Gamma-ray bursts, evolution of massive stars and
star formation at high redshifts
ASI Conference Series, 2012, Vol. 5, pp 59 – 67
Edited by S. B. Pandey, V. V. Sokolov and Yu A. Shchekinov

Early time optical observations of GRB afterglows

S. B. Pandey*
Aryabhatta Research Institute of Observational Sciences (ARIES), Manora Peak, Nainital, Uttarakhand 263129, India

Abstract. Early time optical observations of GRBs are very important for revealing the prompt emission and afterglow properties of these energetic explosions. The observations of the well-studied GRBs by *Swift* indicate that early time properties of the optical light-curves share diverse set of features broadly consistent with the predictions made by various afterglow models though outliers exists. The comparison of a subset of well-monitored GRBs and their early time properties at optical are compared with that seen at X-ray (*Swift*-XRT) and $\gamma-$ray frequencies. In most of the cases, the very early optical observations of GRBs do not trace the canonical decay nature seen at XRT frequencies, suggesting different origins for the observed early emissions in the two bands. In some of the early optical light-curves, the smooth rise and decay 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.

Keywords : gamma-ray bursts: early afterglows prompt emission : optical

1. Introduction

Gamma Ray Bursts (GRBs) are short lived (10^{-3} to 10^{3} seconds) extremely bright (Isotropic equivalent $\gamma-$ray energy $\sim 10^{52} - 10^{54}$ erg) cosmological $\gamma-$ray sources, emitting photons of energy $\sim$ 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 frequencies. Afterglows being longer-lasting than GRB prompt emission, provide a multi-band platform to study these energetic cosmic explosions in detail (Gehrels, Ramirez-Ruiz & Fox 2009). To calculate the overall spectrum due to electrons, it is required to integrate them over the electron's Lorentz factor distribution. It is assumed that the energy

*email: shashi@aries.res.in

distribution of these accelerated electrons with Lorentz factor γ_e is a power-law distribution and is expressed as $N(\gamma_e) \propto \gamma_e^{-p}, \gamma_e > \gamma_m$ (Sari, Piran & Narayan 1998), where γ_m is the maximum cut off of the energy distribution and p is the electron energy index. Usually the value of $p > 2$ is in agreement with the relativistic shock acceleration (Achterberg et al. 2001) but hard electron energy spectrum (*i.e.* $p < 2$) has also been seen in some cases (Bhattacharya 2001). When the forward shock is formed, a reverse shock that propagates backwards into the ejecta is also generated. The brightness of the reverse shock emission decays very rapidly compared to the decay of the forward component (Kobayashi 2000). It is predicted that at early time the reverse shock can produce extremely bright optical flashes while at late time the optical flux is completely dominated by the forward shock emission (Meszaros 1997; Sari & Piran 1999). In reality, the resultant light curve at optical frequencies is a complex, time-dependent mixture of the emissions due to these components and provides important insight into the physics and energetics of the explosion.

We have used the following conventions throughout the article: the power-law flux is given as $F(\nu, t) \propto t^{-\alpha}\nu^{-\beta}$, where α is the temporal decay index and β is the spectral slope; we assume a standard cosmology with $H_0 = 70$ km s^{-1} Mpc^{-1}, $\Omega_m = 0.3$ and $\Omega_\Lambda = 0.7$; all errors and uncertainties are quoted at the 1σ confidence level.

2. Importance of early optical observations

Early optical observations of GRBs during the prompt emission phase 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 could 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).

2.1 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 connection between prompt optical observations and the contemporaneous γ-rays. In a few cases, the optical and prompt γ-ray 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. *Fermi*-LAT observations of GRBs also indicate that the GeV emission is delayed in comparison to the prompt emission observed at GMB frequencies and exhibit power-law decay nature, indicative of an afterglow origin (Ghiselini et al. 2010). Broadly, the contemporaneous observations at optical and γ-rays indicate that deceleration of the fireball occurs earlier than end of the high energy emission.

2.2 Constrains on reverse shock emission

The prompt optical emission was 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 in contrary to the predictions made earlier (Sari & Piran 1999). However, this feature has been clearly observed in handful of cases, for example GRB 061126 (Gomboc et al. 2008) and GRB 090902B (Pandey et al. 2010). The detection and 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.

