IMPLICATIONS OF EARLY TIME OBSERVATIONS OF OPTICAL AFTERGLOWS OF GRBS

S.B. Pandey¹ and W. Zheng²

Abstract. Optical observations of afterglows at very times are very useful towards understanding the least known problem of GRB research field *i.e.* the transition from prompt emission to early afterglows. The comparison of a subset of well-monitored GRBs and their early time properties at optical are compared with that seen at XRT and BAT wavelengths. In most of the observed cases, the very early optical observations of GRBs do not trace the canonical decay nature seen at XRT wavelengths, suggesting different origins for the observed early emissions in the two bands. In some of the early optical light-curves, the decay followed by smooth rise features are consistent with the onset of the afterglow although such features are also expected if the emission is seen off-axis and/or the outflow is structured.

1 Introduction

Gamma Ray Bursts (GRBs) are short lived (10^{-3} to 10^3 seconds) extremely bright (Isotropic equivalent γ -ray energy $\sim 10^{52} - 10^{54}$ erg) cosmological γ -ray sources, emitting photons of energy ~ 10 keV–10 GeV. Followed by the GRB, ultra-relativistically ejected material interact with the surrounding medium through shocks and may produce afterglows, visible in all bands from X-ray to radio wavelengths. Afterglows being longer-lasting than GRB prompt emission, provide a multi-band platform to study these energetic cosmic explosions in detail (Zhang 2007; Gehrels *et al.* 2009).

Unlike to prompt gamma-ray emission, X-ray emission arises from the interaction of relativistic outflow with the ambient medium forming blast wave (Meszaros & Rees 1997; Sari *et al.* 1998). However, part of the early X-ray emission from GRBs (near contemporaneous) seems to be integral part of the prompt emission

---

¹ ARIES, Manora Peak, Nainital 263129, Uttarakhand, India

² Randall Laboratory of Physics, University of Michigan, 450 Church Street, Ann Arbor, MI 48109-1040, USA

Fig. 1. This figure demonstrates examples of 3 GRBs (GRB 061007, GRB 080607 and GRB 090618) with near contemporaneous optical observations (red) along with the *Swift*-BAT (Black) and *Swift*-XRT (blue) observations. The green vertical line is the line at the duration of t_{90} in observer's frame. The optical light-curve in general does not trace the gamma-ray light-curves and follow a power-law rising/decaying behavior.

itself (Margutti *et al.* 2013). Also, the prompt emission gamma-ray spectrum seems broadly consistent with the Band's model (Band *et al.* 1993) showing deviations both at low and high energy ends (Abdo *et al.* 2009). So far, more than 3 dozen of GRBs have been observed at optical frequencies near contemporaneous to the prompt emission gamma-ray duration (Yost *et al.* 2007; Racusin *et al.* 2008). However, majority of the observed optical emissions does not seem like following the extrapolated Band's function, indicating a different origin for the emission at the two frequencies.

In the *Swift* era, $>10\%$ of the optical afterglows have been observed during the rising phase, peaking at time t_p and decaying as a power-law at later epochs. Such early rising optical afterglows are expected in a variety of models that describe the deceleration of the initial fireball (Sari & Piran 1999), off-axis emission (Panaitescu *et al.* 1998) and the outflow structure (Rossi *et al.* 2002). The peak time t_p and the brightness at the peak time of GRB optical afterglow light curves are distributed over several orders of magnitude (Oates *et al.* 2009; Panaitescu & Vestrand 2011; Rykoff *et al.* 2009).

2 Early time optical light curves of afterglows

Early optical observations of GRBs during the prompt emission or soon after, are clean tracers of the crucial properties of the fireball. Specifically, the early time monotonically rising light curves seen at optical frequencies can be used to understand the onset of the forward shock emission (Sari & Piran 1999) and reveal possible geometric effects associated with the structure of the jet (Panaitescu *et al.* 1998; Rossi *et al.* 2002).

In the case of thin shell approximation for fireball model (Sari & Piran 1999), *i.e.* $t_p > t_{90}$ (duration of the prompt emission), the light curve at optical frequencies should have a rising index of ~ 2 ($\nu_c < \text{optical}$) or ~ 3 ($\nu_c > \text{optical}$) in the case of *ISM* or 0.5 for a *WIND* density profile (Panaitescu & Vestrand 2011).

