Gamma-ray Burst Optical Afterglow

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Abstract Regardless of the progenitor and central engine, the gamma-ray burst (GRB) afterglows are produced by the synchrotron emission external forward shock. *Swift* and the ground-based telescopes provide a rich early afterglow data which revealed many unexpected and interesting features. Based on the statistics of a large GRB sample, this paper gives a brief introduction of the GRB optical afterglow, including observations, emission components and the afterglow puzzle "achromatic or chromatic?". The afterglows provide a very important window between the afterglows and prompt emission to reveal the veil of the progenitor, central engine, ejecta composition and radiation mechanism. GRB 140323A is a good case interpreted with circumburst medium transition from a stellar wind to a homogenous density medium in the external shock model. GRB 140419A and 150910A are good cases for a magnetar spin down to a stable neutron star and the collapse in black hole, respectively.

Keywords: Gamma-Rays Bursts: General, Methods: Statistical, Radiation Mechanisms: Non-Thermal

1. Introduction

Gamma-ray bursts (GRBs) are the most luminous phenomena observed in the Universe, with an isotropic γ-ray energy up to $E_{\gamma,\,\mathrm{iso}} \sim 10^{55}$erg [1], and they are still mysteries after 46 years since they were first discovered by Vela Satellites [2]. Based on the observations, e.g., long GRBs associated with supernovae and the short GRB can be detected associated with the gravitational waves (GW170817/GRB 170817A), they have been proposed to originate from a super-massive black hole or a rapidly spinning magnetized neutron star during core collapses of massive stars or mergers of binary compact objects. (e.g., [3-10]).

Regardless of the progenitor and central engine, a relativistic jet is launched, which is decelerated by a circumburst medium by a pair of external (forward and reverse) shocks. The reverse shock is likely short-lived. The forward shock continues to plow into the medium as the jet is decelerated. The synchrotron radiation of electrons accelerated from the external forward shock powers the broadband electromagnetic radiation, during the interaction between the fireball ejecta and the circumburst medium, and produce the broadband afterglow of GRBs [11-16]. Since *Swift* satellite launched [17], abundant and complicated properties can be discovered by scientist. The afterglows provide a very important window between the afterglow and prompt emission to reveal the veil of the progenitor, central engine, ejecta composition and radiation mechanism.

This paper gives a brief introduction of the GRB optical afterglow, including the observations, emission components in Section 2; the talk about the afterglow puzzle "achromatic or chromatic?" is in Section 3; a recent result of our observation will be shown in Section 4; and then we give a summary in Section 5.

2. Observations

Broadband GRB afterglows were predicted before their discoveries [4], [11], [18]. Shortly after the paper of predictions for the broad-band afterglow based on the external shock model can be seen in the publication by Mészáros and Rees on Feb. 10, 1997 [11], 18 days later, (Feb. 28, 1997), the first X-ray and optical afterglows were discovered for GRB 970228 [19], [20]. 69 days later, the first radio afterglow was discovered for GRB 970508 [21]. Afterglow observations are routinely carried out nowadays.

The GRB optical afterglow observations are relied on the ground-based telescopes. In the pre-*Swift* era [22], observations usually started several hours after the burst trigger. Thanks to rapid *Swift*'s trigger and the rapid ground notification to alert large follow-up telescope network (GCN), we obtain a lot of optical data. Figure 1 shows the GRB optical afterglow apparent magnitude distributions [23]. We can observe the optical just after several seconds later, e.g. GRB 08319B, 080413A and 130427A.For some GRBs the optical prompt emission also can be discovered, e.g. GRB 990123, 041219, 050401, 050820A, 061121, 080913B. This opened a new window to the study of GRBs. The launch of the high-energy mission *Fermi* and other programs, e.g., MAGIC [24], Konus-Wind [25], Insight-HXMT [26], Suzaku [27], has led to discovery of an extended GeV afterglow emission for many bright GRBs, e.g. 090902B, 130427A and 190114C.

