Achromatic Breaks for Swift GRBs: Any Evidence?

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Summary. — The availability of multi-wavelength high-quality data of gamma-ray burst afterglows in the Swift era, contrary to the expectations, did not allow us to fully confirm yet one of the most fundamental features of the standard afterglow picture: the presence of an achromatic break in the decaying light curve. We briefly review the most interesting cases identified so far.

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1. Introduction

In the currently accepted picture, the material powering gamma-ray burst emission is believed to be collimated in a narrow outflow with opening angle \( \vartheta_j \). Following this scenario, the afterglow models predict a steepening in the light curve decay. As long as the bulk Lorentz factor is \( \Gamma \geq 1/\vartheta_j \), an observer whose line of sight is inside this angle has no knowledge of what is outside the jet, and the outer edge of the jet visible to the observer expands just like in the spherically symmetric case. As the flow decelerates, the Lorentz factor eventually drops below \( 1/\vartheta_j \), so that the observer sees the physical edge of the jet and the observed light curve decays faster. This break should happen simultaneously at all frequencies [1][2].
Indeed, in observations over a limited wavelength range, transitions involving a temporal steepening consistent with the theoretical expectations for a jet break have been seen in many cases [3] (see for instance the prototypical case of GRB 990510 [4, 5, 6]). The jet opening angle inferred through these observations imply a significant degree of collimation, so that the total energy budget emitted by GRBs is close to $E_\gamma \sim 10^{51}$ erg [7]. Moreover, following the interpretation of these breaks as due to jetted geometry, several correlations between the beaming-corrected energetics and other GRB properties have been discovered [8], reinforcing the interpretation of these transitions as actual jet breaks.

Although the behaviour in the asymptotic regimes (i.e. well before and after the transition) is well-known, there is still no full consensus about the details of the break shape, where many effects might play a role. However, roughly independently of the jet structure, the break is predicted to be essentially achromatic apart from minor effects which do not deeply affect the overall scenario [9, 10]. It is therefore important to verify whether full achromaticity of breaks interpreted as due to jets are confirmed by means of prompt and follow-up observations in the Swift era.

2. – Optical and X-ray observations

The Swift prompt response to GRBs has allowed unprecedented coverage of the X-ray afterglow evolution from a few tens of seconds up to several weeks after the high-energy event [11]. The coverage in the optical band, on the contrary, could not regularly be of comparable quality. This is due to a combinations of factors. First, there are no large optical facilities on a regular basis devoted to GRB studies. The large increase in the number of GRBs promptly located with arcsec positional accuracy (about 2–3 per week following the Swift launch) has more than compensated the sometime generous time allocation at various observatories. Groups involved in follow-up studies are often forced to concentrate the efforts on a few events neglecting several others. Second, continuous observations are more difficult from ground, due to a number of constraints (visibility, weather conditions, etc.). Moreover, worldwide coordination among afterglow observers to combine together all the observations is still lacking. In particular, when only a few datapoints are available, data frequently remain unpublished or poorly calibrated. Last, as a matter of fact, the optical counterparts of the GRBs localised by Swift are also on average fainter than those localised by previous missions like BeppoSAX and HETE-II [12], probably due to an average larger redshift [13]. This makes it difficult for medium-sized telescopes to follow the afterglow decay long enough to collect a complete light curve. The UVOT telescope [14] onboard Swift is seldom able to monitor the optical afterglow evolution for longer than a few hours.

To further complicate the picture, it is now clear that afterglow light curves are much more rich than previously thought, displaying rebrightenings, flares, phases of shallow and steep decay [15, 16, 17, 18]. At least some of these behaviours are due to extra components contributing to the flux (possibly originating from prolonged activity in the GRB central engine), and to a complex jet dynamical evolution (which may not be adiabatic in the first hours after the GRB). Some of the mechanisms shaping the light curves are also hydrodynamical, and can produce achromatic breaks not related to geometric effects.

