variation of the α parameter distribution with luminosity for any selected T_a^*. We analyze this systematics with respect to the fitted LT correlation line (Dainotti et al. 2008, 2013). Study of the presented systematic trend may allow one for constraining the physical models for GRBs and thus may be a step toward establishing a procedure for GRB standardization. As a simple example of such procedure we used a toy model with simple linear scaling of $\log L_a$ with α at each T_a^* to slightly diminish the luminosity scatter in the LT distribution.

Data

The analyzed GRB light curves were obtained from the Swift catalogue using the BAT and the XRT telescopes with fluxes in the range $0.3-10$ keV (Swift Catalogue website: http://swift.gsfc.nasa.gov/). Each GRB light curve has its own peculiarity thus making difficult to fit the afterglow with simple power-laws (O'Brien et al. 2006). In the present analysis we use power-law fits of α to limited in time parts of the decaying light curve, where where the power-law decay is clearly obeyed. As a reference sample we used the one presented by Dainotti et al. (2013), and updated until July 2014, applying the Willingale et al. model fitting of the full afterglow light curve, providing the characteristic afterglow plateau luminosity L_a, time scale T_a^*, and the decay index α_W for the decaying light curve section (Fig. 1, left panel).

Analysis

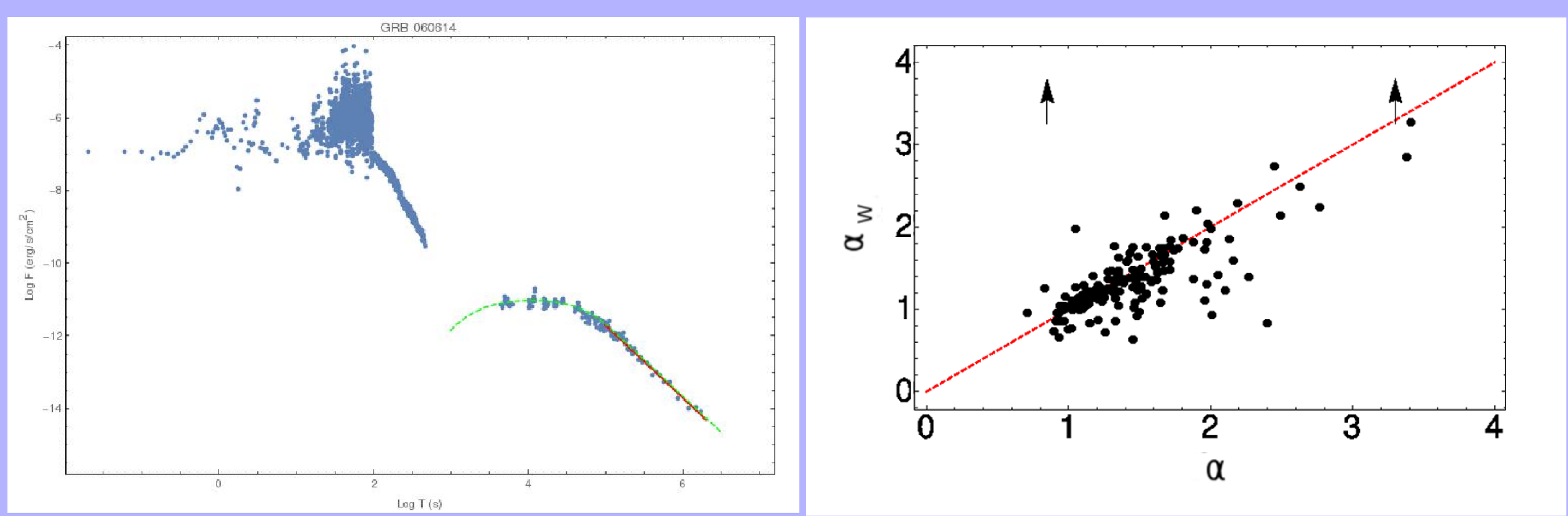

Fig. 1: Left panel: comparision of the light curve fitting methods for the GRB 060614: the power-law model (solid red line) and the Willingale et al. (2007) model (green dashed line). Right panel: the α_W versus α distribution, with the arrows pointing to the outliers (GRB 060607A and GRB 120422A) in the Willingale model fitting.The red dashed line $\alpha = \alpha_W$ is provided for reference.

