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X-ray emission of GRBs: what is the light curve morphology telling us?

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Abstract. The analysis and classification of a sample of X-ray light curves of 64 long Gamma-ray bursts (GRB) observed by *Swift*/XRT without flaring activity reveals indeed similarities among different parts of the light curves. In this paper we focus on the shallow decays phases: we show that a spinning-down magnetar that powers the forward shock can quantitatively account for the shallow decay properties. In particular we demonstrate that this model can account for the plateau luminosity vs. end time anticorrelation found by Dainotti et al. (2008, 2010).

Key words. gamma-ray: bursts – radiation mechanism: non-thermal – X-rays

1. Introduction

We analysed a sample of 64 long GRBs observed by *Swift*/XRT from April 2005 to April 2010. Among all the *Swift* GRBs observed in this period, we selected GRBs with redshift measurements and without flaring activity in their X-ray afterglow. The luminosity light curves in the rest frame were fitted adopting a simple power-law or a smoothly-joined broken power-law model (more details about the data analysis, sample selection and fitting procedure can be found in Bernardini et al. 2011).

The light curves can be classified on the basis of the best-fitting function: Type 0 shows a single power-law decay; Type Ia and Type Ib show one break in the light curve and a shallow-to-steep or steep-to-shallow transition respectively; Type II shows two breaks in the light curve. A three-break model is not required to improve the best fit of any light curve of the sample. The present sample contains 22 Type 0 light curves, 20 Type Ia, 7 Type Ib and 15 Type II.

These different classes reveals indeed similarities among different parts of the light curves. In particular, the K-S test comparing the slopes α_2^{Ib} (the second, shallow segment) of Type Ib and α_2^{II} (the plateau) of Type II for the entire sample gives a 49% probability that they represent the same population. A probability of 6% is found for the K-S test comparing the slopes α_1^{Ia} (the first, shallow segment)

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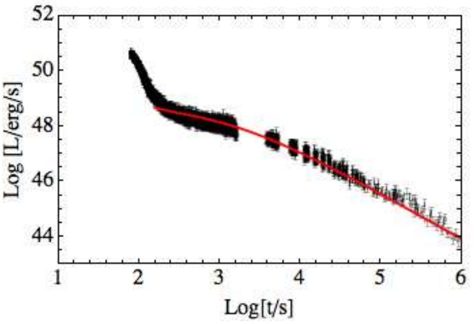

Fig. 1. GRB090618 light curve compared with the best fit obtained with the model presented in Dall'Osso et al. (2011) (red line).

of Type Ia and α_2^{II} of Type II. In this paper we focus on these shallow decay phases and, starting from the predictions of a specific energy injection model for the Type II plateau, we interpret them in a common framework.

2. The shallow decay phase as energy injection from spinning-down neutron star

The intermediate shallow decaying phase observed in Type II light curves is usually identified with an injection of energy into the forward shock (see e.g. Zhang et al. 2006, and references therein). The absence of significant spectral evolution during this stage and the correspondence of the following "normal" decay with the standard afterglow scenario (see Bernardini et al. 2011) are in agreement with this interpretation[1].

A possible source of energy injection is the power emitted by a spinning-down newly-born magnetar (Zhang & Mészáros 2001; Dai & Lu 1998) that refreshes the forward shock (see Dall'Osso et al. 2011 for an analytic treatment of this problem). We applied the solution of Dall'Osso et al. (2011) to our sample and we find that it fits well enough the observed light curves (see e.g. Fig. 1, for details see Bernardini et al. 2011). The major advantage of this interpretation is that all the plateau properties are directly related to the central engine. The basic informations can be derived from two main quantities: the magnetic field B and the period P of the pulsar. In particular they are all is needed to explain the anticorrelation between the plateau luminosity L_p and the second break time $t_{b2} = t_p$ found by Dainotti et al. (2008, 2010).

Assuming that the B and P are normally distributed around the mean values we found for our sample, we calculated the spindown timescale $t_2 \propto B^2/P^2$ and the corresponding luminosity $L(t_2)$ according to the model by Dall'Osso et al. (2011). Using an average spectral index $\tilde{\beta} = 1$, we normalised the luminosity in the rest frame $0.3 - 10$ keV energy band corresponding to the average redshift of the Dainotti et al. (2010) sample, $\tilde{z} = 2.29$. The results are portrayed in Fig. 2: we obtained the normalisation, the slope and the scatter of the Dainotti et al. (2010) anticorrelation.