Despite the above limitations, it is quite surprising that among the 180 bursts so far detected by Swift, Fall of 2006, only a few showed clear breaks in their optical light curves. In many cases, no break at all could be seen in the optical, despite extensive
monitoring. Therefore, just a handful of cases are left to evaluate whether their breaks are achromatic across the optical and X-ray bands. In the following we present a few examples of combined optical/X-ray light curves, and try to assess whether their breaks can be due to the jet effect.

3. – Test cases

Among the Swift GRBs for which a detailed light curve is available in the literature, the best candidates to look for achromatic breaks are so far: GRB 050525A, GRB 050801, GRB 060124 and GRB 060526. For all these events we could single out a possible achromatic break, while the light curve coverage is adequate for a comprehensive discussion.

3'1. GRB 050525A. – GRB 050525A is one of the best sampled GRBs detected by Swift, at both optical and X-ray wavelengths \[19\]-\[20\]. The light curve of GRB 050525A presents some deviations with respect to a simple broken power law (see Fig. 1, left), both in the optical and X-rays. The initial afterglow was indeed modeled by including also a contribution from the reverse shock \[21\]-\[19\]. The presence of an achromatic break is still being discussed. Blustin et al. \[19\] identify a break at \(\tau \sim 0.15\) days, a time which is consistent with the break being simultaneous in the optical and X-ray bands. On the other hand, Della Valle et al. \[20\] find a break in the \(R\) band at a slightly later time of \(t \sim 0.3\) days. Swift-XRT and -UVOT data before the break show a decay and spectral slope consistent with the predictions of standard afterglow models for a uniform interstellar medium \[22\]. Moreover there is no spectral evolution before and after the break. However the temporal index of the post-break decay appears to be too shallow \((p_{\text{post}} = 1.6-1.8)\) compared to the predictions \((p_{\text{post}} = p, \text{where } p = 2.2\) is the electron energy distribution index). Apart from the low inferred \(p\), it is possible that the decay is shallower due to inefficient sideways expansion \[23\]. However, given the uncertainty in the late decay indices (also given the contribution from the associated SN 2005nc \[20\]), it is also possible to model the light curves with a steeper post-break decay, assuming that the jet break takes a finite time to complete and the post-break asymptotic regime has not yet been reached. Recently Sato et al. \[24\] questioned the identification of an achromatic break for GRB 050525A, due to the lack of agreement between broad-band modeling of the afterglow light curves around the break and the standard afterglow model predictions. The issue is therefore still to be settled. GRB 050525A might be one of the strongest outliers for the so called Ghirlanda et al. relation \[25\]. However, it should be also stressed that while the presence of an achromatic break is essentially due to the outflow geometry only, the spectral and temporal indices depend on more subtle and model-dependent details. The collimation factor, and thus the real energetics of the burst, are likely not much affected by these details.

3'2. GRB 050801. – The optical afterglow of GRB 050801 was detected already \(\sim 22\) s after the burst \[20\] and the light curve was then followed for more than 10,000 s (see Fig. 1, right). The combined Swift-XRT and optical light curves identify a clear achromatic break as early as \(\sim 250\) s. Indeed, the whole afterglow evolution did not show any sign of spectral evolution between optical and X-ray, and a single power-law can account for the broad-band spectrum. In spite of the convincingly achromatic nature of this break, interpretation of this transition in term of a jet break is difficult. The spectral and temporal power-law indices are compatible with an outflow moving in a constant density ISM, and rule out a wind environment. The post-break decay is shallow, \(\alpha \sim 1.3\),
requiring therefore a value for the electron energy distribution index as low as $p \sim 1.3$. Such an extreme value is however inconsistent with the essentially flat afterglow evolution observed before the break. A jet break already $\sim 250$ s after the burst would be the earliest detected. An alternative and intriguing possibility is that the achromatic break is due in fact to the afterglow onset [26, 27, 28, 29].