One may note that having the α and α_W distributions similar, for individual fits a significant difference may occur. Inspection of the Willingale et al. global fits shows that in some cases the fitted line do not fit the limited power-law section of the decaying light curve well. Thus in the further analysis we will use only α values fitted by us, to be compared with L_a and T_a^* provided by the global fit.

The distribution of afterglow luminosity versus α is presented at the left panel of Fig. 2. One may note large scatter of points leading only to a weak correlation with the correlation coefficient $\rho = 0.23$ and chance probabilty $P = 0.12$. However, existence of the correlation in the presented data becomes unquestionable if we make comparison of the distributions in three groups (with equal numbers of GRBs) in the luminosity ranges: low $log\ L_a < 47.65$, medium $47.65 < log\ L_a < 48.7$ and high $log\ L_a > 48.7$. Distributions of α in the three analyzed luminosity ranges are presented in Fig. 3, with analyzed subsamples of long GRBs (including or excluding XRFs), short GRBs and XRFs. There is no clear difference between long GRBs and XRFs, but the low luminosity dominated XRF subsample is insufficient for firmly analyzing the trends. The KS test shows that it is highly unlikely ($P = 0.002$) that the low luminosity (red) and the high luminosity (blue) subsample distributions of long GRBs and XRFs are drawn randomly from the same population.

