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On the duration-luminosity relation of GRB pulses during the prompt emission

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Relations linking the temporal and spectral properties of the prompt emission of gamma-ray bursts to the absolute luminosity are of great importance as they both constrain the radiation mechanisms and represent potential distance indicators. In a recent work we took into consideration two of such relations: the lag-luminosity relation and the duration-luminosity relation of GRB pulses. By connecting lags to the spectral evolution and the shape of the pulses from a linear expansion of the pulse properties around the maximum and coupling it to the duration-luminosity relation, we obtained the lag-luminosity and the lag-duration relations, checked also by a Monte-Carlo generation of GRB synthetic populations. We found that the duration-luminosity relation must be satisfied to reproduce the observational peak flux diagram of BATSE GRB pulses.
Here we extend our analysis by discussing how duration-luminosity relation could be compatible with the internal shock model of the prompt emission of GRBs.

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1. Introduction

The duration-luminosity relation (DLR) links the time duration and the absolute luminosity of pulses inside bursts. It is written

$$\log L_{51}(erg/s) = (1.5 \pm 0.2) - (0.85 \pm 0.2) \log w(s), \tag{1.1}$$

where L is the absolute peak luminosity (in $10^{51} erg/s$), w-the time duration (in s), the time interval between intensities Ae^{-3} of the pulse amplitude A. This relation is discovered for 12 pulses inside 7 bursts with known redshifts and 38 pulses inside 22 bursts without known redshifts [1]. The presence of an anticorrelation between peak flux and pulse duration of long GRBs is also found by a statistical study of 307 pulses inside 152 bursts. A fit of the duration w-peak photon flux P diagram with a model

$$\log P = A \log w + B \tag{1.2}$$

gives that $A = -0.27$ (with correlation coefficient $R = 0.36$) [2].
DLR seems to be important for obtaining GRB redshifts by using pulse durations [3].

DLR is obtained at the same time with the correlation between lag and pulse duration:

$$\log w(s) = (1.27 \pm 0.01) + (0.85 \pm 0.01) \log l(s), \tag{1.3}$$

where l is the pulse peak lag between BATSE bands 1 and 3 [1].

In a previous work [4] we recognized that lags are better defined using individual pulses rather than the whole burst profile. We connected in a very transparent way lags between BATSE bands 1 and 3 to the spectrum (peak energy E_p, low and high energy indices α,β), their evolution ($d\alpha/dt$, $d\beta/dt$, dE_p/dt) and the shape (curvature C) of the pulses by using a linear expansion of the pulse properties around maximum. We found:

$$\frac{l}{w} = f(\alpha, \beta, E_p, d\alpha/dt, d\beta/dt, dE_p/dt, C), \tag{1.4}$$

where f is a certain function faintly sensitive to the variation of the above mentioned parameters around the most accepted values found by the observation.
This expression was interpreted as a correlation between lag and pulse duration.
We than coupled this result with the Amati-like relation [5]:

$$E_p(keV) = 380 \left(\frac{L}{1.6 \cdot 10^{52} erg/s} \right)^{0.43} \tag{1.5}$$

to find a theoretical Lag-Luminosity Relation (LLR) [6].

Recently [7], instead of (1.5) we couple our result (1.4) to the DLR for obtaining the theoretical LLR. We find that both relations, LLR and DLR, remain fairly robust even when the parameters are varied by large amounts. At the same time, the agreement with observational data is satisfactory.

2. An Alternative Test for the DLR

In [7] we use also a synthetic population of GRB pulses, for which we predict an observational duration-peak photon flux diagram, to be compared with the real data found in [2]. This population is generated following a Monte-Carlo method, similar to the one previously used by Daigne, Rossi and Mochkovitch [8]:

1. We draw a redshift for each pulse for having GRB rate (R_{GRB}) proportional to the star formation rate SFR3 [9].

2. We draw a luminosity adopting a power law luminosity function $L^{-\delta}$, $1.5 < \delta < 2$, which reproduces the $\log N - \log P$ BATSE curve [8].

3. We draw spectral indices α and β in agreement with the distributions found by Preece et al. [10].

4. The peak energy is either obtained from the luminosity with eq. (1.5) or has a log-normal value, adjusted to provide a good fit of the peak energy distribution of bright BATSE bursts.

The test is based on checking the two ways of defining the pulse duration: we either assume the validity of DLR or adopt a log-normal distribution of central value and dispersion adjusted to reproduce the observed distribution of pulse duration in the Hakkila and Cumbee sample [2]. We take into account an approximate k-correction effect and apply the detection criteria available for BATSE.

A fit of the duration-peak photon flux diagram obtained by a high number of bursts produced with Monte-Carlo method by a power law $P \sim w^{-s}$ gives respectively: $s = 0.27$ with the DLR and $s = 0.09$ without DLR. In the first case, the agreement with the observational data (1.2) is excellent, while the correlation almost disappears in the second case (see [7] for more details).

Our study indicates that an intrinsic correlation of the DLR-kind between pulse duration and luminosity is necessary to reproduce the observed diagram.