3.3. **GRB 060124.** – The most striking example of achromatic break in this sample comes from the analysis of the light curve of GRB 060124 (see Fig. 2 left). The optical and X-ray light curves were well sampled before and after the achromatic break identified at $t_b \sim 1 \text{ day}$ [30, 31]. The pre-break decay ($\alpha_X \sim 1.1$, $\alpha_{\text{opt}} \sim 0.8$) and spectral indices ($\beta_X \sim 1.0$, $\beta_{\text{opt}} \sim 0.4$) are in good agreement with the expectations of the standard fireball theory in the case of homogenous ISM and with an electron energy distribution index $p \sim 2$. However, problems with the identification of this transition as a jet break arise because the post-break temporal decay indices are both too shallow and different in the X-ray and optical ($\alpha_X \sim 1.7$, $\alpha_{\text{opt}} \sim 1.3$). Shallower post-break decays might be produced if, for some reason, the jets are not spreading as effectively as expected. Further hypotheses are required to account for the different decay indices that, in the context of constant density ISM, should equal the electron energy distribution index independent of the wavelength.

3.4. **GRB 060526.** – The X-ray and optical light curves of GRB 060526 are complex and present multiple flares and breaks [32]. The late-time optical light curve shows a well-defined steepening (though the presence of flares may introduce systematic errors in the determination of the decay index; see Fig. 2 right). The X-ray data, despite their sparse sampling, appear to support the presence of such a break, but are also consistent with an uninterrupted decay. Therefore, an achromatic break is not strictly required. The pre-break decay index is $\alpha_{\text{pre}} \sim 1.1$ while the post-break decay index is $\alpha_{\text{post}} \sim 3.4$ (with a large error), mainly constrained by the optical data. The broad-band modeling of the late afterglow is consistent with a single synchrotron component, even though the X-ray data do not strongly constrain the fit. In any case, the post-break temporal
Fig. 2. – Optical and X-ray light curves of GRB 060124 (left) and GRB 060526 (right). For GRB 060124 optical data were taken in different filters and reported to the $R$ band adopting the average spectrum [30, 31].

index is too steep to be accounted for in the standard model, possibly requiring varying micro-physical parameters.

4. – Conclusions

The intrinsic (and to some extent unexpected) complexity of the Swift afterglows has not prevented the identification of breaks in many X-ray light curves, that are sometimes consistent with the requirements of the standard afterglow theory for jet breaks. Things change considerably once optical data are taken into account. For only a few events the optical coverage is as good as in the X-rays. Although jet breaks are part of the so-called canonical Swift-XRT light curve, achromatic breaks have been identified only for a handful of events. Furthermore, in no case the jet-break interpretation holds without the need to introduce additional ingredients. On the contrary, for a few other events, chromatic breaks have also been identified. Modeling these events within the standard afterglow theory requires extra assumptions such as a variation of microphysical parameters for the electron and magnetic energies during the afterglow evolution or, alternatively, that the X-ray and the optical afterglows arise from different components [33, 34].

The paucity of identified jet breaks over a large wavelength range can of course affect the interpretation of correlations such as the Ghirlanda et al. relation [25]. It should be stressed that these relations are so far derived mainly (or only) by means of jet breaks identified at optical wavelengths. It is therefore possible to wonder whether jet breaks identified in the X-rays only carry the same information about the total energetics of GRBs. In any case, the relatively limited energy range covered by BAT onboard Swift did not allow in most cases to measure the spectral peak energy of the prompt GRB emission, thus preventing the check (and possibly the improvement) of the Ghirlanda et al. relation with these events, even if a jet break is identified with the XRT. It should be noted, however, that a model-independent version of the Ghirlanda relation...
exists [35], which involves only the break time (as measured in the optical) and which does not necessarily involve a geometrical interpretation. This relation may remain valid even in the absence of an achromatic break, in this case requiring a completely different interpretation. In any case, a better optical coverage (possibly aided by a better coordination among observers) could improve the light curve sampling of Swift GRBs and allow a firmer identification of jet break transitions.

