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The time lag-luminosity relation: A consequence of the Amati relation?(*)

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Summary. — We use a simple pulse model to investigate the origin of the time lag-luminosity relation (LLR) discovered by Norris *et al.*(*ApJ*, **534** (2000) 248). We show that, at least for single pulse bursts which satisfy both the hardness-intensity and the hardness-fluence correlations, the LLR can be simply obtained as a consequence of the Amati relation.

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1. – Introduction

The problem of the distance to gamma-ray bursts remained unsolved until the discoveries of the afterglows by Beppo-SAX. With now ~ 40 measured redshifts, it has been possible to calibrate relations linking absolute burst outputs (luminosity or total radiated energy) to quantities directly available from the observations in gamma-rays. A Cepheid-like relation between variability and luminosity was for example proposed by Reichart *et al.* [1]. More recently, Atteia [2] used the Amati relation [3] to introduce "pseudo-redshifts" which could for example be useful to rapidly identify high-z GRBs from their gamma-ray properties alone. Here we concentrate on the time lag-luminosity relation discovered by Norris *et al.* [4]. The lags were computed by Norris *et al.*by cross-correlating burst profiles in BATSE bands 1 (20–50 keV) and 3 (100–300 keV). They found that high-luminosity GRBs exhibit small lags and proposed a power law relation

$$L = 1.3 \times 10^{53}\ (\Delta t_{13}/0.01\,\mathrm{s})^{-1.14} \quad \mathrm{erg\,s^{-1}}$$

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between the lag Δt_{13} and the luminosity. The origin of the LLR was then investigated by Kocevski and Liang [5] who found that the observed lags were a consequence of the burst spectral evolution. In this contribution we go a step further and show that the LLR must indeed be satisfied, at least by single pulse GRBs which follow the hardness-intensity (HIC [6]), the hardness-fluence (HFC [7]) and the Amati correlations.

2. – The pulse model

We suppose that the number of photons produced during the pulse per unit time and unit energy can be written $\mathcal{N}(E,t) = A(t)\mathcal{B}\left[E/E_{\rm p}(t)\right]$ where $E_{\rm p}(t)$ is the instantaneous value of the peak energy and $\mathcal{B}(x)$ the spectrum shape, assumed to be two smoothly connected power laws. The function $\mathcal{B}$ depends on $x = E/E_{\rm p}$ only if both the low and high energy slopes α and β of the spectrum do not vary with time during pulse evolution. We make this rather crude approximation which allows a simple estimate of the bolometric photon rate

$$N_b(t) = \int_0^\infty \mathcal{N}(E,t)\mathrm{d}E = A(t)E_{\rm p}(t)\mathcal{B}_0,$$

where $\mathcal{B}_0 = \int_0^\infty \mathcal{B}(x)\mathrm{d}x$. We also suppose that $N_b(t)$ and $E_{\rm p}(t)$ satisfy the HIC and the HFC after a time t_0 during pulse decay

$$E_{\rm p}(t) \propto N_b(t)^\delta \qquad \text{and} \qquad E_{\rm p}(t) \propto e^{-a\Phi_{\rm N}(t)}$$

where $\Phi_{\rm N}(t) = \int_0^t N_b(t')\mathrm{d}t'$ is the photon fluence the photon fluence and a an exponential decay constant. Ryde and Svensson [8] have shown that this implies, for $t > t_0$, that $N_b(t)$ and $E_{\rm p}(t)$ behave as

$$N_b(t) = \frac{N_0}{1+\frac{t-t_0}{\tau}} = \frac{N_0}{1+Q(T-1)}\ ,\ E_{\rm p}(t) = \frac{E_0}{\left(1+\frac{t-t_0}{\tau}\right)^\delta} = \frac{E_0}{\left(1+Q(T-1)\right)^\delta},$$

where $Q = t_0/\tau$ and $T = t/t_0$. When $t < t_0$ we adopt a parabolic form for $N_b(t)$

$$N_b(t) = N_0\left[(2+Q)T - (1+Q)T^2\right],$$

i.e. $N_b(t)$ and its time derivative are continuous at $t = t_0$ ($T = 1$). Also, $N_b(t) = 0$ at $t = 0$ and is maximum at $T_{\max} = (2+Q)/2(1+Q)$. Since the maximum of hardness generally precedes the maximum of count rate we tried for $E_{\rm p}(t < t_0)$ different parabolic shapes having their maximum before $T_{\max}$ but it appeared that a simple linear extension of $E_{\rm p}$

$$E_{\rm p}(t) = E_0\left[1 + \delta\, Q(1-T)\right]$$

gave essentially the same results. Expressions for $N_b(t)$ and $E_{\rm p}(t)$ being known it is possible to obtain the pulse shape $N_{ij}(t)$ in any band $[E_i, E_j]$

$$N_{ij}(t) = N_b(t)\frac{\mathcal{B}_{ij}(E_{\rm p})}{\mathcal{B}_0},$$

where $\mathcal{B}_{ij}(E_{\rm p}) = \int_{x_i}^{x_j}\mathcal{B}(x)\mathrm{d}x$ with $x_{i,j} = E_{i,j}/E_{\rm p}$.

