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Environment, Energy Injection, High-Energy Radiation, and Cosmological Use of Gamma-Ray Bursts

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Abstract The standard fireball shock model is successful at explaining the overall features of afterglows of some bursts, but it cannot fit the observed data quantificationally. Some post-standard effects (i.e., environment, energy injection, and high-energy radiation) have been studied to fit well the observed data. This paper reviews these important effects and cosmological use of GRBs.

Key words: gamma rays: bursts

1 INTRODUCTION

In the standard afterglow shock model (for reviews see Piran 1999, 2004; van Paradijs, Kouveliotou & Wijers 2000, Mészáros 2002; Zhang & Mészáros 2004), a gamma-ray burst (GRB) afterglow is usually believed to be produced by synchrotron radiation or inverse Compton scattering in an ultrarelativistic shock wave expanding in a homogeneous medium. As more and more ambient matter is swept up, the shock gradually decelerates while the emission from such a shock fades down, dominating at the beginning in X-rays and progressively at optical to radio energy band. This model is based on the following basic assumptions: (1) the total energy of an isotropic shock is released impulsively before its formation; (2) the medium swept up by the shock is homogeneous and its density (n) is the one of the interstellar medium $\sim 1\,\mathrm{cm}^{-3}$; and (3) the electron and magnetic field energy fractions of the shocked medium and the index (p) in the accelerated electrons' power-law distribution are constant during the whole evolution stage. The standard model is successful at explaining the overall features of afterglows of some bursts, but it cannot fit the observed data quantificationally. Some post-standard effects (i.e., environment, energy injection, and high-energy radiation) have been studied to fit well the observed data. This paper reviews these important effects and cosmological use of GRBs.

2 ENVIRONMENTAL EFFECT

In the current theories of gamma-ray bursts (GRBs), the properties of circumburst environments remains one of the most important issues. On one hand, the environmental properties are directly related to the progenitors of GRBs. Two currently popular models for the progenitors are the mergers of compact stars (neutron stars or black holes) and the explosions of massive stars. It has been argued that GRBs produced by the mergers of compact binaries occur in a

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uniform low medium because initial kick velocities of the compact stars are so high that such compact binaries should merge at a site far from their birth place. And GRBs in the latter model may occur in pre-burst winds (Chevalier & Li 1999) and/or giant molecular clouds (Dai & Lu 1999; Galama & Wijers 2001; Reichart & Price 2002) because massive progenitor stars should have lost their outer envelopes prior to the bursts and/or because there may be dense giant molecular clouds surrounding the bursts. Thus, an environmental signature is expected to provide a clue about the GRB progenitors. On the other hand, the environmental properties can directly influence the decay rates of afterglows. For example, afterglows arising from the interaction with pre-burst winds should decay more rapidly than afterglows do in a constant low-density medium (e.g., an interstellar medium) (Dai & Lu 1998; Mészáros, Rees & Wijers 1998; Panaitescu, Mészáros & Rees 1998; Chevalier & Li 1999, 2000). Furthermore, ultrarelativistic fireballs (or jets) in a uniform dense medium (e.g, galactic-like giant molecular clouds) must evolve to the non-relativistic regime within a few days after the bursts, leading to more rapid decay of the afterglows (Dai & Lu 1999, 2000; Wang, Dai & Lu 2000). It is thus natural that an afterglow signature can probe the ambient matter as well as the progenitors.