REFERENCES

[1] Rhode J., Astrophys. J., 525 (1999) 737
[2] Sari R., Piran R., and Halpern J.P., Astrophys. J., 519 (1999) L17
[3] Zeh A., Klose S., and Kann D.A., Astrophys. J., 637 (2006) 889
[4] Israel G.L., Marconi G., Covino S., et al. Astron. Astrophys., 348 (1999) L5
[5] Stanek K.Z., Garnavich P.M., Kaluzny J., Pych W., and Thompson I., Astrophys. J., 522 (1999) 39
[6] Harrison F.A., Bloom J.S., Frail D.A., et al. Astrophys. J., 523 (1999) L121
[7] Frail D.A., Kulkarni S.R., Sari R., et al. Astrophys. J., 562 (2001) L55
[8] Ghirlanda G., Ghisellini G. and Firmani C., New Journal of Phys., 8 (2006) 123
[9] Mészáros P., Rept. Prog. Phys., 69 (2006) 2259
[10] Zhang B., and Mészáros P. Int. J. Mod. Phys. A, 19 (2004) 2385
[11] Gehrels N., Chincarini G., Giommi F., et al. Astrophys. J., 611 (2004) 1004
[12] Roming P.W.A., Schady P., Fox D.B., et al. Astrophys. J., (2006) in press (astro-ph/0509273)
[13] Jakobsson P., Levan A., Fynbo J.P.U., et al. Astron. Astrophys., 447 (2006) 897
[14] Roming P.W.A., Kennedy T.E., Mason K.O., et al. Space Sci. Rev., 120 (2005) 95
[15] Tagliaferri G., Goad M., Chincarini G., et al. Nature, 436 (2005) 985
[16] Chincarini G., Moretti A., Romano P., et al. in preparation
[17] Burrows D., Romano P., Falcone A., et al. Science, 389 (2005) 1933
[18] Nousek J.A., Kouveliotou C., Grupe D., et al. Astrophys. J., 642 (2006) 389
[19] Blustin A.J., Band D., Barthelmy S., et al. Astrophys. J., 637 (2005) 901
[20] Delia Valle M., Malesani D., Bloom J.S., et al. Astron. Astrophys., 642 (2006) L103
[21] Shao L. and Dai G., Astrophys. J., 633 (2005) 1027
[22] Sari R., Piran T., and Narayan R., Astrophys. J., 497 (1998) L17
[23] Panaitescu A. and Mészáros P., Astrophys. J., 526 (1999) 707
[24] Sato G., Yamazaki R., Ioka K., et al. Astrophys. J. (2006) in press (astro-ph/0611148)
[25] Ghirlanda G., Ghisellini G., Lahtti D., Astrophys. J., 616 (2004) 331
[26] Rykoff E.S., Mango M., Yost S.A., et al. Astrophys. J., 638 (2006) L5
[27] Kobayashi S. and Zhang B., Astrophys. J. (2006) in press (astro-ph/0608132)
[28] Cenko S.B., Kasliwal M., Harrison F.A., et al. Astrophys. J., 652 (2006) 490
[29] Molinari E., Vergani S., Malesani D., et al. (2006) (astro-ph/0612607)
[30] Curran P.A., Kann D.A., Ferrero P., Rol E., and Wijers R.A.M.J., these proceedings (2006) (astro-ph/06010067)
[31] Kann D.A., Curran P.A., Ferrero P., et al. in preparation
[32] Dai X., Halpern J.P., Morgan N.D., et al. Astrophys. J. (2006) submitted (astro-ph/0609269)
[33] Panaitescu A., Mészáros P., Burrows D., et al. MNRAS, 369 (2006) 2059
[34] Panaitescu A., these proceedings (2006) (astro-ph/0607396)
[35] Liang E., and Zhang B., Astrophys. J., 633 (2005) 624