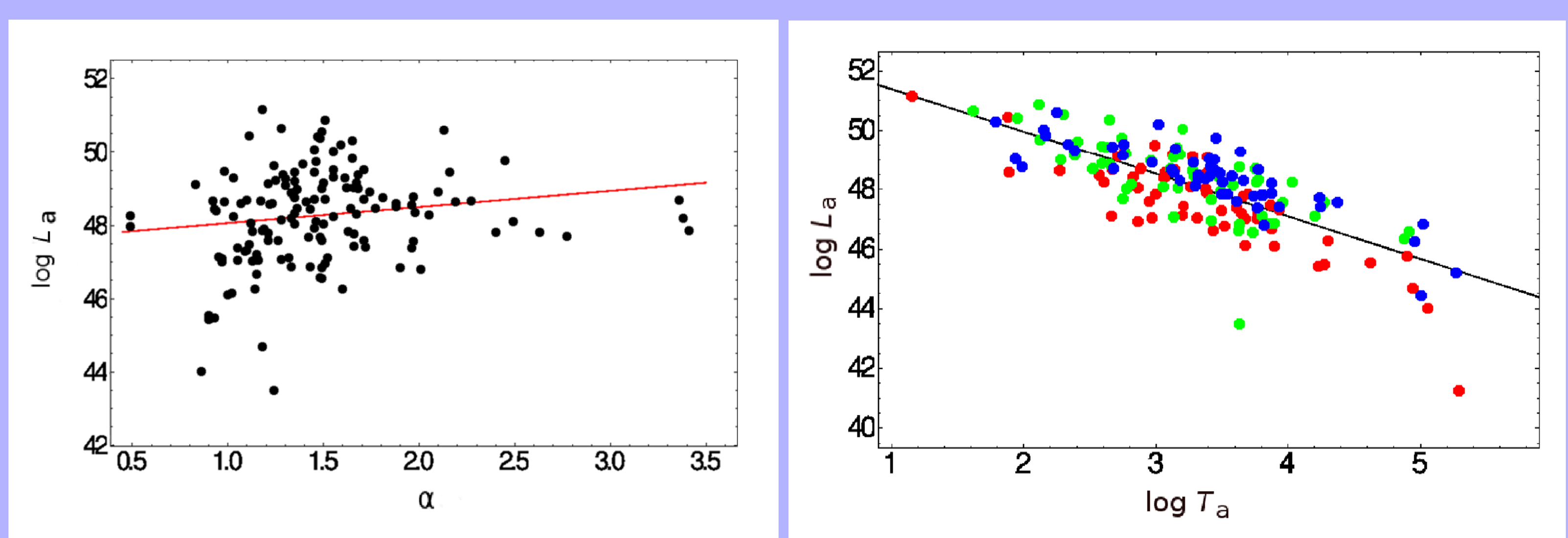

Fig. 2: Left panel: distribution of $\log L_a$ versus α. The line presents a fitted weak correlation. Right panel: distribution of selected α subsamples: $0.53 < \alpha < 1.23$ (red), $1.23 < \alpha < 1.54$ (green) and $1.54 < \alpha < 3.41$ (blue). The presented LT correlation line was derived for the full sample.

Having the above result in mind and the pointed by Dainotti et al. (2008) LT correlation, we decided to analyze the LT distribution with α as a third parameter. To proceed we split our GRB sample into three subsamples for α ranges, the flat $0.53 < \alpha < 1.23$ (red), the medium $1.23 < \alpha < 1.54$ (green) and the steep $1.54 < \alpha < 3.41$ (blue) subsamples, each with the same number of elements (Fig. 2, right panel). One may note a systematic relative vertical shift of these distributions. To describe it in a more quantitative way we relate each $\log L_a$ at a given T_a^* to the value at the correlation line, $\log L_{a,0}$, as a "distance" $\log L_a - \log L_{a,0} \equiv \log\ (L_a/L_{LT})$. Distribution of such distances versus α (Fig. 4, left panel) reveals a significant correlation, fitted as

$$\log L_a - \log L_{LT} = 0.64\,\alpha - 0.90 \quad . \qquad (1)$$

Here, for the observed tendency of having steeper light curve decay for higher – with respect to the LT correlation line – afterglow luminosity, the correlation coefficient is $\rho = 0.47$, but due to large number of points the correlation is highly significant with $P = 3.2 \times 10^{-9}$. In the right panel a histogram of the distributions of $\log L_a(T_a^*) - \log L_{LT}(T_a^*)$ for the three α ranges is presented.

