Part 9

Gamma Ray Bursters

High Energy Processes and Phenomena in Astrophysics
IAU Symposium, Vol. 214, 2003
X. D. Li, V. Trimble, and Z. R. Wang, eds.

Some Recent Developments in γ-ray Burst Afterglow and Prompt Emission Models

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Abstract. Extensive observational campaigns of afterglow hunting have greatly enriched our understanding of the gamma-ray burst (GRB) phenomenon. Efforts have been made recently to explore some afterglow properties or signatures that will be tested by the on-going or the future observational campaigns yet come. These include the properties of GRB early afterglows in the temporal domain; the GeV-TeV afterglow signatures in the spectral domain; as well as a global view about the GRB universal structured jet configuration. These recent efforts are reviewed. Within the standard cosmological fireball model, the very model(s) responsible for the GRB prompt emission is (are) not identified. These models are critically reviewed and confronted with the current data.

1. Introduction

Gamma-ray bursts (GRBs) belong to one of those classes of mysterious objects whose nature took great efforts to identify. For years after their discovery, our knowledge about the objects had been limited to the "gamma-ray" in the spectral domain, and the "burst" in the temporal domain. The revolutionary discovery and the extensive hunting and monitoring of the broadband afterglows for dozens of GRBs greatly extended our knowledge about the events both in the spectral domain (from radio to X-rays) and in the temporal domain (from minutes to years). We now have some good knowledge about at least one subset of GRBs, i.e. the so-called long GRBs whose durations are longer than 2 seconds. These include that they are originated from cosmological distances, likely associated with the deaths of massive stars; that the afterglow is emission from the external forward shock when the fireball impacts the ambient interstellar medium (ISM); and that the fireballs are likely collimated at least for some GRBs (e.g., Piran 1999; van Paradjis, Kouveliotou, & Wijers 2000; Mészáros 2002). It is expected that some new progress will be made in the GRB study in the coming years, thanks to the observational advances led by some future space and ground-based multi-wavelength telescopes, especially by the two NASA missions, Swift and GLAST. Among others, the very early afterglows including the bridge between the GRB prompt phase and the afterglow phase will be carefully studied; the broad-band afterglow campaign will be extended to high energy (GeV-TeV) regimes; and a large sample of dataset combining the redshifts and the GRB prompt emission & afterglow properties will be available, leading to a global view of the GRB jet configuration and the identification of the GRB prompt emission site(s) and mechanism(s). Below we will review some recent theoretical efforts in anticipation of these upcoming observational breakthroughs.

2. Early afterglows

GRBs involve extremely relativistic bulk motion of the fireballs. At the time when most of the current afterglow observations are made (typically hours after the burst trigger), a fireball has already decelerated substantially to mildly relativistic (e.g. $\Gamma(t) \sim 20(E_{52}/n)^{1/8}[t_h/(1+z)]^{-3/8}$, where E_{52} is the isotropic fireball energy in unit of 10^{52} ergs, n is the ISM density, z is the redshift, and t_h is the epoch of observation in the observer frame in unit of hour), and the erratic central engine activity has usually ceased. Catching the detailed information in the very early epoch of the afterglow emission is of great interest in catching precious information about the fireball relativistic motion and the central engine behavior.

2.1. Early post-injection signatures

The observer's time at the on-set of the afterglow emission is approximately $t_{dec} \sim 2.4 \text{ s } (E_{52}/n)^{1/3} \, (\Gamma_0/300)^{-8/3}(1+z)$, where Γ_0 is the "initial" bulk Lorentz factor of the fireball at the deceleration radius, which is scaled with a typical value, 300. This timescale is largely determined by the fireball intrinsic parameters E_{52} and Γ_0, as well as the environmental parameter n. The time scale for the central engine activity, t_{eng} on the other hand, is completely defined by the life time of the central engine (e.g. the life time of the black hole - torus system; the collapsar envelope fallback time scale; or the life time of the temporal strong toroidal magnetic field for the magnetar central engine case). This is usually manifested as the duration of the GRB (but in principle could be longer), which is found to vary substantially among bursts. These two time scales are independent, and as long as $t_{eng} > t_{dec}$, post-energy-injection into the fireball in the afterglow phase is inevitable.