3. DLR and the Internal Shock Model

Assuming the validity of the duration-luminosity relation, we try to see if it can be understood in the context of the internal shock model for the prompt emission of GRBs. For this purpose, we adopt a numerical code generating photon's high energy emission (first established and used by Daigne and Mochkovitch [11]), when layers with different velocities collide inside a relativistic wind with a highly non-uniform distribution of the Lorentz factors. The dissipated energy is radiated in the gamma-ray range by means of synchrotron shock emission.

Our input data are:

1. A distribution of Lorentz factors with a contrast value 4.

2. Three different values for the released energy during the shocks: $10^{51.5} erg$, $10^{52.5} erg$ and $10^{53.5} erg$. These values are taken in agreement with the observed E_{iso} distribution [12], where $10^{52.5} erg$ is the mean energy and $[10^{51.5}, 10^{53.5}]$ is $1-\sigma$ interval around this value.

3. The intrinsic photon spectrum for each collision is considered a broken power-law with a break at energy E_p and low and high energy slopes α, β. The peak energy is taken (see also [13]):

$$E_p = C\rho^x \varepsilon^y, \tag{3.1}$$

where ρ is the post shock density and εc^2, the dissipated energy per unit mass in the commoving frame. We fix two reference cases for the eq. (3.1): $x = 1/2$, $y = 1/2$ and $x = 1/4$, $y = 1/4$ (for more arguments see [14]). To fix the value of C in each burst we make use of the Amati-like relation (1.5).

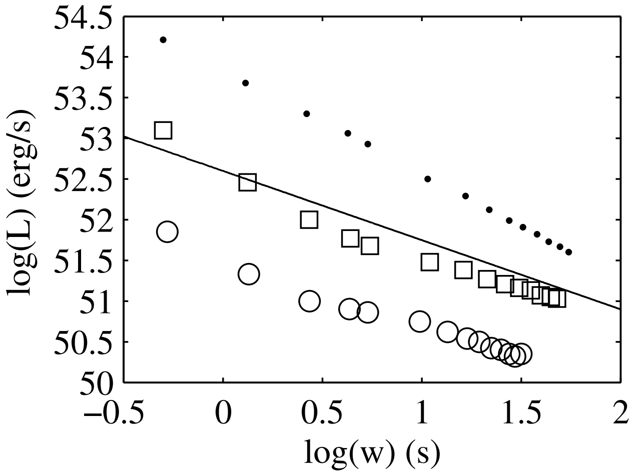

Figure 1: Three sequences of bursts corresponding to $E_p = C\rho^x\varepsilon^y$ with $x = 1/2$, $y = 1/2$. The circles correspond to the total released energy $10^{51.5}erg$, squares to energy $10^{52.5}erg$ and points to $10^{53.5}erg$. The most probable zone would be that around the squares. The continuous line represents the observed DLR.

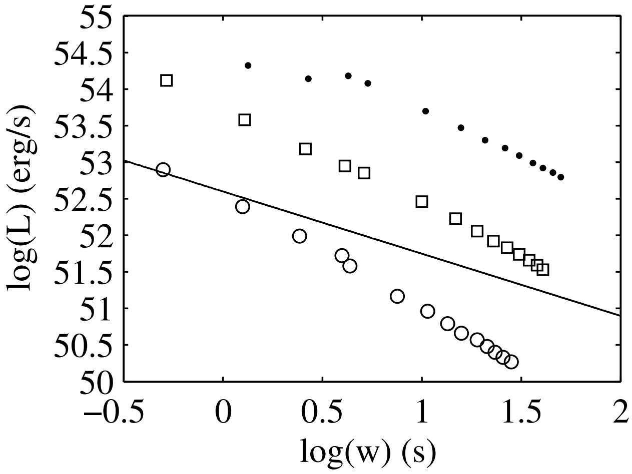

Figure 2: Three sequences of bursts corresponding to $E_p = C\rho^x\varepsilon^y$ with $x = 1/4$, $y = 1/4$. The circles correspond to the total released energy $10^{51.5}erg$, squares to energy $10^{52.5}erg$ and points to $10^{53.5}erg$. The most probable zone would be that around the squares. The continuous line represents the observed DLR.

We get monopulse GRBs with different peak luminosities and durations. We plot the diagram $\log L - \log w$ in each reference case, obtaining three sequences of bursts corresponding to the above mentioned released energies (see fig.1 and fig.2). At each figure we put the representative straight line of the observed DLR.

We tested the variations in Lorentz factor distribution and found that they slightly change the slope of burst sequences, keeping always the decreasing tendency.

We find an interesting agreement between the theoretical and observed DLR and deduce that the DLR can be understood in the context of ISM for the prompt emission of GRBs. Remark that the case 1 approaches better the observational data, so the DLR's slope can be seen as an indicator of the interior physical processes.

4. Conclusions

1. There is a need for better measuring and understanding GRB pulse properties, which could be more closely linked to the physics of GRB than the burst itself.

2. Different approaches indicate the possibility of a duration-luminosity correlation.

3. The DLR would offer a new method to estimate GRB distances, simpler and easier to use than LLR.

4. The DLR can be explained in the context of the Internal Shock Model.

5. The internal physical processes of the gamma-ray production would be responsible for the shape of the DLR.

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