Fig. 2. In the *left panel*, ROTSE light curves of 8 afterglows observed at very early epochs showing the rising phase scaled to a common redshift of 2.0. The flux values of the GRBs have been corrected for the respective values of Galactic extinction and intergalactic absorptions. In the *right panel*, we plot α_r vs. ratio of t_p and T_{90} for 28 GRBs. Vertical solid line is line at $t_p = T_{90}$. Horizontal dotted line represents a line for $\alpha_r = 2.0$. A range of α_r values could be reproduced for different viewing angles if the emission is seen off-axis. These shallower rise indices might also indicate a possible contribution from early energy injection into the forward shock and/or the irregular structure of the early fireball.

2.1 A sub-sample of rising light-curves of afterglows

Analysis of very early observations of rising/decaying light-curves at optical frequencies for more than 40 GRBs (Rykoff *et al.* 2009; Melandri *et al.* 2010; Pandey *et al.* 2011) are discussed in the present analysis. The distribution of rising temporal indices are $0.1 < \alpha_r < 10$ and the values of α_r for a good fraction of the sample are flatter (see Fig. 2, right panel) than those predicted by various afterglow models (Sari & Piran 1999; Oates *et al.* 2009). The peak time of these light-curves were used to derive the fireball deceleration time t_p , which along with isotropic equivalent gamma-ray energy E_{iso} were used to estimate the bulk Lorentz factor Γ_0 using the formula described in (Molinari *et al.* 2007) for the deceleration of the fireball and the thin shell approximation (Sari & Piran 1999). The derived values of Γ_0 have a range of values varying from 100 to 1000 and seems like linearly correlated with respective values of E_{iso} (see Fig. 3, left panel) indicating that energetic GRBs have higher values of Γ_0 (Rykoff *et al.* 2009; Liang *et al.* 2012; Pandey *et al.* 2011).

A similar empirical correlation is also evident between Γ_0 and the rest-frame value of E_{peak} , the peak energy of the prompt emission spectrum of GRBs (Pandey *et al.* 2011). However, this correlation is poor due to underlying uncertainty in the determination of E_{peak} values for different GRBs. If the hint for the linear correlation between Γ_0 and E_{peak} is real (see Fig. 3, right panel), it could be useful to constrain models describing the geometry of the outflow, understanding the nature of XRFs in more detail (Dermer *et al.* 1999; Rossi *et al.* 2002; Yamazaki *et al.* 2007) and to understand the empirical relations (Amati and Ghirlanda) in

Fig. 3. In the *left panel*, we plot Isotropic equivalent gamma-ray energy E_{iso} vs. Γ_0 of 51 Swift GRBs, discussed in the present analysis. The line is a linear fit to the data assuming the limiting values of Γ_0 to be absolute and described as $\log \Gamma_0 = (0.41 \pm 0.05) \log E_{iso} + (2.16 \pm 0.23)$. In the *right panel*, we plot E_{peak} vs. Γ_0 for 40 GRBs and the fitted line is described as $\log \Gamma_0 = (0.82 \pm 0.29) \log E_{peak} + (0.45 \pm 0.70)$.

a more physical way. We hope to get more precise measurements of E_{peak} values of many more GRBs in near future from *Swift* and *Fermi*.

2.2 Constrains on reverse shock emission

The prompt optical emission were first detected for GRB 990123 (Akerlof *et al.* 1999) showing an optical flare that was interpreted as the signature of a reverse shock emission passing through the relativistic ejecta. In case of *Swift* GRBs, the early observations at optical-IR frequencies indicate that the reverse shock feature is not very common (Gomboc *et al.* 2009) in contrary to the predictions made earlier (Sari & Piran 1999). However, this feature has been clearly observed in handful of cases, for example GRB 060117 (Jelinek *et al.* 2006), GRB 061126 (Gomboc *et al.* 2008), GRB 090902B (Pandey *et al.* 2010) and GRB 110205 (Zheng *et al.* 2012). The detection/non-detection of reverse shock feature is very useful in constraining the outflow to be magnetized or baryon dominated. Early observations at much lower frequencies like radio and polarization observations in near future will help to know more about the nature of reverse shock emission for GRBs.