2.3 Onset of the forward shock emission and off-axis emission

In the *Swift* era, > 10% of the optical afterglows have been observed exhibiting the rising phase in their light-curves, peaking at time t_p (Rykoff et al. 2009) 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). Early optical light-curves have an advantage in determining the values of peak time t_p as early XRT data is contaminated with late time central engine activities. 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 2010; Rykoff et al. 2009; Pandey et al. 2011) and could be used to infer Γ_0, the initial Lorentz factor and the radius of the fireball (Molinari et al. 2007; Sari & Piran 1999).

Other possible reasons that might exhibit very early features in the optical light curves are: inhomogeneities in the jet, multi-component outflow, energy injection and passage of spectral breaks passing through optical bands.

2.4 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-IR frequencies have enabled the collection of a good sample of such long duration GRBs, the underlying possible explanations and the fraction of the population in comparison to normal GRBs with optical afterglows (Salvaterra et al. 2011; 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$-\alpha$ forest and that some of the bursts might occur in dusty environments. Recently, Melandri et al. (2011) analyzed a sub-sample of well-known dark GRBs with known redshifts and found that the 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. Comparison of early time optical and XRT light curves

In *Swift* era, rapid follow-up observations at optical frequencies 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 show signatures broadly suggesting the onset of the afterglow and/or off-axis emission for most of the observed features at early times.

Analysis of a subset of GRBs observed both by *Swift*-UVOT and XRT (Oates et al. 2011) indicate that the early time Xray and optical-UV light curves are remarkably different during the first 500 s after the BAT trigger, while they are broadly consistent with the forward shock model for a constant ambient medium during the middle phase of the afterglow, i.e. between 2000 s and 20000 s. During this period of time, temporal decay indices at optical, α_{opt}, are less than α_X, the near-contemporaneous temporal decay indices seen at XRT frequencies. Also, spectral indices at XRT frequencies β_X are steeper than the combined spectral indices seen at XRT and optical frequencies i.e. $\beta_{X\text{-}opt}$. These observed features clearly indicate towards the forward shock model (Sari, Piran & Narayan 1998). In many cases, chromatic breaks are noticed between optical and X-ray light-curves. At XRT frequencies, observed chromatic breaks in the form of steepening with no spectral evolution could be explained in terms of jet breaks or the cessation of energy injection episode. The properties of the GRBs exhibiting chromatic breaks could not be explained in terms of passage of break frequencies through the observed bands and might indicate towards multi-component outflow, additional emission components or more complex jet structures.