Whether the post-injection behavior is noticeable depends on the comparison between the initial energy, E_{imp}, already entrained in the fireball and the additional energy input, E_{inj}. Only if the latter is comparable to or larger than the former, could the injection process leaves noticeable signatures in the afterglow lightcurves (Zhang & Mészáros 2002a). Also the central engine activity is expected to diminish at later times. Therefore the early afterglow phase is the most likely epoch to study the injection signatures.

The injection signatures depend on the nature of the injected energy flow. 1. If the GRB wind is mainly dominated by a cold, magnetic dominated component, as some GRB central engine models expect, the injection wind is likely to give an achromatic, gradual bumping signature in the broad-band afterglow lightcurves (Fig.1 of Zhang & Mészáros 2002a). One example of such a Poynting-dominated-injection is that from a strongly magnetized millisecond pulsar (Dai & Lu 1998; Zhang & Mészáros 2001a), which presents a well-defined, easy-modeling injection signature (Zhang & Mészáros 2002a). A detection of such a signature can give a possible identification of the GRB central engine otherwise poorly known.

Whether a strong reverse shock is developed in such an injection case is unclear, and the contribution from the reverse shock is neglected in the current modeling. 2. In the conventional "hot" fireball scenario, the injected energy is typically in the form of the kinetic energy of the expanding shell. In a simple case, a fireball is composed of multi-minishells with increasing Lorentz factors at later times. Such a scenario is known as the "refreshed" shock scenario (Rees & Mészáros 1998; Sari & Mészáros 2000), and there is already a claim that such a scenario may be able to interpret the peculiar flat decaying lightcurves of GRB 010222 (Björnsson et al. 2002). In more complicated scenarios, an injection process is more appropriately viewed as the interactions among three shells (ISM, initial shell, and the injective shell). The hydrodynamics of such a process is analyzed in great detail in Zhang & Mészáros (2002a). Because multi-shocks are involved, the injection signatures for a violent collision are complicated (Fig.5 in Zhang & Mészáros 2002a). The recent peculiar wiggling R-band lightcurve of GRB 021004 may be modeled as such violent injection events, although other interpretations (e.g. Lazzati et al. 2002) may be also reasonable.

Other mechanisms to interpret lightcurve bumps include supernova contribution (e.g. Bloom et al. 1999), dust echo (Esin & Blandford 2000), collisions of the fireball with the ambient density bumps (Dai & Lu 2002a), and the gravitational microlensing effect (Garnavich, Loeb & Stanek 2000). The main differentiable character of an injection signature is that the afterglow level is systematically raised after the injection (Zhang & Mészáros 2002a).

2.2. Reverse shock emission

During the initial interaction of the fireball with the ISM, a reverse shock will cross the fireball shell and emit a comparable amount of energy as in the forward shell (Mészáros & Rees 1997). After the shell crossing, the shocked fireball cools adiabatically, leading to a fading emission component. The emission is peaked in the UV-optical band, and it has been claimed that the optical flash detected in GRB 990123 is due to such an emission component (Mészáros & Rees 1999; Sari & Piran 1999). Due to complicated regimes involved (Kobayashi & Sari 2000; Kobayashi 2000), a bright optical flash is not always expected to be detectable. In any case, when early afterglows are caught, the emission signatures dominated by the reverse shock should be attainable.

