

What do γ -ray bursts look like?¹

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Abstract

There have been great and rapid progresses in the field of γ -ray bursts (denoted as GRBs) since BeppoSAX and other telescopes discovered their afterglows in 1997. Here, we will first give a brief review on the observational facts of GRBs and direct understanding from these facts, which lead to the standard fireball model. The dynamical evolution of the fireball is discussed, especially a generic model is proposed to describe the whole dynamical evolution of GRB remnant from highly radiative to adiabatic, and from ultra-relativistic to non-relativistic phase. Then, Various deviations from the standard model are discussed to give new information about GRBs and their environment. In order to relax the energy crisis, the beaming effects and their possible observational evidences are also discussed in GRB's radiations.

Keywords: γ ray: bursts - shock waves - ISM: jets and outflows

1 Introduction

γ -ray burst (or shortly, GRB) is an astronomical phenomenon of short duration enhancement of γ -rays from cosmic space. It was discovered by R.W. Klebesadel et al. in 1967 and published in 1973. There have been more than 2000 GRBs discovered now. If there are appropriate satellites in the sky, people could discover one or two GRBs everyday in average. However, they are still among the most mysterious astronomical objects even at present time (Mészáros 1999; Piran 1999a). The difficulty encountered in this field lies in that GRBs occur at random, people can not prepare to observe in advance, they are too short in duration to be studied in detail, they were observed only in γ -ray band which has very low precision in localization and could not be identified or associated with other objects of known distances. Without the knowledge of distances, no serious studies could be made in astrophysics.

In early 1997, the Italian-Dutch Satellite, BeppoSAX, brought the great break-through by rapid and accurate GRB localization and thus provided a small arcmin (or even smaller) error box. With so small an error box, it identified an X-ray counter-part (now known as X-ray afterglow) of GRB970228 even 8 hours after the γ -ray trigger (Costa et al. 1997). Several hours later, its optical afterglow was also observed (Groot et al. 1997; van Paradijs et al. 1997). Since then, BeppoSAX has observed more than 20 GRBs, of which almost all exhibited X-ray afterglows. Based on the precise localization, many telescopes observed about a dozen optical afterglows and about ten radio afterglows. Up to now, people have observed host galaxies of more than ten GRBs with large redshifts, showing them definitely at cosmological distances. These great discoveries lead to rapid

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developments. A lot of questions have now been clarified. However, compared with GRB itself, afterglow appears to be simpler and has been known much better. In contrast, the GRB itself, especially its energy source and origin, still keeps to be mysterious.

The main observational facts of GRBs are as follows (Piran 1999a):

Temporal properties: The GRB duration (T) is very short, usually only a few seconds or tens of seconds, or occasionally as long as a few tens of minutes or as short as a few milli-seconds. Their time profiles are diverse, some may be simply shaped, others complicated, multi-peaked. There seems to be a roughly bimodal distribution of long bursts of $T \geq 2$ s and short bursts of $T \leq 2$ s. The time scales of variability (δT), especially their rising time, may be as short as only milli-seconds or even sub-milli-seconds. Typically, $\delta T \sim 10^{-2}T$.

Spectral properties: The photon energy radiated in GRB is typically in the range of tens keV to a few MeV. However, high energy tail up to GeV or even higher than 10 GeV does exist. The spectra are definitely non-thermal and can usually be fitted by power law $N(E)dE \propto E^{-\alpha}dE$ (or break power law) with index α within about 1.8 to 2.0. The γ -ray fluences are typically in the range of $(0.1 - 10) \times 10^{-6}$ ergs/cm².

Spatial distribution: After the launch of the CGRO (Compton Gamma-Ray Observatory) Satellite in 1991, the Burst and Transient Source Experiment (BATSE) showed clearly that the spatial distribution of GRB sources is highly isotropic with almost zero dipole and quadrupole components (Meegan et al. 1992). This distribution favors GRBs at cosmological distances at least statistically. However, GRBs at extended dark halo of our Galaxy could also explain this feature. This led to a great debate between Galactic origin and cosmological origin.

Afterglows: Afterglows are counterparts of GRBs at wave bands other than γ -rays, may be in X-ray, optical, or even radio bands. They are variable, typically decaying according to power laws: $F_\nu \propto t^{-\alpha}$ (ν = X, optical,) with $\alpha = 1.1 - 1.6$ for X-ray, $\alpha = 1.1 - 2.1$ for optical band. X-ray afterglows can last days or even weeks; optical afterglows and radio afterglows months. The most important discovery is that many afterglows show their host galaxies being definitely at cosmological distances (with large red-shifts up to $Z = 3.4$ or even 5). Thus, the debate is settled down, GRBs are at cosmological distances, they should be the most energetic events ever known since the Big Bang.