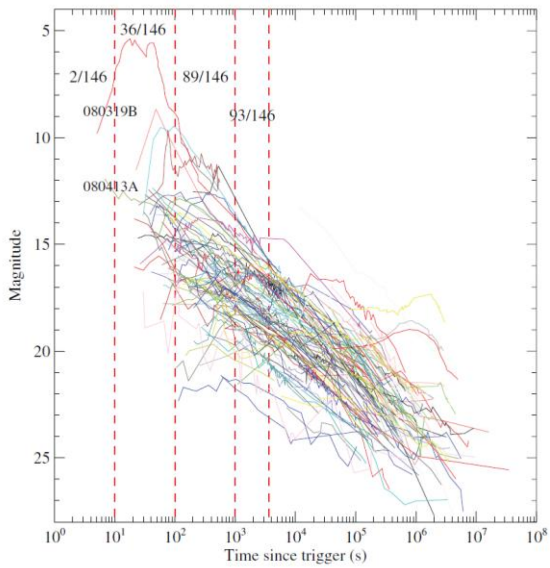

***Fig1**. GRB optical afterglow apparent magnitude distributions [wang 2013]*

One can see that the individual X-ray/optical light curves differ significantly. Reference [28] after synthesizing the *Swift*/XRT light curves, summarizes the observational properties of the X-ray afterglow emission as five-component canonical X-ray light curve [28] (as shown in the left panel of Figure 2):

- I. Steep decay phase, which is the tail of prompt emission;
- II. Shallow decay phase (or plateau), which is incorporated within the external shock, and need continuous energy injection into the blast wave [28-30];
- III. Normal decay phase, which is the typical decay expected in the standard forward shock afterglow model;
- IV. Late steepening phase, which is the jet break expected in the standard forward shock afterglow model;
- V. X-ray fares, which are related to late central engine activities.

Similarly, the synthetic optical light curve includes eight components, which have distinct physical origins.

The joint light curve of optical and X-ray afterglows also can be delineated as a canonical light curve, which generally includes 8 emission components [31]. These components are as follows.

- Ia. Prompt & late optical flares, which is related the prompt emission;
- Ib. Reversed shock emission, which is an early optical flare from the reverse shock in the standard forward shock afterglow model, observing only in few cases;
- II. Shallow decay:, which need energy injection from center engine;
- III. Standard afterglow component with an onset hump followed by a normal decay segment, which is the typical decay expected in the standard forward shock afterglow model;
- IV. Post-jet-break phase, which is the jet break expected in the standard forward shock afterglow model;
- V: Optical flares, which is related the prompt emission;
- VI: Rebrightening humps, which is similar to the early afterglow onset hump but occurs much later;
- VII. Late supernova (SN) bumps.

Components II–V in the optical light curves can find their counterparts in X-ray. It should be notified that not all GRBs show all these components.

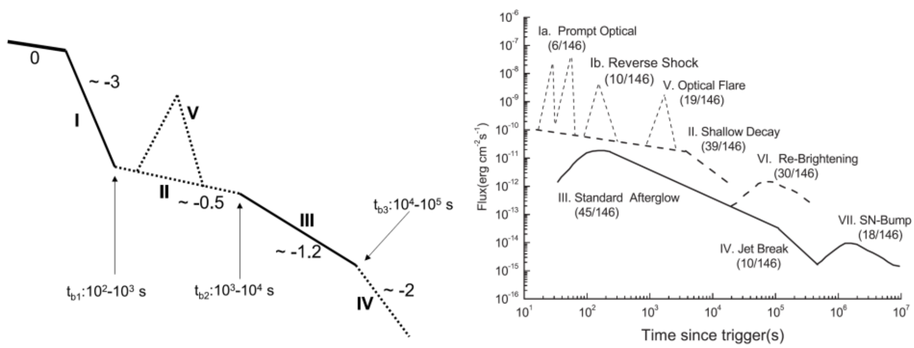

Fig2. *Left: Synthetic Cartoon X-ray Light Curve Based on the Observational Data from the Swift XRT; Right: Synthetic Cartoon Optical Light Curve Based on the Observational Data from the Ground Based Telescopes.*

