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On the origin of afterglow "plateaus" in gamma-ray bursts

A broad-band spectro-temporal analysis

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Abstract. The afterglow emission of gamma-ray bursts (GRBs) often shows a nearly constant flux evolution ("plateau") lasting ∼hours after the prompt emission. Plateaus are typically observed in X-rays but in a fraction of events they are also observed in the optical bands. The origin of the plateau is still unknown and several interpretations have been proposed. In this work we investigate the spectro-temporal properties of plateaus observed in X-rays with well monitored optical counterparts for a sample of 29 GRBs, aiming to disentangle different interpretations. We identify a "golden" sample of 15 GRBs, and for 13 of which we find evidence of a plateau also in optical, with *R*-band flux densities consistent with a broad-band synchrotron spectrum in the framework of the standard external-shock model. Considering the full sample, 26 GRBs (∼ 90%) have the optical and X-ray flux densities consistent with the same synchrotron spectrum during the X-ray plateau temporal window. We discuss our findings in the context of two possible interpretations of the plateau origin. As a general conclusion, our broad-band analysis proved to be a powerful diagnostic to identify GRBs with plateau features consistent with a standard synchrotron scenario and those for which a more complex scenario should be considered in their interpretation.

Key words. Stars: gamma-ray bursts

1. Introduction

Gamma Ray Bursts (GRBs) are among the most fascinating astrophysical sources and the recent association of the gravitational wave source GW170817 (Abbott et al. 2017b) with the short GRB 170817A (Abbott et al. 2017a) has further increased the interest in these objects also in the nascent field of multi-messenger astrophysics. Despite the huge steps forward that have been achieved in our understanding of GRBs over the last two decades, a number of open questions still remains to be answered. Among the most compelling is the issue of whether a stable newborn neutron star (NS) is left after the burst rather than a black hole. The GRB remnant nature has profound implications for the physics of jet formation, the neutron star equation of state, as well as the possible detection of continuous emission of gravitational waves from newly-born NS temporally and spatially identified through the GRB emission.

The general properties of GRB afterglow emission at late times (i.e. $> 0.5 - 1$ day) are fairly well described within the paradigm of the standard fireball model by synchrotron radiation from shock-accelerated electrons (Sari et al. 1998). However, the fast pointing capabilities (~minutes) of the X-ray telescope (XRT) onboard the *Neil Gehrels Swift Observatory* (Gehrels et al. 2004) enabled the discovery of unpredicted features in the early afterglow light-curves (< 0.5 day). In particular, a large fraction ($\sim 70\%$) of X-ray afterglows show a peculiar shallow flux decay phase ("plateau", e.g. Nousek et al. 2006) not accompanied by any spectral evolution during the later transition to the "standard" afterglow decay. Among the X-ray afterglows with evidence of a plateau, about $\sim 40\%$ have an optical counterpart (e.g. Dainotti et al. 2020). Past studies have shown average optical plateau properties to be consistent with those found in X-rays (e.g. Si et al. 2018; Dainotti et al. 2020).

So far no firm conclusion has been reached on the plateau origin, but they are widely believed to encode crucial information on GRB physics. The current leading interpretation invokes a continuous energy injection into the external shock that originates the afterglow. The source of energy can be a newly formed spinning-down NS with a large magnetic field (a magnetar). This scenario has been successfully tested on the observed X-ray afterglow light curve morphologies and luminosities (Dall'Osso et al. 2011; Rowlinson et al. 2013; Li et al. 2018; Strang et al. 2021). Stratta et al. (2018) adopted the spinning-down NS model to fit individual X-ray light-curves of 40 GRBs with an X-ray plateau, and found further support for the magnetar scenario in the resulting magnetic field (B) versus spin period (P) distribution. The latter was indeed perfectly consistent with the well known spin-up line for accreting Galactic X-ray pulsars (e.g. Bhattacharya & van den Heuvel 1991; Pan et al. 2013), with for typical NS masses (~ 1 $M_\odot$) and radii ($\sim 10 - 20$ km), once re-scaled for the mass accretion rates expected in GRBs (10^{-4} $M_\odot$/s $< \dot{M} < 0.1$ $M_\odot$/s).