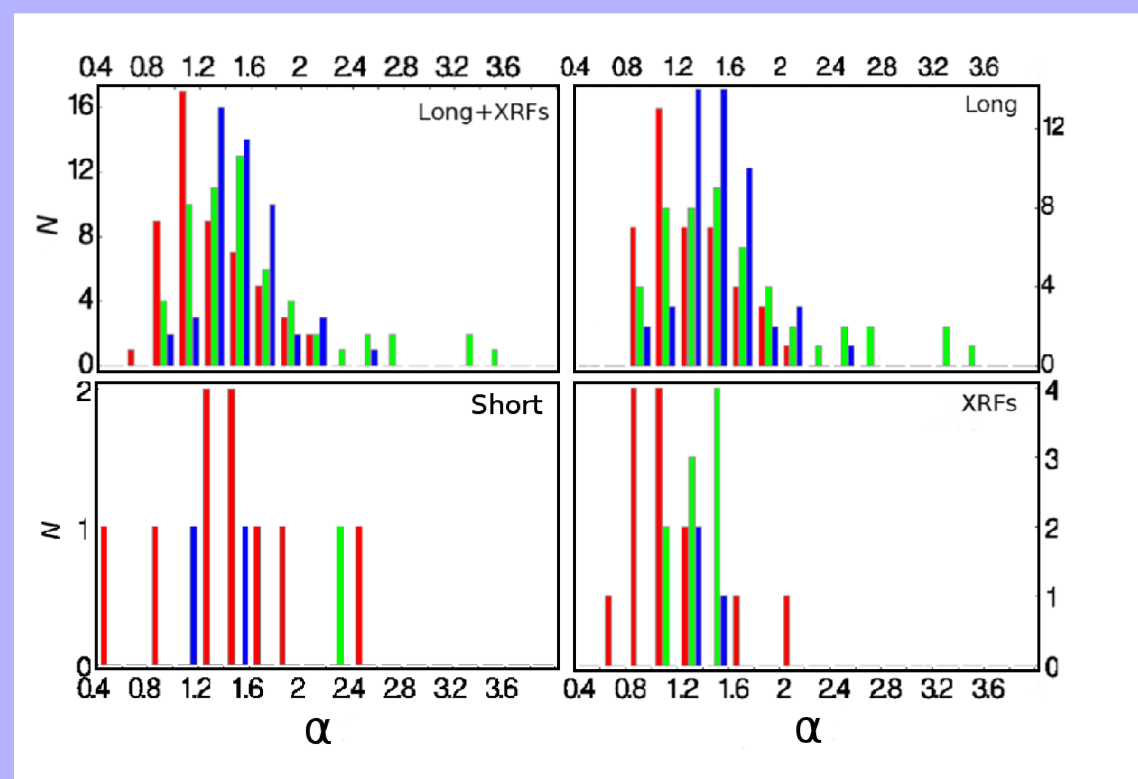

Fig. 3: Distributions of α indices for the analyzed GRB subsamples in 3 considered luminosity ranges: $\log L_a < 47.65$ (red), $47.65 < \log L_a < 48.7$ (green) and $L_a > 48.7$ (blue). Top: on the left the distribution of α is presented for 164 long GRBs and XRFs; on the right the distribution for 142 long GRBs (excluding XRFs). Bottom: on the left the distribution of α for 12 short GRBs, while on the right the distribution for 25 XRFs.

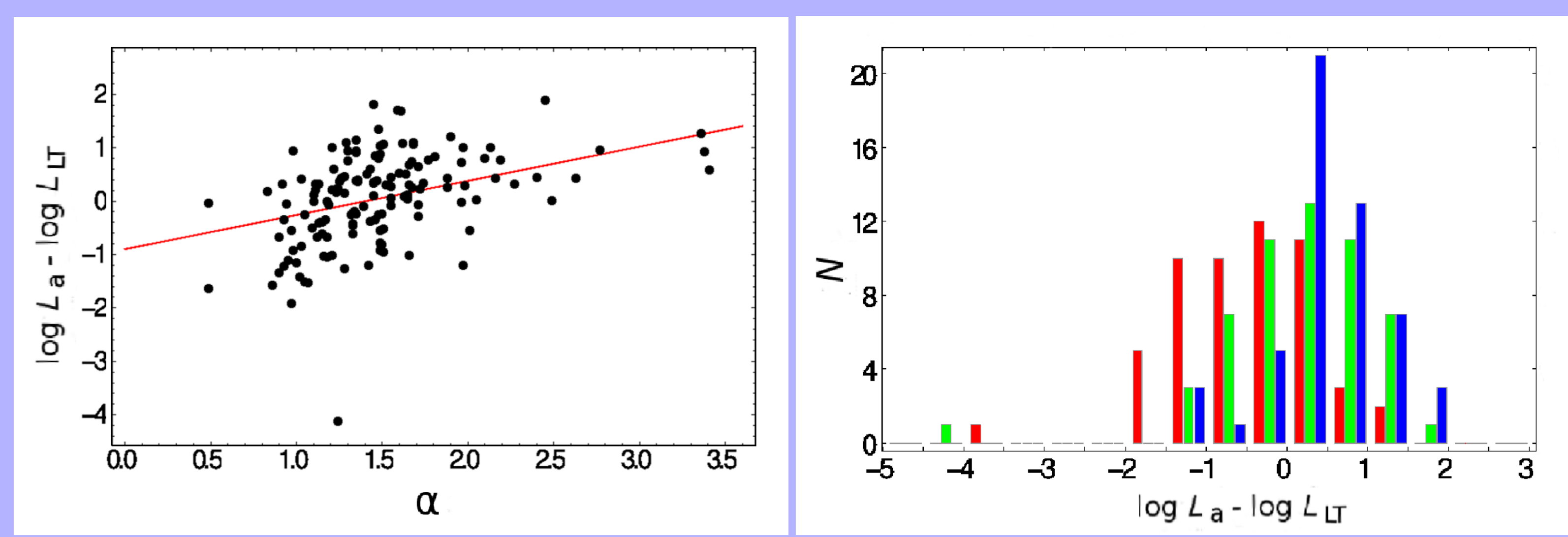

Fig. 4: Left panel: distribution of $\log L_a - \log L_{LT}$ versus α, with the fitted correlation line (see Eq. 1). Right panel: distributions of $\log L_a - \log L_{LT}$ for the three considered ranges of α.