3. Achromatic or Chromatic?

According to such an interpretation that the afterglow comes from the external shock, there are two types of temporal breaks. The first one is related to a characteristic frequency in the observational band [13], e.g. spectral breaks occur at different epochs in different energy bands (called chromatic). The second one is related to the hydrodynamic or geometric properties of the system, temporal breaks in different energy bands (e.g., X-ray and optical bands) should occur around the same observational time (called achromatic). The observations show that there are no spectral changes across the break time [32-33], and the theoretical simulations also show spectral beaks are very smooth and barely observable [34]. However, some authors based on the statistical data shows that most GRB afterglows are chromatic. Is the multiband afterglow achromatic or chromatic? Actually, the answer is related to the open question: how bad or how good are the external forward shock models in interpreting the GRB afterglow data?

Trying to answer this question, reference [35] systematically investigated all *Swift* GRBs that have X-ray and optical afterglow data, including 900 X-ray light curves from the *Swift* XRT data archive and 260 optical light curves from published papers or GCN Circulars. Based on the rich afterglow data, and using the closure relation predicted by the external shock model, at least ∼53% of GRBs can be interpreted within the external shock models. Up to ∼96% of GRBs may be accounted for external shock models, which need a more advanced modeling invoked, e.g., long-lasting reverse shock, structured jets, arbitrary circumburst medium density profile. Only less than 4% GRBs with direct evidence of chromatic behaviors, can be classified as truly violate external shock models.

4. Recently interesting observations

As is known, the afterglow not only can present the properties of the external shock, but also provide a very important window to constrain the physics of progenitor, central engine, ejecta composition and radiation mechanism. Ground-based optical telescopes continue to observe the GRB afterglow, e.g., KAIT [36], GWAC-F60, TNT [37], SAO-RAS [38], ISON-NM [39], NOT [40], GROND [41], BOOTES [42], MONDY [43], MASTER [44]. Here we list the GRB 140423A, 140419A and 150910A as an example.

The optical observation shows that GRB 140423A have an onset bumps in the early epoch [45], then show steeper ($\alpha_1 \sim -1.6$) to flatter decay ($\alpha_2 \sim -1.1$) with a break at ~5000 s. It can be well interpreted with the standard external shock model by considering the circumburst medium which transited from a stellar wind having a density distribution $\rho(r) \propto r^{-2}$ to a homogenous density medium.

The GRBs central engines could be a black hole with accretion disk systems or a millisecond magnetar. When a millisecond magnetar as central engine for a long GRB, they can produce an internal plateau as it spins down in the afterglow light curves. If the post plateau the temporal decay index is steeper than -3, it may indicate that the magnetar collapses into a black hole. If the mass of the magnetar is not so massive, it may spin down to a stable neutron star, and post plateau decay index between -2 and -3. GRB 140419A [46] and 150910A [47] are good cases for a magnetar spin down to stable neutron star and collapse in black hole, respectively. For GRB 140419A, we obtain the magnetar parameters with magnetic field of the magnetar B_p, the spin period of the magnetar P_0, and the radiative efficiency of prompt emission η is $\sim 10^{15}$ G, $\sim$ 0.96 ms, and $\sim$ 2.2%, respectively. However, the radiative efficiency of internal plateau η_X is larger than 18.1%. For GRB 150910A, the deriving of physical parameters of the putative magnetar is $P_0 \sim (0.96 \sim 1.52)$ ms and $Bp \sim (0.41 \sim 1.03) \times 10^{15}$ G, respectively.

5. Summarizes

The scientist have learn a lot of the GRB in the past a half century. However, there are still a lot things we need to understand more, e.g. progenitor, central engine, ejecta composition and radiation mechanism, and will push the observation forwards. The GRBs occur randomly in space at unknown time. We not only need the larger space mission to detect the high energy emission in the future, e.g., SVOM [48], ATHENA [49], HESEUS [50], eXTP [51], ET [52], TAP [53] and ISS-TAO. We also need large survey ground-based optical telescopes with deeper detection ability, to discover or follow the GRB-like transients. We believe the next decade will be an exciting era of GRB study.

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