2 The Standard Fireball Shock Model

Stellar level event: The variability time scale is usually very short. Let $\delta T \sim$ ms, then, the space scale of the initial source, $R_i < c\delta T \sim 3 \times 10^2$ km. Hence, even for black hole, considering $R = 2GM/c^2$, we have $M \leq \frac{c^3\delta T}{2G} \sim 10^2 M_\odot$. If the burster is not a black hole, its mass should be much smaller. Thus, we can conclude that the GRB should be **a stellar phenomenon** and the burster should be **a compact stellar object** which may be related with neutron star (or strange star) or stellar black hole.

Fireball: From the measured fluence F and the measured distance D , if emission is isotropic, we can calculate the total radiated energy to be $E_0 = F(4\pi D^2) \approx 10^{51}(F/(10^{-6}\text{ergs/cm}^2))(D/(3\text{Gpc}))^2$. Thus, very large energy (10^{51} ergs) is initially contained in a small volume of $(4/3)\pi R_i^3 \sim 1 \times 10^{23}$ cm³. This should be inevitably a fireball, of which the optical depth for $\gamma\gamma \rightarrow e^+e^-$, $\tau_{\gamma\gamma}$, is very large. Consider a typical burst with an observed fluence F , at a distance D , with a temporal variability time scale δT , its average optical depth can be written as:

$$\tau_{\gamma\gamma} = \frac{f_p \sigma_T F D^2}{R_i^2 m_e c^2} \sim 10^{17} f_p \left(\frac{F}{10^{-6}\text{ergs/cm}^2} \right) \left(\frac{D}{3 \text{ Gpc}} \right)^2 \left(\frac{\delta T}{1 \text{ ms}} \right)^{-2}, \quad (1)$$

where f_p denotes the fraction of photon pairs satisfying $\sqrt{E_1 E_2} > m_e c^2$.

For so large an optical depth, there seem to appear two serious difficulties. First, the radiation in an optically thick case should be thermal, while the observed radiation is definitely non-thermal. Second, high energy photons should be easily converted into e^+e^- pairs, while the observed high energy tail indicates that this conversion has not happened. However, it is very interesting to note that just such a large optical depth paves the way to solve both of them.

Compactness problem: In fact, the luminosity of the thermal radiation, according to the Stefan-Boltzmann law, should be proportional to the surface of the fireball which is initially so small that the thermal radiation can not be observed. However, just due to the large optical depth, the radiation pressure should be very high and could accelerate the fireball expansion to become ultra-relativistic with a large Lorentz factor γ . After expanding to a large enough distance, it may be getting optically thin. At this time, the non-thermal γ -ray bursts can be observed. Does such a large distance contradict the compactness relation $R_i \leq c\delta T$ compared with the milli-second variabilities? To answer this question, let us first note that this relation holds only for non-relativistic (rest) object with R_i denoting its space scale. For an ultra-relativistically expanding fireball, the compactness relation should be relaxed to

$$R_e \leq \gamma^2 c \delta T, \quad (2)$$

here R_e is the space scale of the expanding fireball with Lorentz factor γ . Considering two photons we observed at two different times apart by δT , as the emitting region is moving towards the observer with a Lorentz factor $\gamma \gg 1$, the second photon should be emitted at a far nearer place than the first one. This gives effectively short time variabilities and leads to the additional factor γ^2 appearing in the above compactness relation.

The factor f_p in the optical depth $\tau_{\gamma\gamma}$ also sensitively depends on the ultra-relativistic expansion of the fireball. As for this case, the observed photons are blue-shifted, in the comoving frame, their energy should be lower by a factor of γ , and fewer photons will have sufficient energy to produce pairs. This gives a factor depending on spectral index α , namely a factor of $\gamma^{2\alpha}$ in $\tau_{\gamma\gamma}$.

Ultra-relativistic expansion: Therefore, the optical depth $\tau_{\gamma\gamma}$ will decrease by a factor of $\gamma^{4+2\alpha}$ for the ultra-relativistically expanding fireball (Goodman 1986; Paczyński 1986; Piran 1999a; Krolik & Pier 1991):

$$\tau_{\gamma\gamma} = \frac{f_p}{\gamma^{2\alpha}} \frac{\sigma_T F D^2}{R_e^2 m_e c^2} \approx \frac{10^{17}}{\gamma^{(4+2\alpha)}} f_p \left(\frac{F}{10^{-6} \text{ergs/cm}^2} \right) \left(\frac{D}{3 \text{ Gpc}} \right)^2 \left(\frac{\delta T}{1 \text{ ms}} \right)^{-2}. \quad (3)$$