Dai & Lu (1998) suggested, for the first time, that the environment of GRB 970616 is likely to be a stellar wind with density $n \propto R^{-2}$ based on the rapid fading indicated by X-ray flux measurements. Mészáros, Rees & Wijers (1998) discussed the evolution of an afterglow in a general case of $n \propto R^{-s}$. Subsequently, Chevalier & Li (1999) argued that GRB 980519 is an excellent wind interactor based on its X-ray, optical and radio data, and they (Chevalier & Li 2000) also discussed the wind model in more details. More evidence for this model was suggested for GRB 991208 and GRB 021004 (Li & Chevalier 2001, 2003). The properties of early afterglows in the wind model were discussed by Wu et al. (2003) and Kobayashi & Zhang (2003), and the evolution of late afterglows from jets in winds was modelled numerically by Gou et al. (2001), Panaitescu & Kumar (2000) and Wu et al. (2004). The observations on the afterglow of GRB 990123 show that its R-band temporal decay steepened about 2.5 days after this burst (Kulkarni et al. 1999; Castro-Tirado et al. 1999; Fruchter et al. 1999). Dai & Lu (1999) proposed, for the first time, the nonrelativistic interpretation in which a shock expanding in a dense medium has evolved from a relativistic to nonrelativistic phase. They found that this model fits well the observational data if the medium density is about $3\times10^6\,\mathrm{cm}^{-3}$. More detailed analysis and calculations were carried out by Dai & Lu (2000) and Wang, Dai & Lu (2000). Such a medium could be a giant molecular cloud. Of course, the steepening in the light curves of the afterglows may be due to lateral spreading of a jet, as analyzed by Rhoads (1999) and Sari, Piran & Halpern (1999) for the electron energy distribution index $p > 2$, and by Dai & Cheng (2001) for $1 < p < 2$. An implication of the jet model is that the beaming-corrected gamma-ray energy release is found to be narrowly clustered around 10^{51} ergs (Frail et al. 2001; Bloom et al. 2003). However, it should be emphasized that the nonrelativistic mechanism as an interpretation of the light curve break does not conflict with the jet model. This is because both a dense medium and a jet may exist for long-duration GRBs associated with massive stars (Livio & Waxman 2000).

In the afterglow shock models mentioned above, the environments of GRBs are usually assumed to be continuous media (e.g., interstellar medium and wind). Actually, there are possibly some complicated structures (e.g., jumps or bumps) in the density profile of the ambient media of GRBs associated with massive stars. Such structured media may be produced by several astrophysical processes, e.g., the deceleration of winds in their external medium (Ramirez-Ruiz et al. 2001; Wijers 2001; Dai & Wu 2003; Chevalier et al. 2003) or the interaction of fast and slow winds (Luo & McCray 1991; Vikram & Balick 1998). Dai & Lu (2002) performed a careful analysis for the afterglow emission when a post-burst relativistic blast wave interacts with such a density-jump medium, and Dai & Wu (2003) used this model to explain the afterglow of GRB 030226, as shown in Figure 1. Recently, Chevalier et al. (2003) considered the shocked wind model (whose picture is similar to that of the model of Dai & Wu except for the pressure of an outer medium) to discuss the afterglows of GRBs 020405 and 021211.

3 ENERGY INJECTION

In currently popular scenarios for GRBs, a rapidly rotating black hole surrounded by an accretion disk seems to be a common remnant (Narayan, Paczyński & Piran 1992; Woosley 1993; Mészáros & Rees 1997; Paczyński 1998). However, a millisecond magnetar has also been argued as an alternative interesting product (Usov 1992; Duncan & Thompson 1992; Kluźniak & Ruderman 1998; Dai & Lu 1998; Spruit 1999; Ruderman, Tao & Kluźniak 2000; Wheeler et al. 2000). To explain the complex temporal feature, the burst itself, in some of these energy models, is understood to arise from a series of explosive reconnection events in a rising, amplified magnetic field because of the Parker instability. This in fact dissipates the differentially rotational energy and magnetic energy of the newborn magnetar or accretion disk.