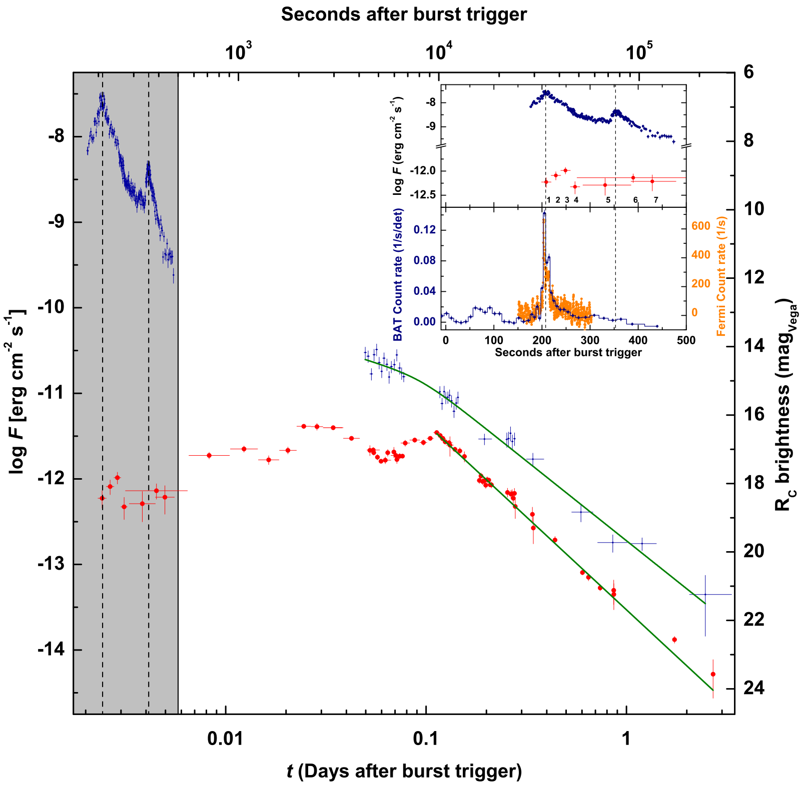

Figure 1. Temporal evolution of the optical (composite light curve with all data shifted to the R_c band) and X-ray afterglow (0.3 to 10 keV) of GRB 080928 (optical: red circles, X-ray: blue error bars). The upper limits are not shown here to avoid confusion. The zoom-in shows the early phase (also highlighted in gray in the big figure) where it is compared with the BAT-GBM prompt emission. The dashed vertical lines indicate the peak times of the two X-ray flares. The curve represents the best fit of the late-time data. This figure has been adopted from Rossi et al. (2011).

3.1 Observations of GRB 080928, a case study

GRB 080928, for example, a long duration burst detected by *Swift*/BAT and *Fermi*/GBM, is an interesting case, exhibiting an early time complex light-curve at optical frequencies as seen by ROTSE-III and *Swift*-UVOT (Rossi et al. 2011). From Fig. 1, it is clear that nearly for 100 seconds simultaneous optical, X-ray and gamma-ray data provide a coverage of the spectral energy distribution of the transient source from about 1 eV to 150 keV. Despite the rich variability in the early afterglow, the late-time evolution is consistent with a power law decay. After 4.2 ks, the X-ray light curve could be described by a broken power law (Beuermann et al. 1999) with $\alpha_1^X = 0.72 \pm 0.35$, $\alpha_2^X = 1.87 \pm 0.07$, $t_b = (8100 \pm 1600)$s (observer frame) and a fixed

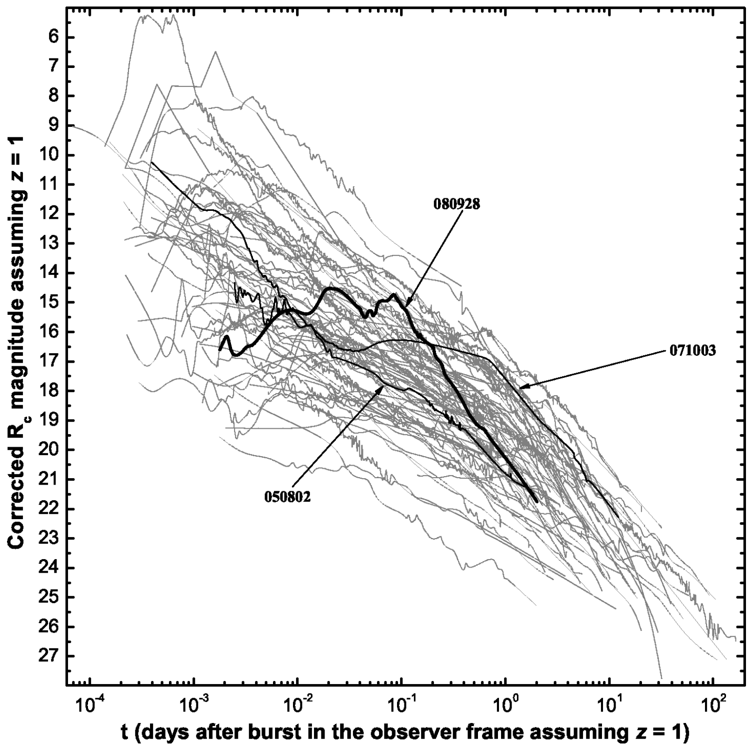

Figure 2. The optical afterglow light-curve of GRB 080928 (thick line) compared with the sample of extinction-corrected well-monitored optical afterglows shifted to $z = 1$ from (Kann et al. 2010). For comparison, the GRBs within a redshift interval of 0.1 around the redshift of GRB 080928 for which we have optical data are highlighted and labeled. All magnitudes are Vega magnitudes. This figure has been adopted from Rossi et al. (2011).

smoothness parameter $n = 5$ (χ^2/d.o.f. = 55.4/33 = 1.68; Fig. 1. The optical data do not allow for a fit with a broken power law. For $t_{\rm obs} > 10$ ks the fit with a single power law gives $\alpha^{\rm opt} = 2.17 \pm 0.02$ (χ^2/d.o.f. = 56.8/34 = 1.67). The optical/NIR and X-ray data suggest similar small variability after 20 ks, which we cannot study further for lack of good data.