The dependence of the afterglow luminosity on α reflects variation of some particular parameter in the GRB physical mechanism, then the discovered correlation can be used to scale GRBs with different luminosities to the one for a particular single value of this parameter. Such standardization procedure for GRBs, qualitatively resembling the one used for standardization of SN Ia light curves (Phillips 1993), can not be applied in a simple way due to large scatter in the $\log\ (L_a/L_{LT})$ versus α distribution. Before carefully analyzing this issue planned for the future work let us present an *illustrative toy model* for such approach. By arbitrary defining the standard (reference) GRB as the one characterized with the value of the decay index $\alpha_0 = 1.4$, approximately the mean value for our α distribution, one can propose the following scaling procedure for deriving the standardized GRB luminosity $L_{a,0}$, from the observed L_a, with scaling from the decay index α to α_0. Using Eq. 1:

$$\log L_{a,0} = \log L_a + 0.64\,(\alpha_0 - \alpha) \quad . \qquad (2)$$

This procedure applied for all 164 events in the analyzed sample of long GRBs (including XRFs) results in increasing the LT correlation coefficient absolute value, from $\rho = -0.75$ for the original ($\log L_a$, $\log T_a^*$) data to $\rho_0 = -0.81$ for the modified distribution ($\log L_{a,0}$, $\log T_a^*$).

Conclusions

1) We discovered a systematic difference of the α index distributions between the afterglow low, medium and high luminosity GRB subsamples.
2) When analyzing the LT distribution we discovered systematic, statistically significant shifts of low, medium and high α range subsamples with respect to the LT correlation line.
3) The $\log L_a - \log L_{LT}$ versus α analysis could be helpful to decrease the scatter in analysis of the LT distribution.
4) The work on application of this feature for GRB standardization is in progress.

Acknowledgements

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References

Dainotti, M.G., Cardone, V.F., & Capozziello, S. (2008), *"A time-luminosity correlation for γ-ray bursts in the X-rays"*, MNRAS, 391, L79.
Dainotti, M.G., Petrosian, V., Singal, J., & Ostrowski, M. (2013), *"Determination of the Intrinsic Luminosity Time Correlation in the X-Ray Afterglows of Gamma-Ray Bursts"*, ApJ, 774, 157.
O'Brien, P. T., Willingale, R., Osborne, J., Goad, M. R., Page, K. L., Vaughan, S., Rol, E., Beardmore, A., Godet, O., Hurkett, C. P., Wells, A., Zhang, B., Kobayashi, S., Burrows, D. N., Nousek, J. A., Kennea, J. A., Falcone, A., Grupe, D., Gehrels, N., Barthelmy, S., Cannizzo, J., Cummings, J., Hill, J. E., Krimm, H., Chincarini, G., Tagliaferri, G., Campana, S., Moretti, A., Giommi, P., Perri, M., Mangano, V., & LaParola, V. (2006), *"The Early X-Ray Emission from GRBs"*, ApJ, 647, 1213.
Phillips, M.M. (1993) *"The absolute magnitudes of Type IA supernovae"*, ApJL, 413, L105.
Willingale, R., O'Brien, P.T., Osborne, J.P., Godet, O., Page, K.L., Goad, M.R., Burrows, D.N., Zhang, B., Rol, E., Gehrels, N., & Chincarini, G. (2007), *"Testing the Standard Fireball Model of Gamma-Ray Bursts Using Late X-Ray Afterglows Measured by Swift"*, ApJ, 662, 1093.