In a completely different paradigm, plateaus have been interpreted as delayed prompt high latitude emission (HLE) from a structured jet where the energy and velocity distributions decrease gradually towards the edges (Oganesyan et al. 2020). The expected HLE from structured jets lasts longer compared to a spherical emitting shell in which all parts travel at the same speed. Morevoer, the wider relativistic beaming angle at increasing latitudes from the jet axis results in an observed flattening of the flux for some time, during which the Doppler factor is roughly constant while the emission from lateral portions of the jet progressively reaches the observer. This model, that was successfully tested on two GRBs (Oganesyan et al. 2020), can explain the temporal evolution of the plateau and post-plateau phases. At the same time it allows for spectral chromaticity of the plateau, as the X-ray component comes from the structured jet while the optical one is produced by the external shock (Oganesyan et al. 2020), or even from the structured jet itself.

In this work we explore the broad-band spectro-temporal behaviour of the plateaus, from X-rays to optical, for a sample of GRBs for which this feature is identified. We aim at constraining the plateau origin by looking for inconsistencies with one or both of the two above mentioned scenarios.

2. The sample

The very definition of a "plateau" is not compatible with the predictions of the standard fireball model for GRB afterglows (e.g. Sari et al. 1998). Specifically, plateaus are defined by a phase of very shallow afterglow flux decay that steepens ~ hours after the burst, with no evidence of spectral evolution at or after the steepening. This behaviour is in contrast with the expectations from synchrotron emission where flux decay steepenings mark the crossing of a characteristic synchrotron frequency in that band, with consequent spectral softening[1].

Plateaus are typically observed in X-rays, thus we build our sample of GRBs with evidence of plateaus by analyzing their X-ray afterglow properties. X-ray afterglow light curves were taken from the publicly available Swift/XRT Repository[2] (Evans et al. 2007, 2009) and modelled with a series of power-law segments $F(t) \propto t^{-\alpha}$. We selected those events that present at least one segment with $-0.8 \leq \alpha \leq 0.8$ within errors that is followed by a steeper decay and for which no spectral softening during the transition and no spectral evolution during the plateau is evident.

This phenomenology is indeed not predicted by the standard afterglow model (Sari et al. 1998). In order to test the plateau luminosity from a magnetar remnant, we selected only GRBs with known redshift to compute the intrinsic luminosity (Ronchini et al. in prep.).

The final sample counts ~ 145 GRBs. Among these GRBs, 29 events have optical afterglows for which a continuous long monitoring was performed, ensuring light curves with good temporal resolution (i.e. > 10 data points) within 1 day after the burst (Kann et al. 2010, 2011, Kann et al. 2022 in prep.). For 14 GRBs the optical afterglow shows early rising phases, multiple "bump" features or late rebrightenings that prevent reaching any conclusion on the possible presence of a plateau counterpart (hereafter "silver sample"). For the remaining 15 GRBs such additional features are not dominant and the optical light curves can be smoothly described by simple or multiple power-laws with increasing decay index that allow a clear identification of possible plateau counterparts (hereafter "golden sample").

3. Data analysis

3.1. Optical and X-ray temporal evolution

We first compare the afterglow temporal properties in X-rays and the optical band for the GRBs belonging to the "golden sample" without making any assumptions on the plateau origin. To this aim, we fitted a smoothly broken power-law model to the X-ray and optical data as $F(t) \propto [(t/T_b)^{s\alpha_1} + (t/T_b)^{s\alpha_2}]^{-1/s}$ by assuming a realistic smoothness parameter of $s = 3$ and then we compare the best fit parameters. We excluded from our fit the late time observations that could be described by a second temporal break and a further steepening of the power-law decay, possibly due to a jet break (see e.g. Sari et al. 1999).

3.2. Optical to X-ray spectral evolution

We further investigate the broad-band behaviour of the afterglow light-curves with the goal of verifying whether on not the optical counterparts of X-ray plateaus are consistent with being part of the same synchrotron spectrum that fits the X-ray data. In this analysis, we included also the "silver subsample" for which we were unable to robustly identify a plateau feature in the optical.

Independently of the assumed interstellar matter density profile (i.e. constant or wind), the optical-to-X-ray afterglow synchrotron spectrum after the peak emission (i.e. during the decay phase) can be a simple or broken power-law. In this work, we restrict our analysis to the slow cooling regime where the peak emission at frequency ν_m is below

[1] Achromatic flux steepenings can be due also to a "jet break" (Sari et al. 1999) but these are typically observed at late epochs (> few days).