Using the forward shock afterglow model (Zhang et al. 2004; Piran 2005; Panaitescu & Vestrand 2010), it is difficult to explain the different slopes of the optical and X-ray light curves given that they are on the same power law segment of the spectrum. Assuming the cooling frequency, ν_c, is above the X-ray band, the spectral slope gives an electron energy index of $p = 2\beta + 1 \approx 3$. The light curve slope of $\alpha \approx 2$ then indicates we have a pre-break evolution in a stellar wind. This would be problematic for the early-time evolution, as it is difficult to get a rising afterglow with a stellar-wind external medium. The second possibility is that ν_c is below the optical bands, resulting in $p = 2\beta \approx 2$. If the external medium is *ISM*, then this does not contradict

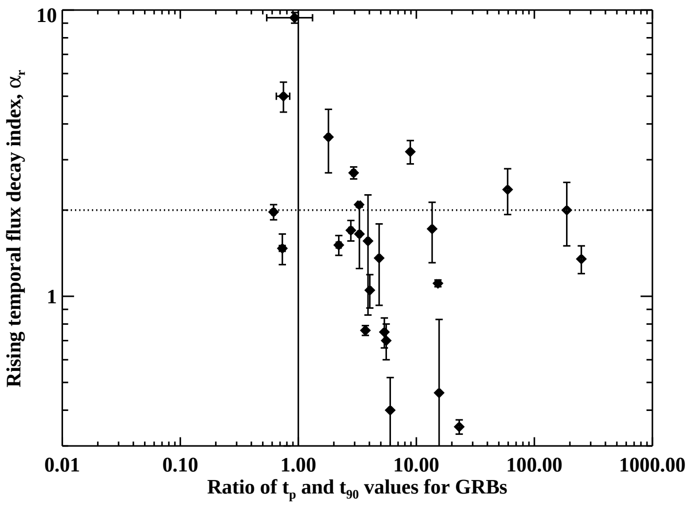

Figure 3. A plot of rising temporal flux decay indices α_r and ratio of t_p (fireball deceleration time) and T_{90} (the burst duration at BAT frequencies) values of 30 GRBs taken from the literature (Rykoff et al. 2009; Melandri et al. 2010; Pandey et al. 2011). Vertical solid line is line at $t_p = t_{90}$ representing the thin-shell case as described in (Sari & Piran 1999). It is clear from the figure that most of the rising afterglows have $t_p > t_{90}$ i.e. belong to thin shell case Sari & Piran (1999) and observed t_p values being spread over more than 2 magnitudes in time. Horizontal dotted line represents a line for $\alpha_r = 2.0$. From the figure, it is also obvious that in case of majority of bursts, the rising temporal index α_r is flatter than 2, the value expected for the onset of the forward shock emission in case of *ISM* model (Sari, Piran & Narayan 1998; Panaitescu & Vestrand 2010).

the early-time observations, given a small enough initial Lorentz factor. The optical fluctuations have a long timescale that is more consistent with energy injection into the forward shock than with central engine activity.

From Fig. 2, it is also clear that at early epochs the afterglow light-curve is comparatively faint, nearly eight magnitudes fainter than the brightest events. Its multiple rebrightenings, which are a notable signature of this afterglow, then bring the late-time light curve close to the mean magnitude of the distribution one day after the GRB (at $z = 1$).

4. Rising light curves at optical bands and their implications

Rising light-curves at optical frequencies have been observed for more than 20 GRBs localized by *Swift* (Rykoff et al. 2009; Melandri et al. 2010; Pandey et al. 2011). 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. 3) then those predicted by various afterglow models (Oates et al. 2009; Sari & Piran 1999). The peak time of the light-curves could be used to derive the fireball deceleration time t_p, which along with isotropic equivalent gamma-ray energy E_{iso} could be used to estimate the bulk Lorentz factor Γ_0 using the formula described in Molinari et al. (2007) for the thin shell case (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} indicating that energetic GRBs have higher values of Γ_0 (Rykoff et al. 2009; Liang et al. 2010; 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, the 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, it could be useful to constrain models describing the geometry of the outflow and to understand the nature of XRFs in more detail (Dermer, Chiang & Bottcher 1999; Rossi et al. 2002; Yamazaki et al. 2004). We hope to get more precise measurements of E_{peak} values of many more GRBs in near future from *Swift* and *Fermi*.