After the GRB, the remaining object is reasonably assumed to be a millisecond magnetar or a rapidly rotating black hole surrounded by an accretion disk. For the latter object, the magnetic field in the disk could have been amplified initially by differential rotation to a magnetar-like strength of $\sim 10^{15}$ G, and particularly, within the framework of the collapsar/hypernova model, such a field could be kept, due to longevity (with days or longer) of the disk maintained by fallback of the ejecta. During the afterglow, the object at the center will directly lose its rotational energy by the magnetic dipole radiation or the Blandford-Znajek mechanism. Dai (2004) suggested, based on the successful models of the well-observed Crab Nebula (Rees & Gunn 1974; Kennel & Coroniti 1984), that a realistic, continuous outflow during the afterglow may be ultra-relativistic and dominated by the energy flux of electron-positron pairs. As in the Crab Nebula, even if an outflow from the pulsar is Poynting-flux-dominated at small radii, the fluctuating component of the magnetic field in this outflow can be dissipated by magnetic reconnection and used to accelerate the outflow, which is eventually dominated by the energy flux of e^+e^- pairs within a larger radius $\sim 10^{17}$ cm (Coroniti 1990; Michel 1994; Kirk & Skjæraasan 2003). In the case of an afterglow, therefore, it is natural to expect that the central object still produces an ultra-relativistic e^+e^--pair wind, whose interaction with the fireball leads to a relativistic wind bubble. Dai (2004) explored the dynamics of such a wind bubble and its emission signatures (shown in Figure 2).

Dai & Lu (1998, 2000), Zhang & Mészáros (2001) and Chang, Lee & Yi (2002) discussed the evolution of a relativistic fireball by assuming a pure electromagnetic-wave energy injection rather than electron-positron energy injection. Rees & Mészáros (1998), Sari & Mészáros (2000), Kumar & Piran (2000), Zhang & Mészáros (2002), Nakar, Piran & Granot (2003), and Granot, Nakar & Piran (2003) took into account a variable and baryon-dominated injection. One reason for the latter energy injection mechanism is that many pulses during the prompt gamma-ray emission are due to collisions between relativistically-expanding shells with different Lorentz factors (i.e., internal shocks), and thus longer-duration collisions after the GRB are expected.

4 ULTRAHIGH ENERGY COSMIC RAYS AND HIGH ENERGY NEUTRINOS

The popular understanding of GRBs and afterglows is based on the fireball shock model. According to this model, GRBs are understood to be due to the dissipation of kinetic energy of an ultrarelativistically-expanding fireball with an average Lorentz factor more than 10^2 in the internal shocks produced by collisions between shells with different Lorentz factors in the fireball. Afterglows are also interpreted to be due to the dissipation of kinetic energy in the external shocks generated by collision of the fireball with its surrounding medium. In the fireball shock model, the electrons are accelerated by the shocks to produce the prompt gamma-ray emission and the subsequent long-term afterglow emission. It is natural to expect that the protons in the fireball and in the swept-up medium are also accelerated by the same shocks. Vietri (1995), Waxman (1995), and Milgrom & Usov (1995) discussed such accelerated protons to explain the observed cosmic ray spectrum above 10^{18}eV. These authors suggested that the GRBs could be sources of ultrahigh energy cosmic rays. This suggestion has been questioned on some grounds such as the Greisen-Zatsepin-Kuzmin (GZK) cutoff (e.g., Gallant & Achterberg 2001; Stecker 2000). More detailed discussions on this topic were recently presented by Wick, Dermer & Atoyan (2004).

No matter whether or not GRBs can accelerate protons to observed ultrahigh energy cosmic rays on some grounds (e.g., the GZK cutoff), they must be able to accelerate protons to some high energies. An implication of such accelerated protons is the emission of high energy neutrinos and high energy photons. The processes of high energy neutrinos discussed widely in the literature include $p\gamma$ process, pp process and pn process. The first process takes place at the Δ-resonance, at which the observed proton energy and the observed photon energy satisfies the condition $\epsilon_p \epsilon_\gamma \sim 0.3\Gamma^2\,\mathrm{GeV}^2$, where Γ is the Lorentz factor of the fireball. The threshold condition for the latter two processes is that the relative energy between the accelerated baryons is not smaller than 140 MeV. If an ultra-relativistic jet penetrates through a stellar envelope or is choked within the envelope in the collapsar model of gamma-ray bursts, this jet will produce strong multi-TeV neutrino signals (Mészáros & Waxman 2001; Razzaque, Mészáros & Waxman 2003). If the fireball/jet also consists of some neutrons, a large relative drift velocity between protons and neutrons during the fireball acceleration phase can lead to multi-GeV neutrinos (Bahcall & Mészáros 2000; Mészáros & Rees 2000). During the prompt gamma-ray burst and afterglow phase, the $p\gamma$ process will generate neutrinos above 100 TeV (Waxman & Bahcall 1997, 2000; Dermer 2002), and even in the wind model of afterglows, the neutrino energy can be as high as 10^{17} eV (Dai & Lu 2001). In the supranova model, a GRB is assumed to occur at some time after the supernova explosion (Vietri & Stella 1998). According to this model, the interaction of the accelerated protons with either the protons or soft photons in the supernova ejecta was recently analyzed to generate high energy neutrinos (Guetta & Granot 2003; Granot & Guetta 2003; Dermer & Atoyan 2003).