[2] https://www.swift.ac.uk/xrt_curves/

the cooling frequency ν_c. In this regime, the optical-to-X-ray spectrum can be a broken power-law with indices $\beta_{\rm opt} = \beta_X - 0.5$ or a power-law with index $\beta_{\rm opt} = \beta_X$ (Sari et al. 1998). We start by measuring the afterglow X-ray spectral indices β_X at different epochs during and after the plateau phase. Then, at each epoch, we compute the maximum and minimum allowed R-band fluxes by extrapolating the X-ray fluxes to the R-band for $\beta_{\rm opt} = \beta_X$ and $\beta_{\rm opt} = \beta_X - 0.5$, respectively (see Figure 1 as an example). Results has been stored in a dedicated, publicly available repository[3]. A self-consistency check has been applied by proving that the expected optical spectral index $\beta_{\rm opt}$ is consistent with the one independently measured from the observations of each GRB. To this aim, the optical fluxes have been corrected for dust extinction within our galaxy and the host galaxy.

To obtain reliable constraints on measured β_X at different epochs, we decreased the temporal resolution of the light-curves by widening the time bins provided by the Swift/XRT Repository. In particular, we adopted the following criteria: 1) the bin should contain $>$ 500 counts; 2) the plateau phase should contain $>$ 2 bins. In each temporal bin, we perform a spectral analysis using XSPEC, version 12.10.1 and PyXspec. We consider only photons in the band 0.5 − 10 keV. We assume an absorbed power-law spectrum. Since for all the GRBs of our sample the redshift is known, we distinguish a Galactic absorber and the host galaxy absorber. The specific syntax in XSPEC is tbabs*ztbabs*pow. The Milky Way host equivalent hydrogen column density N_H is set to the values provided by Kalberla et al. (2005), while the GRB host galaxy N_H is set to the value measured from the integrated spectra during the post-plateau phase where we do not expect strong spectral evolution, as also has been verified in the literature.

[3] `https://giovixo.github.io/grb-plateau/`

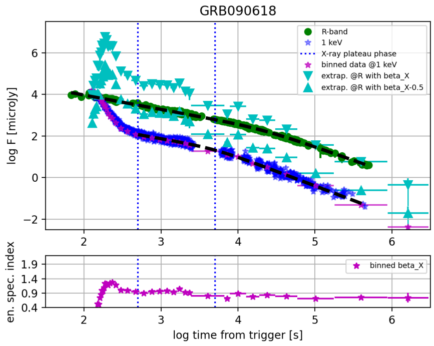

Fig. 1. Example of a broad-band spectro-temporal analysis, for GRB 090618. *Top panel:* Blue stars and green dots represent the afterglow X-ray and R-band flux density, respectively. The black dashed line is the broken power-law fitted over the data set spanned by the line. Vertical blue dotted lines indicate the X-ray plateau afterglow phase lasting at $T_{b,X}$. Cyan down and up triangles mark the maximum and minimum flux values extrapolated from X-rays assuming a simple power-law with spectral index $\beta_{opt,X} = \beta_X$ and $\beta_{opt,X} = \beta_X - 0.5$, respectively. Magenta points represent the rebinned data where the X-ray spectral index was measured. In this case, the optical data during the X-ray plateau phase are clearly consistent with the allowed range of values for synchrotron emission, with ν_c slowly crossing the optical band. *Bottom panel:* The X-ray spectral index evolution with time.

4. Results

From the temporal analysis of the optical light curves belonging to the “golden sample”, 13 out of 15 GRBs show a plateau-like feature[4]. In addition, the optical flux of each of these GRBs is within the range predicted by extrapolating the corresponding X-ray flux into the optical band, assuming a synchrotron spectrum in the slow cooling regime (§3). Moreover, when the plateau durations (T_b) are well constrained by the data both in the X-ray and optical band[5], we

[4] The two outliers, GRBs 060908 and 140419A, show a steep ($\alpha > 0.8$) power-law decay in the optical with no temporal break.

[5] For GRB 140430A the X-ray plateau duration could not be constrained due to missing XRT data. For GRB 060502 T_b could be only poorly constrained by optical data.

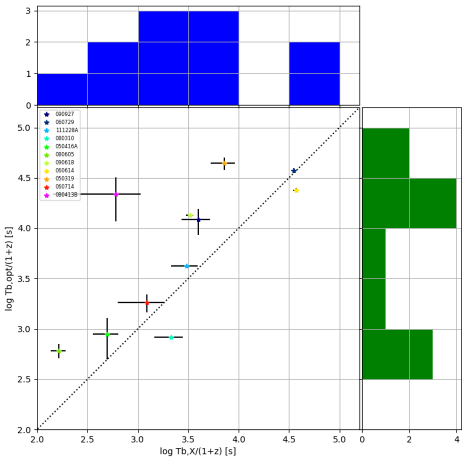

Fig. 2. Plateau rest-frame durations in the X-ray (horizontal) and optical (vertical) regime for the GRBs belonging to the "golden" sample for which the end of the plateau (T_b) could be well constrained both in the X-ray and optical band.

compare their rest-frame values and find that in 4 out 11 (~ 36%) of the cases they are consistent within 1σ; these plateaus can be considered as strictly achromatic (see Fig. 2). In 5 of the remaining 7 GRBs the optical plateaus last longer than in the X-rays (from a few to a several times longer), implying some degree of chromaticity. In two cases (GRBs 060614 and 080310) the optical plateau is slightly shorter than the X-ray one (hence still a "chromatic" behaviour).