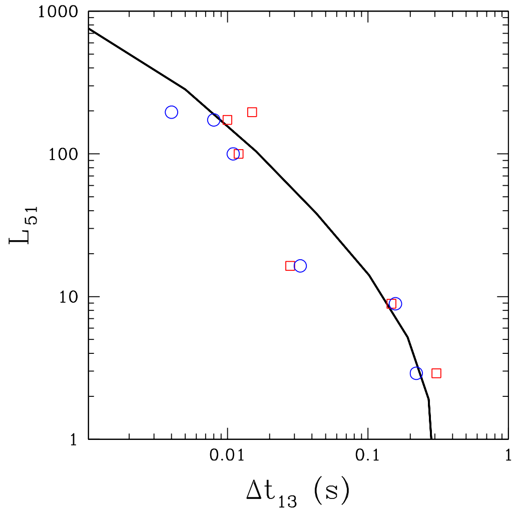

Fig. 1. – Lag-luminosity relation obtained with our model compared to the Norris *et al.* [4] data points. The squares and circles respectively correspond to lags calculated from profiles going down to 0.1 and 0.5 of the peak intensity.

3. – The lag-luminosity relation

3˙1. *Method of calculation.* – We obtain the time lag-luminosity relation by using the Amati relation coupled to our pulse model. For a given pulse shape (fixed by the values of Q, δ and t_0) we choose E_0, the value of E_p at $t = t_0$ and cross-correlate the profiles in BATSE bands 1 and 3 to get the time lags. We then compute the spectrum for the whole pulse and determine its global E_p. When E_p is known the Amati relation

$$\mathcal{E}_\mathrm{iso} = 10^{52}\left[\frac{E_\mathrm{p}}{200\,\mathrm{keV}}\right]^{2.17}\ \mathrm{erg}$$

gives the isotropic radiated energy $\mathcal{E}_\mathrm{iso} = \int_0^\infty L_b(t)\mathrm{d}t$, where $L_b(t)$ is the bolometric luminosity. The bolometric luminosity reads

$$L_b(t) \propto N_b(t)\, E_\mathrm{p}(t)$$

and the value of $\mathcal{E}_\mathrm{iso}$ from the Amati relation fixes the proportionality constant which finally allows to compute the peak luminosity L_max of the pulse.

3˙2. *Results.* – We present in fig. 1 the lag-luminosity relation for $Q = 0.5$, $\delta = 0.75$, $t_0 = 2$ s and $z = 1$. These values lead to a pulse lasting 10–15 s and the adopted spectral parameter δ is typical of the results obtained by Ryde and Svensson [8] ($0.4 < \delta < 1$). The agreement with the data points [4] is satisfactory (for each of the bursts the Norris *et al.* [4] is satisfactory (for each of the bursts the squares and circles respectively correspond to lags calculated from profiles going down to 0.1 and 0.5 of the peak intensity).

We have then considered the effects of a variation of the pulse parameters δ and Q on the lag-luminosity relation. It appears that changes of the spectral evolution (δ) and pulse shape (Q) do not strongly affect the LLR. Moreover, these quantities can in principle be determined from the data if it is of sufficient quality.

But this does not mean that estimating burst distances with the LLR is an easy task. The curve in fig. 1 was obtained assuming a fixed redshift $z = 1$ but in practice the redshift is just the quantity to be determined. Variations of redshift affect the LLR through K-corrections on the pulse profiles in different energy bands and time dilations of the lags. A method to correct the observed lags from these cosmological effects has been proposed by Norris [9]. The method allows to fix the redshift via an iterative procedure when the modeled peak flux agrees with the observed one. A preliminary analysis in the context of our model however shows that this method remains partially degenerate, especially for large lags where it appears difficult to distinguish between weak bursts at small z and bright ones at large z.

4. – Conclusion

We have presented a simple pulse model to show that the lag-luminosity relation discovered by Norris *et al.* [4] can be considered as a consequence of the HIC, HFC and Amati relation. We have studied the sensitivity of the LLR relative to the parameters fixing the pulse shape and spectral evolution. Concerning the use of the LLR as a distance indicator we believe that it is not accurate enough to yield the redshift of any specific burst but could still be useful for the analysis of large samples.

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