5 GAMMA RAY BURSTS AS A PROBE OF COSMOLOGY

Long-duration GRBs originate from the collapse of massive stars. One widely believes that GRBs are able to occur at redshifts $z \geq 6$. This is because the first stars in the universe have formed as early as $z \sim 20$, implied by the WMAP observations (Spergel et al. 2003), and indicated by the theoretical simulations of the first star formation (e.g., Abel et al. 2002). This is also because some empirical correlations show that a good fraction of GRBs have redshifts $z \geq 6$ (Fenimore & Ramirez-Ruiz 2000). Theoretically, the emission from high-redshift GRBs and afterglows is currently believed to provide a unique probe of the high-z universe, particularly because the observed flux of the prompt gamma-ray emission and the afterglow emission do not decrease rapidly with increasing redshifts (Lamb & Reichart 2000; Ciardi & Loeb 2000), based on the effects of the cosmological time dilation and the afterglow flux decay.

The studies of high-z GRBs have the following implications: (1) High-z GRBs might provide a constraint on the dark energy and the cosmological parameters (e.g., the Hubble diagram) based on some correlations between the observed quantities (Schaefer 2003; Bloom et al. 2003). (2) High-z afterglows provide a probe of the reionization history of the early universe and the ionization fraction of the intergalactic medium (Barkana & Loeb 2003; Ioka 2003). (3) Detection of early afterglows at high redshifts would help to constrain local environments of GRBs and their redshift evolution (Gou et al. 2001). (4) Observations of high-z GRBs may also provide a probe of the star formation rate at high redshifts (Bromm & Loeb 2002). Some great progress on this topic would be expected in the *Swift* era.

A correlation between the isotropic-equivalent γ-ray energy ($E_{\gamma,\rm iso}$) and the νF_ν peak energy (E'_p) in the local observer frame, $E'_p \propto E_{\gamma,\rm iso}^{1/2}$, was discovered by BeppoSAX observations (Amati et al. 2002), and confirmed by HETE-2 observations (Sakamoto et al. 2004). It not only holds among BATSE GRBs (Lloyd-Ronning & Ramirez-Ruiz 2002) but also within one GRB (Liang, Dai & Wu 2004). From this correlation, Liang & Dai (2004) found a bimodal distribution of the observed peak energy. However, the dispersion around this correlation is too large to obtain useful information on the universe from the current GRB sample. An $E_{\gamma,\rm jet} - E'_p$ relationship with a small scatter for current γ-ray burst (GRB) data was recently reported, where $E_{\gamma,\rm jet}$ is the beaming-corrected γ-ray energy and E'_p is the νF_ν peak energy in the local observer frame (Ghirlanda et al. 2004). By considering this relationship for a sample of 12 GRBs with known redshift, peak energy, and break time of afterglow light curves, Dai, Liang & Xu (2004) constrained the mass density of the universe and the nature of dark energy. From Figures 3 and 4, we found that the mass density $\Omega_M = 0.35\pm^{0.15}_{0.15}$ (at the 1σ confident level) for a flat universe with a cosmological constant, and the w parameter of an assumed static dark-energy equation of state $w = -0.84\pm^{0.57}_{0.83}$ (1σ). Our results are consistent with those from type Ia supernovae. A larger sample established by the upcoming *Swift* satellite is expected to provide further constraints. Finally, Wu, Dai & Liang (2004) have found a strong correlation between the luminosity and time of light curve breaks for some observed afterglows. This correlation might be used to probe the universe, being similar to the Phillips relation in the supernova cosmology.