From the broad-band spectro-temporal analysis of the "golden" and "silver" samples, we find that in all but three cases (GRBs 060906, 060908 and 081029), i.e. ~ 90% of the events, the optical flux in each time bin of the X-ray plateau duration lies between the minimum and maximum extrapolation of the X-ray flux measured in the same time bin, having assumed a synchrotron spectrum.

Moreover, in the two cases with highest statistics and smooth optical light-curve (GRBs 090618 plotted in Fig. 1 and 111228A) we were able to identify a steady drift of the optical flux from the minimum extrapolation of the X-ray flux (at early times) to the maximum extrapolation of the X-ray flux (at later times). This result implies an evolution of the broad-band synchrotron spectrum from a broken to a simple power law, a behaviour consistent with the expected evolution of the cooling frequency from $\nu_{\rm opt} < \nu_c < \nu_X$ to $\nu_c < \nu_{\rm opt}$ (Sari et al. 1998).

5. Discussion and conclusions

In this work we analyzed 29 GRBs with evidence of a plateau in the X-ray afterglow light-curve and well monitored optical counterparts, searching for possible inconsistencies with or confirmations of the main scenarios invoked for the plateau origin (§1). The results of our analysis of the "golden sample" show that in 13 out 15 GRBs the plateau has an optical-to-X-ray spectrum fully consistent with synchrotron emission from a single shock-accelerated electron population. The comparison of the temporal properties of the X-ray and optical plateaus further confirm this interpretation. Indeed, the fact that the optical flux densities lie within the allowed range of values extrapolated from X-ray fluxes assuming a single synchrotron spectrum, allows us to infer $\nu_{\rm opt} \leq \nu_c < \nu_X$. This condition implies a slower evolution of the optical plateau than the X-ray one, in agreement with our findings that $T_{b,\rm opt} \geq T_{\rm b,X}$ in most of the GRBs belonging to the "golden sample" (Fig. 2).

The consistency of the optical and X-ray data with a single spectrum can be interpreted as an indication that both X-ray and optical photons originate from the same region. For the magnetar scenario, in which the spinning-down newborn NS pumps energy into the forward shock, this is a very natural result being the emitting region the forward-shock front. In the HLE hypothesis, on the other hand, our findings could only be explained if the optical emission is coming from the same region of the jet that is producing the X-rays and not, e.g., from another region of the jet with a lower Lorentz factor, and by requiring that the prompt HLE always dominates over the afterglow. The lack of significant spectral changes at the transition from the plateau to the post-plateau phase in X-rays adds to the difficulties of this interpretation, as it would require that even the post-plateau is dominated by HLE from the prompt region.

When we include the "silver sample" in our analysis (i.e. 14 more for a total 29 GRBs) the compatibility with a single spectrum remarkably still holds for most. However, we also find three cases in which the optical data not only do not show clear evidence of a plateau but are also incompatible with a single broad-band spectrum. For these three events we can therefore confidently exclude that a single synchrotron-emitting region can explain the observed broad-band spectrum.

In particular, for GRBs 060906 and 060908 the optical data lie below the minimum flux allowed by the X-ray flux extrapolation and additional exploration of the spectral parameter space is required to interpret this phenomenology. On the other hand, the optical data of GRB 081029 lie above the maximum flux allowed by the X-ray flux extrapolation and this afterglow also shows a complex light-curve morphology. If we assume a magnetar origin of the X-ray plateau in this GRB, then we need to invoke the presence of an additional and unexpected component to account for the optical emission. The HLE scenario, on the contrary, naturally predicts two separate emission regions, namely the structured jet (X-rays) and the external shock (optical), and is thus better suited to explain cases similar to GRB 081029, though more detailed investigations are required.

As a general conclusion, the broad-band spectro-temporal analysis shown in this work proved to be a powerful diagnostic to identify GRBs with plateaus that are fully consistent with an external shock origin in energy injection scenarios, separating them from plateaus that support multiple emission regions and therefore alternative scenarios, and even to isolate outliers whose unexpected properties prevent a simple classification and call for further exploration of the analyzed parameter space.

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