Thanks to the prompt localization by HETE II, lately the R-band afterglow of GRB 021004 was caught $\sim$ 9 minutes after the burst, marking the earliest record of catching GRB afterglows and the best monitored afterglow so far (see extensive observational reports in the GRB Coordinates Network, http://gcn.gsfc.nasa.gov/gcn/gcn3_archive.html). An apparent re-brightening in the R-band lightcurve is observed at around 0.1 day. Among other interpretations (e.g. Lazzati et al. 2002), Kobayashi & Zhang (2002) show that this re-brightening is well interpreted within the framework of the standard fireball model in which both the emissions from the forward shock and from the reverse shock are considered. The low-frequency (e.g. optical, IR & radio) lightcurve from the forward shock is expected to rise initially and to decay after the typical synchrotron frequency ν_m crosses the observational band (Fig.2b of Sari, Piran & Narayan 1998). Although such a behavior has been observed in the radio band, previous optical afterglow observations were only made at too late a time to catch the rising part of the lightcurve. Kobayashi & Zhang (2002) argue that such a phase was caught for GRB 021004, together with a rapid decaying ($F_\nu \propto t^{-2}$) emission component from the reverse shock. The superposition of both the forward shock and the reverse shock emissions can well fit for the 0.1-day re-brightening feature of the GRB 021004 R-band early afterglow. For the example case presented in Kobayashi & Zhang (2002), the standard shock parameters as inferred from other GRBs (Panaitescu & Kumar 2001, 2002) are adopted, and the model can also interpret the X-ray and radio afterglow data. This hints that such a re-brightening signature may be a common feature in early afterglows, which could be readily tested in the near future by the UVOT telescope on board Swift mission.

3. High energy afterglows

The term "high energy afterglow" is defined with respect to the conventional low-energy (X-ray, optical, radio) afterglows which are believed to be originated from the synchrotron emission of the electrons accelerated in the forward shocks as the fireball decelerates in the ISM. The origins of the possible high energy afterglows are well justified. There are several high energy spectral components in the standard shock scenario which are not important in the low energy band. These include the synchrotron self-inverse Compton (IC) emission of the electrons, and the baryon-related emission components such as the proton synchrotron emission, synchrotron emission from the secondary muons or direct π^0 decay from the photomeson interactions. Zhang & Mészáros (2001b) presented a coherent study of the high energy spectral components with respect to the conventional synchrotron component, and discussed the shock parameter regimes in which various components dominate. Because baryons are redundant emitters compared with electrons, the baryon-related emission components can overwhelm the electron synchrotron emission only when the electron equipartition factor ϵ_e is very small while the magnetic field is near equilibrium ($\epsilon_B \sim 1$). On the other hand, there is a large parameter regime in the $\epsilon_e - \epsilon_B$ space that the IC component is important (regime II of Fig.1 in Zhang & Mészáros 2001b, typically $\epsilon_e/\epsilon_B > 1$). It turns out that the current broadband afterglow fits result in typical ϵ_e and ϵ_B parameters which lie right in this IC-dominated regime (Panaitescu & Kumar 2001).

A direct consequence for these "typical" (regime II) GRBs is that the IC-origin high energy afterglows should be detectable. The IC emission forms a separate four-segment broken power law spectral component at the high energy end of the conventional synchrotron component (e.g. Sari & Esin 2000). As the blast wave decelerates, the two-hump spectrum will evolve towards down-left. Fixing a certain band, the observer will initially receive power-law-decaying synchrotron emission until, at a critical time $t_{\rm IC}$, the IC component overtakes the synchrotron component. For the electron power-law index $p = 2.2$, this critical time is (Zhang & Mészáros 2001b)

$$t_{\rm IC} = 3.4 \text{ days } (\epsilon_e/0.5)^{0.89} (\epsilon_B/0.01)^{0.08} E_{52}^{-0.06} n^{-0.66} (1+z)^{-0.36} \nu_{18}^{-0.68} \qquad (1)$$

After $t_{\rm IC}$, the lightcurve then climbs up until reaching the peak flux of the IC component, and declines later after $\nu_{m,\rm IC}$ crosses the band. This results in a bumping signature in the fixed band lightcurve. Equation (1) shows that in order to have a noticeable signature at an early time, the frequency has to be high enough (X-ray upwards), and a dense environment tends to ease the IC-dominant condition. Late X-ray bump in the GRB 000926 has been attributed to the IC high energy afterglow (Harrison et al. 2001).