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References

Abel T., Bryan G. L., Norman M. L., 2002, Sci, 295, 93
Amati L., et al. 2002, A&A, 390, 81
Bahcall J. N., Mészáros P., 2000, PhRvL, 85, 1362
Barkana R., Loeb A., 2003, Natur, 421, 341
Bloom J. S., Frail D. A., Kulkarni S. R., 2003, ApJ, 594, 674
Bromm, V., Loeb, A. 2002, ApJ, 575, 111
Castro-Tirado A. J., et al., 1999, Science, 283, 2069
Chang H. Y., Lee C. H., Yi I., 2002, A&A, 381, L5
Chevalier R. A., Li Z. Y., 1999, ApJ, 520, L29
Chevalier R. A., Li Z. Y., 2000, ApJ, 536, 195
Chevalier R. A., Li Z. Y., Fransson, C., 2003, submitted to ApJ, astro-ph/0311326
Ciardi B., Loeb A., 2000, ApJ, 540, 687
Coroniti F. V., 1990, ApJ, 349, 538
Dai Z. G., 2004, ApJ, 606, 1000
Dai Z. G., Cheng K. S., 2001, ApJ, 558, L109
Dai Z. G., Liang E. W., Xu D., 2004, ApJ, 612, L101
Dai Z. G., Lu T., 1998a, MNRAS, 298, 87
Dai Z. G., Lu T., 1998b, Phys. Rev. Lett., 81, 4301
Dai Z. G., Lu T., 1999, ApJ, 519, L155
Dai Z. G., Lu T., 2000, ApJ, 537, 803
Dai Z. G., Lu T., 2001, ApJ, 551, 249
Dai Z. G., Lu T., 2002, ApJ, 565, L87
Dai Z. G., Wu X. F., 2003, ApJ, 591, L21