2.3 Dark GRBs

GRBs with no optical afterglows or having X-ray to optical spectral index $\beta_{OX} < 0.5$ are classified as dark GRBs (Jakobsson *et al.* 2004; van der Horst *et al.* 2009). During *Swift* era, rapid follow-up observations of afterglows at optical and near-NIR frequencies have enabled to collect a good sample of long duration GRBs (*e.g.* ROTSE, BOOTES, TORTORA, P60 and Faulkus telescopes), the underlying possible explanations and the fraction of the population in comparison to normal

GRBs with optical afterglows (Salvaterra *et al.* 2012; Nava *et al.* 2011; Greiner *et al.* 2011). The possible explanations for this population of bursts include, low-density environments, bursts occurring at higher redshifts with extinguished optical emission due to Lyman- α forest and that some of the bursts might occur in dusty environments. Recently, Melandri *et al.* (2012) analyzed a sub-sample of well-known dark GRBs with known redshifts and found that majority of dark GRBs have rather high X-ray flux and X-ray luminosity and at the same time lower observed optical flux. Also, these bursts have prompt properties similar to those normal bright events. This clearly indicates that most of the dark GRBs might belong to denser environments and their darkness might be related to circum-burst dust absorption.

3 Correlation between prompt optical/ γ -ray emission

Spectral energy distribution of the prompt emission of GRBs is one of the least-understood area. There are handful of known cases with optical emission detected contemporaneously with γ -rays for example GRB 990123 (Akerlof *et al.* 1999), GRB 041219A (Vestrand *et al.* 2005), GRB 050401 (Rykoff *et al.* 2005), GRB 050904 and GRB 051111 (Yost *et al.* 2007), GRB 080319B (Racusin *et al.* 2008) and GRB 080607 (Perley *et al.* 2011). However, in none of the cases there is any consistent correlation between prompt optical observations and the contemporaneous γ -rays. In Figure 4 (right panel), we plot 12 such examples of near contemporaneous observations, indicating that the emission at two frequencies have different physical origins. In a few cases, the optical and prompt γ -rays emissions seems to be correlated (GRB 051111, see Yost *et al.* 2007) and GRB 080319B (see Racusin *et al.* 2008) whereas in some of the cases the two emission components require a spectral break or some other possible origins. Broadly, the near contemporaneous observations at optical and γ -rays indicate that deceleration of the fireball occurs earlier than end of the high energy emission.

4 Early time optical and XRT light curves

In the *Swift* era, rapid follow-up observations at optical frequencies have collected a good number of GRBs with near-contemporaneous observations to those seen at XRT frequencies. The analysis of the temporal decay nature of these GRBs indicate that early time properties of GRBs have a diverse set of features, broadly consistent with the predictions made by the synchrotron fireball model for afterglows though outliers exist (Oates *et al.* 2009; Rykoff *et al.* 2009; Melandri *et al.* 2010). Specifically, the very early optical observations of most of GRBs do not trace the canonical decay nature seen at XRT frequencies and are broadly consistent with the “onset of the afterglow” or off-axis emission scenario for most of the observed features at early times. Also, at early epochs, spectral indices at XRT frequencies β_x are steeper than the combined spectral indices seen at XRT and optical frequencies *i.e.* β_{x-opt} (see Fig. 4, right panel). These observed features clearly

Fig. 4. In the *left panel*, we plot the *Swift*-BAT spectral index *vs.* spectral index between BAT and optical frequencies for 12 long-duration GRBs based on the preliminary analysis of our sample. The dashed line is the line of equality. In the *right panel*, we plot the *Swift*-XRT spectral index *vs.* spectral index between XRT and optical frequencies for 20 long-duration GRBs. The steeper XRT spectral indices in comparison to combined XRT-optical ones suggest for the *ISM* forward shock origin of the data.

indicate towards the forward shock model (Sari *et al.* 1998) for the observed data at optical and XRT frequencies for the early afterglows of long duration GRBs.

So, early time optical data along with those observed at Gamma-ray and X-ray frequencies are very helpful in understanding the nature of these energetic cosmic explosions. With the help of many more upcoming robotic optical observatories, we hope to address some of the unsolved issues of this interesting research field.

This research has made use of the data obtained through the High Energy Astrophysics Science Archive Research Center On-line service, provided by the NASA/Goddard Space Flight Center. The authors thankfully acknowledge The ROTSE project to use some of the valuable data used for the present work.