At higher frequencies, the IC-dominated era as well as the IC peak time move to earlier epochs. For the nominal GLAST band (0.4-200 GeV), the afterglow is dominated by the IC component as soon as the afterglow starts, and the IC peak sweeps the band in about an hour. Given the GLAST sensitivity, a typical regime II GRB at $z = 1$ could be detected by GLAST from minutes to about a day after the trigger, leading to an extended high energy afterglow (Fig.4 of Zhang & Mészáros 2001b). According to this scenario, the long term GeV emission detected by EGRET in GRB 940217 (Hurley et al. 1994) may have been due to such an IC component for a nearby GRB (see also Mészáros & Rees 1994; Dermer, Chiang & Mitman 2000).

Besides this standard model, an extended GeV afterglow may be also interpreted by some alternative mechanisms. One possibility is the secondary IC scattering off the microwave background photons by the pairs produced by the TeV gamma-rays generated in the GRB internal shocks through interacting with the IR background photons (Dai & Lu 2002b), if the intergalactic magnetic field is not strong enough for prominent lepton reflection to occur. Another possibility is the direct interaction of the GRB fireball with the hot ambient pulsar wind nebula (Wang, Dai & Lu 2002; Granot & Guetta 2002). Future detailed data from GLAST and other space or ground-based high energy telescopes will provide clues to differentiate among these scenarios.

4. A quasi-universal structured jet model

Achromatic steepening of the afterglow lightcurves infer that most long GRBs, if not all, are originated from collimated jets. Frail et al. (2001) collected a sample of GRBs with redshift and jet break measurements before Oct. 2000, and found the remarkable fact that the product of the "isotropic" gamma-ray energy and the square of the inferred jet angle is a standard value, i.e., $E_\gamma = E_{iso}\theta_j^2 \sim$ const. The θ_j angle is obtained from the jet breaking time by assuming the simplest uniform sharp-edge jet configuration (Rhoads 1999; Sari, Piran & Halpern 1999; Panaitescu & Mészáros 1999; Moderski et al. 2000; Huang et al. 2000; Granot et al. 2001) and by assuming a roughly constant ambient ISM density ($n \sim 1\ \mathrm{cm}^{-3}$). Although n could in principle vary from burst to burst, that most of the later-observed GRBs seem to fall into the Frail et al. (2001)'s empirical law suggests that the collimated jets are indeed the promising interpretation of the lightcurve breaks, and that n is not fluctuating significantly. Within the conventional uniform jet model, the jet aperture solid angle is proportional to θ_j^2, so that the finding of Frail et al. (2001) suggests that long GRBs have a quasi-standard energy reservoir, although such a standard energy budget is distributed with different concentrations among different bursts.

The same data may be interpreted within another, probably more elegant, picture. Stimulated by Frail et al (2001)'s result, Rossi, Lazzati & Rees (2002a) and Zhang & Mészáros (2002b) have independently shown that the wide variety of burst phenomenology could be attributed to a standard non-uniform jet configuration being viewed from different orientations. The jet is structured such that the closer to the jet axis, the more energy is concentrated and the higher the bulk Lorentz factor is achieved. The jet break angles as inferred from the observational break times are a manifest of the observer's viewing angle rather than the real jet opening angle. The shape of the jet structure is modeled as a power-law, i.e., $\epsilon(\theta) \propto \theta^{-k}$, and for $k \sim 2$, such an interpretation is almost non-differentiable from the conventional uniform jet model. Zhang & Mészáros (2002b) further proposed that the observed jet breaks can be interpreted within such a scenario for a much broader categories of the energy distribution functions (e.g. no longer a power law, or even not a simple analytical form) of the jets. The lightcurve predictions for these configurations as well as for all the $k \neq 2$ power-law configurations are not solely equivalent to the predictions from the conventional jet model (R. Sari, personal communication), but the conventional model is not fully satisfactory anyway (e.g. a large dispersion of the electron power law indices p as inferred from the broadband afterglow fits, while computer simulations on the shock acceleration indicate that p is likely universal). A closer study on the structured jet model both analytically and numerically (although may not be easy) is therefore desirable.