5. Results

The importance of the early observations of GRBs at optical frequencies is highlighted. Early observations of GRBs at optical frequencies are very useful to reveal the nature of prompt emission spectrum, diverse nature of the afterglow emission and possible geometric effects associated with the structure of the jet. Optical observations of many GRBs do not exhibit correlations with emission at γ-rays. Also, reverse shock emission at optical frequencies seems like a not very common feature at early times. Rising temporal indices α_r of the monotonically rising early time optical light-curves are shallower in comparison to the predicted values for the onset of the forward shock emission models. A range of α_r values could also be reproduced for different viewing angles if the emission is seen off-axis. These shallower rising indices might also indicate a possible contribution from early energy injection into the forward shock and/or the irregular structure of the early fireball. Assuming onset of the forward shock emission as the most probable explanation for the rising afterglows, the peak time t_p is used to determine the values of initial Lorentz factors Γ_0, ranging from ~ 100 to ~ 1000. Also, Γ_0 seems to be correlated with E_{iso} and prompt emission properties like E_{peak}. Shallower rising light curves at optical frequencies peaking at rather later epochs along with the respective prompt emission properties like E_{peak} and Γ_0 seems originating due to some other reasons like possible geometric effects i.e. off-axis emission and/or structured outflows.

Acknowledgments

The author acknowledges the Indo-Russian DST-RFBR project 2011-13 (INT/RFBR/P-100) for this work. The author sincerely acknowledges the financial support from

DST-India to host this workshop successfully at ARIES Nainital and also the ROTSE project to cite some of the scientific results produced using ROTSE data.

References

Achterberg A., Gallant Y. A., Kirk J. G., et al., 2001, MNRAS, 328, 393
Akerlof C. W., Balsano R., Barthelmy S. D., et al., 1999, Nature, 398, 400
Beuermann K., Hessman F. V., Reinsch K., et al., 1999, A&A, 352, 26
Bhattacharya D., 2001, BASI, 29, 107
Dermer C., Chiang J., Bottcher M., 1999, ApJ, 513, 656.
Gehrels N., Ramirez-Ruiz E., Fox D. B., ARAA, 2009, 47, 567
Ghiselini G., Ghirlanda G., Nava L., et al., 2010, MNRAS, 403, 926
Gomboc A., Kobayashi S., Guidorzi C., et al., 2008, ApJ, in press, arXiv:0804.1727
Greiner J., Krhler T., Klose S., et al., 2011, A&A, 526, 30
Jakobsson P., Hjorth J., Fynbo J. P. U., et al., 2004, ApJ, 617, L21
Kann D. A., Klose S., Zhang B., et al., 2010, ApJ, 520, 1513.
Kobayashi S., 2000, ApJ, 545, 807
Liang E. W., Yi S. X., Zhangi J., et al., 2010, ApJ, in press, arXiv:0912.4800
Melandri A., Kobayashi S., Mundell C. G., et al., 2010, ApJ, 723, 1331
Melandri A., Sbarufatti B., D'Avanzo P., et al., 2011, MNRAS, in press, arXiv:1112:4480
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, MNRAS, in press, arXiv:1112.4470
Oates S. R., Yi S. X., Zhang J., 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., 2010, MNRAS, arXiv:1009.3947 (submitted)
Pandey S. B., Castro-Tirado A. J., Jelnek 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 Conference proceedings, 1358, 158
Perley D., Morgan A.N., Updike A., et al., 2011, AJ, 141, 36
Piran T., 2005, Rev. Modern Physics, 76, 1143
Racusin J. L., Karpov S.V., Sokolowski M., et al., 2008, Nature, 455, 183
Rossi A., Schulze S., Klose S., et al., 2011, A&A, 529, 142
Rossi E., Lazzati D., Rees M. J, 2002, MNRAS, 332, 945
Rykoff E. S., Aharonian F., Akerlof C. W., 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., 2011, ApJ, in press, arXiv:1112:1700
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 B., Mészáros P., 2004, Int. J. Mod. Physics, 19, 2385