References

- Abdo, A.A., Achermann, M., Ajello, M., *et al.*, 2009, ApJ, 706, L138
 Akerlof, C.W., Balsano, R., Barthelmy, S., *et al.*, 1999, Nature, 398, 400
 Band, D., Matteson, J., Ford, L., *et al.*, 1993, ApJ, 413, 281
 Dermer, C., Chiang, J., & Bottcher, M., 1999, ApJ, 513, 656
 Gehrels, N., Ramirez-Ruiz, E., & Fox, D.B., ARA&A, 2009, 47, 567
 Gomboc, A., Kobayashi, S., Guidorzi, C., *et al.*, 2008, ApJ, 687, 443
 Gomboc, A., Kobayashi, S., Mundel, C.G., *et al.*, 2009, AIP Conf. Proc., 1133, 145
 Greiner, J., Kruhler, T., Klose, S., *et al.*, 2011, A&A, 526, 30
 Jakobsson, P., Hjorth, J., Fynbo, J.P.U., *et al.*, 2004, ApJ, 617, L21
 Jelinek, M., Prouza, M., Kubanek, P., *et al.*, 2006, A&A, 454, L119
 Liang, E.W., Li, L., Gao, H., *et al.*, 2012, submitted to ApJ [[arXiv:1210.5142](#)]
 Margutti, R., Zaninoni, E., Bernardini, M.G., *et al.*, 2013, MNRAS 428, 729

- Melandri, A., Kobayashi, S., Mundell, C.G., *et al.*, 2010, ApJ, 723, 1331
- Melandri, A., Sbarufatti, B., D’Avanzo, P., *et al.*, 2012, MNRAS, 421, 1265
- Mészáros, P., & Rees, M., 1997, ApJ, 482, L29
- Molinari, E., Vergani, S.D., Malesani, D., *et al.*, 2007, A&A, 469, 13
- Nava, L., Salvaterra, R., Ghirlanda, G., *et al.*, 2011, accepted to MNRAS [arXiv:1112.4470]
- Oates, S.R., Page, M.J., Schady, P., *et al.*, 2009, MNRAS, 395, 490
- Oates, S.R., Page, M.J., Schady, P., *et al.*, 2011, MNRAS, 412, 561
- Panaitescu A., Mészáros P., & Rees, M.J., 1998, ApJ, 503, 314
- Panaitescu, A., & Vestrand, W.T., 2011, MNRAS 414, 3537
- Pandey, S.B., Castro-Tirado, A.J., Jelínek, M., *et al.*, 2009, A&A, 504, 45
- Pandey, S.B., Swenson, C.A., Perley, D.A., *et al.*, 2010, ApJ, 714, 799
- Pandey, S.B., Akerlof, C.W., Zheng, W., *et al.*, 2011, GRBs 2010-Annapolis, AIP Conf. Proc., 1358, 158
- Perley, D., Morgan, A.N., Updike, A., *et al.*, 2011, AJ, 141, 36
- Piran, T., 2005, Rev. Mod. Phys., 76, 1143
- Racusin, J.L., Karpov, S.V., Sokolowski, M., *et al.*, 2008, Nature, 455, 183
- Rossi, E., Lazzati, D., & Rees, M.J., 2002, MNRAS, 332, 945
- Rossi, A., Schulze, S., Klose, S., *et al.*, 2011, A&A, 529, 142
- Rykoff, E., Mangano, V., Yost, S., *et al.*, 2005, ApJ, 631, L12
- Rykoff, E.S., Aharonian, F., Akerlof, C.W., *et al.*, 2009, ApJ, 702, 489
- Salvaterra, R., Campana, S., Vergani, S.D., *et al.*, 2012, ApJ 749, 68
- Sari, R., & Piran, T., 1999, ApJ, 520, 641
- Sari, R., Piran, T., & Narayan, R., 1998, ApJ, 497, L17
- van der Horst, A.J., Kouveliotou, C., Gehrels, N., *et al.*, 2009, ApJ, 699, 1087
- Vestrand, W.T., Wozniak, P.R., Wren, J.A., *et al.*, 2005, Nature, 435, 178
- Yamazaki, R., Ioka, K., & Nakamura, T., 2004, ApJ, 607, L103
- Yost, S.A., Aharonian, F., Akerlof, C.W., *et al.*, 2007, ApJ, 667, 1107
- Zhang, Bing, 2007, ChJAA, 7, 1
- Zhang, W., Shen, R.F., Sakamoto, T., *et al.*, 2012, ApJ, 751, 90