Although the conventional jet model is not easily ruled out, there are already several arguments in favor of the universal structured jet model. 1. To interpret the spectral-lag vs. luminosity correlations found in the GRB prompt emission data (Norris et al. 2000), one natural way is to incorporate a structured jet configuration and the line-of-sight effect (Salmonson 2001; Salmonson & Galama 2002; Norris 2002). A coherent picture is achievable for both the prompt emission and the afterglow within the framework of the universal jet model. 2. Within the top candidate of the progenitor models, i.e., the collapsar model, a structured jet configuration is naturally expected from numerical modeling (Woosley et al. 2002; Zhang et al. 2002). 3. A prediction about GRB luminosity function is available for the universal jet model (but not for the conventional jet model), which is a power law with index around 2 (Rossi et al. 2002a; Zhang & Mészáros 2002b). Such a prediction is consistent with the GRB luminosity function derived from the prompt emission data (Schaefer et al. 2001; Schmidt 2001) or even with the one measured directly from those bursts with luminosity information (Perna, Sari & Frail 2002).

There are several ways to differentiate the universal jet model from the conventional jet model. 1. Besides the well-defined luminosity function testable in the Swift era (which can add proofs or constraints on the universal jet model but not on the conventional jet model due to the lack of the prediction power of the latter), the GRB-to-orphan afterglow rate are different between different models (e.g. Totani & Panaitescu 2002). Future detections of the orphan afterglows as well as their statistics may shed light onto the issue, although the orphan afterglows arising from the dirty fireballs may complicate the clean picture (Huang, Dai & Lu 2002). 2. The different afterglow polarization predictions for both models may be helpful to tell the difference (Rossi et al. 2002b). 3. Future gravitational radiation polarization data may shed light on the correctness of the universal jet scenario (Kobayashi & Mészáros 2002).

5. Prompt emission models

Despite of the extensive observational campaigns and theoretical modeling of the afterglows, the nature of the GRB prompt emission is not fully understood. The location and mechanism of the prompt emission or even the energy context of the fireball are not unambiguously identified, leading to a variety of the cosmological fireball model variants.

Most generically, a fireball consists of a hot component with luminosity L_h (which is essentially the conventional fireball initially composed of in-equilibrium photons and pairs, and which is accelerated and coasted until the energy is stored in the form of the kinetic energy) and a cold component with luminosity L_c (which is essentially of the form of a Poynting flux, analogous to the case of a pulsar wind). A parameter, $\sigma \equiv L_c/L_h$, can be defined to categorize the fireball. Based on the proposed emission site of the GRB prompt emission, the GRB models can be also divided into the external models (where the prompt emission occurs at the deceleration radius, i.e., $r = r_{dec}$), internal models (where the prompt emission occurs before deceleration but beyond the photosphere, i.e. $r_{ph} < r < r_{dec}$), and the innermost models (where the prompt emission occurs right above the photosphere, i.e. $r \gtrsim r_{ph}$). A unified picture of these model variants is analyzed in Zhang & Mészáros (2002c).

It is not a easy task to identify the very mechanism(s) responsible for the observed GRB prompt emission. In any case, for those well-studied models, clear predictions are available which could be directly compared against the current and future data. Besides the complex lightcurve information which requires erratic central engine behaviors or a clumpy ambient environment, the spectral information, especially the information about the spectral break, E_p, can provide some useful clues. Two interesting issues include (1) the distribution of the measured E_p within different bursts or among various epochs of one single burst (which is found to be narrowly distributed for the bright BATSE bursts, Preece et al. 2000), and (2) the possible correlation of E_p with other measurable parameters (e.g. a positive correlation between E_p and luminosity L, Amati et al. 2002; Lloyd-Ronning & Ramirez-Ruiz 2002). Assuming synchrotron radiation as the mechanism, Zhang & Mészáros (2002c) have compiled all the predictions of E_p as functions of various measurable parameters as well as some unknown parameters (their Table 1). Adopting some distribution functions of the parameters (either from the observations or from the assumptions), they modeled the narrowness of the E_p distributions for various models. The results are compared against the current data. Although any unambiguous clue for the identification of the "right" model is not yet available, some important constraints have been posed on various models.