We plot in Fig. 2 the luminosity at the break time $L(t_{b1})$ of Type Ia light curves in the rest frame energy band corresponding to $\tilde{z} = 2.29$ and we find that they follow the same luminosity-time anticorrelation, and they can be interpreted as the spin-down luminosity of a millisecond pulsar for the same distribution of B and P than for Type II. We add to Fig. 2 also Type Ib last observation as a lower limit on the end of the injection phase and an upper limit on the luminosity. The possibility to have injection times up to 10^5 s, as observed in Type Ib light curves, is allowed within reasonable values of the magnetic field and period (see Fig. 2). However, the upper limit on luminosity found for some Type Ib is lower than the expected one, unless we assume that the injection time is $\gtrsim 10^6$ s. We argue that a different beaming factor and/or efficiency in converting the spin-down power in X-rays may account for such Type Ib light curves.

3. Conclusions

In this work we show that similarities among the shallow decays in Type Ia, Ib and II point to a common origin. We adopt the analytic

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[1] The applicability of the magnetar model to GRBs displaying a very steep decay after the plateau inconsistent with the forward shock emission has been investigated by Lyons et al. (2010).

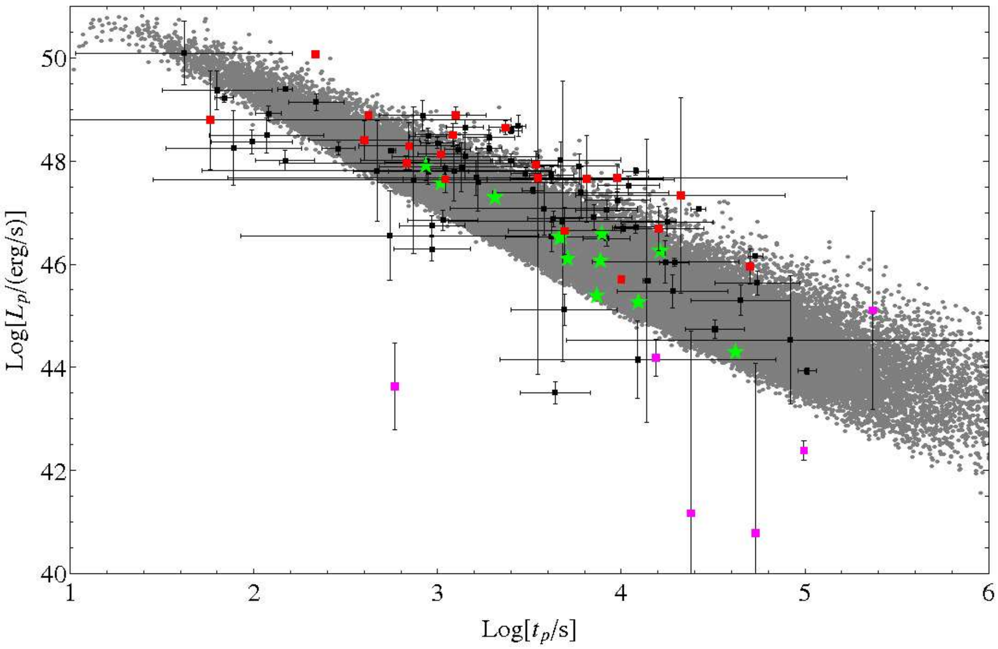

Fig. 2. Luminosity at the end time versus end time of the plateau phase. The black squares are the sample analysed by Dainotti et al. (2010). The red squares are Type Ia light curves of our sample and the pink squares are the luminosity of the last observation in Type Ib light curves of our sample. The gray dots are the 100000 simulations of the luminosity at the spindown time and the spindown time assuming that the magnetic field and the NS period are normally distributed around the mean values we found for our sample. The green stars are the values found for our best fit with Dall'Osso et al. (2011) model.

model detailed by Dall'Osso et al. (2011) that describe the energy injection into the forward shock powered by a spinning-down newly-born magnetar and we showed that:

- the injection phase observed in Type Ia and II can be interpreted as power emitted from spinning-down ultramagnetised neutron star that refreshes the forward shock. We applied such a model to a our sample and we found that it fits well enough the data;
- this scenario accounts for the observed $L_p - t_p$ anticorrelation Dainotti et al. (2008, 2010): we reproduced the normalisation, slope and scatter of the anticorrelation starting from plausible values of the parameters. The consistency of Type Ia shallow decay with the anticorrelation within 99% confidence level suggests that they can be reproduced by this model with the same distribution of B and P than for Type II.

The magnetar model is suitable to explain the different morphology of the X-ray continuum and the properties of the shallow decay. Its main constraint is related to the energy budget. The maximum energy emitted in such a model is of the order of a few 10^{52} erg and limited by the maximum rotation energy attainable by a rotating neutron star (Usov 1992). The energy budget strongly depends on the uncertain estimate of the jet angle, however in few cases the released energy may be high enough to challenge the model (Cenko et al. 2010).

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