Dermer C. D., 2002, ApJ, 574, 65
Dermer C. D., Atoyan A., 2003, PhRvL, 91, 1102
Duncan R. C., Thompson C., 1992, ApJ, 392, L9
Fenimore E.E, Ramirez-Ruiz E., astro-ph/0004176
Frail D. A., et al., 2001, ApJ, 562, L55
Fruchter A. S., et al., 1999, ApJ, 519, L13
Galama T. J., Wijers R. A. M. J., 2001, ApJ, 549, L209
Gallant Y. A., Achterberg A., 1999,MNRAS, 305, L6
Ghirlanda, G., Ghisellini, G., Lazzati, D. 2004, ApJ, in press
Gou L. J., Dai Z. G., Huang Y. F., Lu T., 2001, A&A, 368, 464
Guetta D., Granot J., 2003, PhRvL, 90, 1103
Granot J., Guetta D., 2003, PhRvL, 90, 1102
Granot J., Nakar E., Piran T., 2003, Nature, 426, 138
Ioka K., 2003, ApJ, 598, L79
Kennel C. F., Coroniti F. V., 1984, ApJ, 283, 710
Kirk J. G., Skjæraasan O., 2003, ApJ, 591, 366
Kluźniak W., Ruderman M., 1998, ApJ, 505, L113
Kobayashi S., Zhang B., 2003, ApJ, 597, 455
Kulkarni S. R., et al., 1999, Nature, 398, 389
Kumar P., Piran T., 2000, ApJ, 532, 286
Lamb D. Q., Reichart D. E., 2000, ApJ, 536, 1
Liang E. W., Dai Z. G., Wu X. F. 2004, ApJ, 606, L29
Liang E. W., Dai Z. G. 2004, ApJ, 608, L9
Li Z. Y., Chevalier R. A., 2001, ApJ, 551, 940
Li Z. Y., Chevalier R. A., 2003, ApJ, 589, L69
Lloyd–Ronning, N. M., & Ramirez-Ruiz, E. 2002, ApJ, 576, 101
Livio M., Waxman E., 2000, ApJ, 538, 187
Luo D., McCray R., 1991, ApJ, 379, 659
Mészáros P., Rees, M. J., 2000, ApJ, 541, L5
Mészáros P., & Waxman E., 2001, PhRvL, 87, 1102
Mészáros P., 2002, ARA&A, 40, 137
Mészáros P., Rees M. J., 1997, ApJ, 482, L29
Mészáros P., Rees M. J., Wijers R. A. M. J., 1998, ApJ, 499, 301
Michel F. C., 1994, ApJ, 431, 397
Milgrom M., Usov V., 1995, ApJ, 449, L37
Nakar E., Piran T., Granot J., 2003, NewA, 8, 495
Narayan R., Paczyński B., Piran T., 1992, ApJ, 395, L83
Paczyński B., 1998, ApJ, 494, L45
Panaitescu A., Kumar P., 2000, ApJ, 543, 66
Panaitescu A., Mészáros P., Rees M. J., 1998, ApJ, 503, 314
Piran T., 1999, Phys. Rep., 314, 575
Ramirez-Ruiz E., Dray L. M., Madau P., Tout C. A., 2001, MNRAS, 327, 829
Rees M. J., Gunn, J. E., 1974, MNRAS, 167, 1
Rees M. J., Mészáros P., 1998, ApJ, 496, L1
Razzaque S., Mészéros P., Waxman E.,2003, PhRvL, 90, 1103
Reichart D. E., Price P. A., 2002, ApJ, 565, 174
Rhoads J., 1999, ApJ, 525, 737
Ruderman M. A., Tao L., Kluźniak W., 2000, ApJ, 542, 243
Sakamoto, T., et al. 2004, ApJ, 602, 875
Sari R., Piran T., Halpern J. P., 1999, ApJ, 519, L17
Sari R., Mészáros P., 2000, ApJ, 535, L33
Schaefer B. E. 2003, ApJ, 583, L67

Spergel D. N., et al.,2003, ApJS, 148,175
Spruit H. C., 1999, A&A, 341, L1
Stecker F. W., 2000, APh, 14, 207
Takahashi K. et al.
Usov V. V., 1992, Nature, 357, 472
Vietri M., 1995, ApJ, 453, 883
Vietri M., Stella L.,1998, ApJ, 507, L45
van Paradijs J., Kouveliotou C., Wijers R. A. M. J., 2000, ARA&A, 38, 379
Vikram D., Balick B., 1998, ApJ, 497, 267
Wang X. Y., Dai Z. G., Lu T., 2000, MNRAS, 317, 170
Waxman E., 1995, PhRvL, 75, 386
Waxman E., Bahcall J., 1997,PhRvL, 78, 2292
Waxman E., Bahcall J., 2000, ApJ, 541, 707
Wheeler J. C., Yi I., Höflich P., Wang L., 2000, ApJ, 537, 810
Wick S. D., Dermer C. D., Atoyan A., 2004, APh, 21, 125
Wijers, R. A. M. J. 2001, in Gamma-Ray Bursts in the Afterglow Eraed. E. Costa, F. Frontera, & J. Hjorth (New York: Springer), 306
Woosley S. E., 1993, ApJ, 405, 273
Wu X. F., Dai Z. G., Huang Y. F., Lu, T., 2003, MNRAS, 342, 1131
Wu X. F., Dai Z. G., Huang Y. F., Ma H. T., 2004, ChJAA, in press (astro-ph/0311358)
Wu X. F., Dai Z. G., Liang E. W. 2004, ApJ, in press (astro-ph/0407742)
Zhang B., Mészáros P., 2001, ApJ, 559, 110
Zhang B., Mészáros P., 2002, ApJ, 566, 712
Zhang B., Mészáros P., 2004, Int. J. Mod. Phys. A, in press (astro-ph/0311321)