1. About the width of E_p distribution: None of the current GRB models can reproduce the narrow E_p distribution found by Preece et al. (2000), including the well-discussed internal shock and the external shock models. A narrow E_p distribution favors those models whose E_p prediction relies on less free parameters with low power indices. A high σ internal model or a pair-dominated internal model are good in this respect due to their (essentially) constant E'_p value in the comoving frame. However, these models are less studied compared to the standard optically-thin shock scenarios. There are two issues that may bring data closer to the predictions in the shock models. First, the growing

population of the so-called X-ray flashes (XRFs, Heise et al. 2001; Kippen et al. 2001) may broaden the real E_p distribution. Second, there may be some intrinsic conspiracy among some parameters in the shock models which tend to narrow the final E_p distribution. In any case, the internal scenarios are generally favored against the external scenarios, and the IC-origin GRB models are less favored than the synchrotron models since they tend to amplify the E_p scatters. A recent "supercritical pile" model invoking resonant baryonic pair production instability (Kazanas et al. 2002) seems to be favorable in interpreting the narrow E_p distribution. It is of interest to investigate the compatibility of this model with other observational aspects.

2. About the positive $E_p - L$ correlation: Whether a model is compatible with the positive $E_p - L$ correlation (Amati et al. 2002; Lloyd-Ronning 2002) depend on the unknown $L - \Gamma$ correlation, where Γ is the bulk Lorentz factor. For the most straightforward scenario in which Γ is positively correlated with L, the internal shock model is not favored, essentially because the model predicts a lower E_p for a larger Γ since a larger Γ corresponds a larger shock dissipation radius where the magnetic field is lower. The internal high-σ model or the internal pair-rich model are however compatible with the data. In order to make the internal shock model remain a promising candidate, essentially no correlation between L and Γ is required.

3. About the nature of X-ray flashes (XRF): The XRFs (Heise et al. 2001; Kippen et al. 2001) and GRBs are likely different appearances of a same type of event. In various models, the E_p scatter is caused by the contribution of the scatters of many independent parameters. Thus it is not straightforward to regard the scatter of one particular parameter (e.g., Lorentz factor or redshift) as the reason for the XRF/GRB discrimination. Nonetheless, a direct reasoning from the "Lorentz boost" argument is that XRFs are dirty fireballs while GRBs are clean fireballs (e.g. Dermer et al. 1999). This interpretation, together the standard structured jet configuration as discussed in Section 4, suggests that XRFs are those GRBs viewed at large viewing angles (e.g. Woosley et al. 2002). A premise of such an interpretation, however, is that prompt emission is not from internal shocks because the internal shock model expects high E_p's for dirty fireballs. An alternative interpretation of the XRFs and X-ray rich GRBs is in terms of the standard shock model with the dominant emission components from either the baryonic or the pair photospheres (Mészáros et al. 2002). Spectral and redshift information for XRFs would be essential to testify these interpretations.

6. Conclusions

A new epoch for the GRB study is coming within the next several years, especially following the launches of Swift and GLAST, and the utilization of some other broad-band advanced facilities. It is optimistic to expect the following breakthroughs in the coming years:

- Early afterglows will be carefully studied. The missing link between the prompt emission and the afterglow will be identified, including the detailed reverse shock information. The information from the central engine may be retrievable through well-modeled injection signatures.

- High energy afterglows will be monitored and studied in conjunction with the low energy afterglows, which will bring invaluable information about the unknown shock physics and the GRB environments.
- The GRB jet configuration will be identified. We expect the universal structured jet model will be validated by future data.
- With accumulation of a large sample of the redshift and spectral information for GRBs/XRFs in the Swift era, the right emission site(s) and mechanism(s) for the prompt emission may be identified (or at least strongly constrained). The fireball content and the nature of the relativistic wind from the central engine may be also understood.

Acknowledgments. We thank Shiho Kobayashi for stimulating collaborations. This work is supported by NASA grants NAG5-9192 and NAG5-9153.

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