Note, the spectral index α is approximately 2, we will have $\tau_{\gamma\gamma} < 1$ for $\gamma > 10^{17/(4+2\alpha)} \sim 10^2$. Thus, in order for the fireball to become optically thin, as required by the observed non-thermal spectra of γ -ray bursts, its expanding speed should be ultra-relativistic with Lorentz factor

$$\gamma > \sim 10^2.$$

This is a very important character for GRBs, which limits the baryonic mass contained in the fireball seriously. If the initial energy is E_0 , then the baryonic mass M should be less than

$$E_0/(c^2 \gamma) \leq 10^{-5} M_\odot (E_0/(2 \times 10^{51} \text{ergs})), \quad (4)$$

otherwise, the initial energy can not be converted to the kinetic energy of the bulk motion of baryons with such a high Lorentz factor. Most models related with neutron stars contain baryonic mass much higher than this limit. This is the famous problem named as ‘‘baryon contamination’’.

It is worthwhile to note that this very condition $\gamma > \sim 10^2$ can also explain the existence of the high energy tail in the GRB spectra, as the observed high energy photons should be only low energy photons in the frame of emitting region, they are not energetic enough to be converted into e^+e^- pairs.

Internal-external shock: What is the radiation mechanism in the fireball model? The fireball expansion has successfully made a conversion of the initial internal energy into the bulk kinetic energy of the expanding ejecta. However, this is the kinetic energy of the associated protons, not the photons. We should have another mechanism to produce radiation, otherwise, even after the fireball becoming optically thin, the γ -ray bursts can not be observed. Fortunately, the shocks described below can do such a job.

The fireball can be regarded as roughly homogeneous in its local rest frame, but due to the Lorentz contraction, it looks like a shell (ejecta) with width of the initial size of the fireball. As the shell collides with inter-stellar medium (ISM), shocks will be produced (Rees & Mészáros 1992; Katz, J., 1994; Sari & Piran 1995; Mitra 1998). This is usually called as external shocks. Relativistic electrons that have been accelerated in the relativistic shocks will usually emit synchrotron radiation. As the amount of swept-up interstellar matter getting larger and larger, the shell will be decelerated and radiation of longer wave length will be emitted. Thus, an external shock can produce only smoothly varying time-dependent emission, not the spiky multi-peaked structure found in many GRBs. If the central energy source is not completely impulsive, but works intermittently, it can produce many shells (or many fireballs) with different Lorentz factors. Late but faster shells can catch up and collide with early slower ones, and then, shocks (internal shocks) thus produced will lead to the observed bursting γ -ray emission (Rees & Mészáros 1994; Paczyński & Xu 1994). This is the so called external-internal shock model, internal shocks give rise to γ -ray bursts and external shocks to afterglows. The internal shocks can only convert a part of their energies to the γ -ray bursts, other part remains later to interact with the interstellar medium and lead to afterglows. Typically, the GRB is produced at a large distance of about 10^{13} cm to the center, such a large distance is allowed according to the relaxed compactness relation $R_e \leq \gamma^2 c \delta T$, while its afterglows are produced at about 10^{16} cm or even much farther. This internal-external shock scenario, under the simplified assumptions of uniform environment with typical ISM number density of $n \sim 1 \text{ cm}^{-3}$, isotropic emission of synchrotron radiation and only impulsive energy injection, is known as the standard model.

Spectra of afterglows: The instantaneous spectra of afterglows, according to this model, can be written as $F_\nu \propto \nu^\beta$, with different β for different range of frequency ν (Sari et al. 1998; Piran 1999b). Let ν_{sa} be the self absorption frequency, for which the optical depth $\tau(\nu_{sa}) = 1$. For $\nu < \nu_{sa}$, we have the Wien's law: $\beta = 2$. For $\nu_{sa} < \nu < \min(\nu_m, \nu_c)$, we can use the low energy synchrotron tail, $\beta = -1/3$. Here ν_m is the synchrotron frequency of an electron with characteristic energy, ν_c is the cooling frequency, namely the synchrotron frequency of an electron that cools during the local hydrodynamic time scale. For frequency within ν_m and ν_c , we have $\beta = -1/2$ for fast cooling ($\nu_c < \nu_m$) and $\beta = -(p-1)/2$ for slow cooling ($\nu_m < \nu_c$). For $\nu > \max(\nu_m, \nu_c)$, we have $-p/2$. Here, p is the spectral index of the emitting electrons: $N(E) \propto E^{-p}$.

3 Dynamical Evolution of the Fireball

During the γ -ray bursting phase and the early stage of afterglows, the fireball expansion is initially ultra-relativistic and highly radiative, but finally it would be getting into non-relativistic and adiabatic, a unified dynamical evolution should match all these phases. In fact, the initial ultra-relativistic phase has been well described by some simple scaling laws (Mészáros & Rees 1997a; Vietri 1997; Waxman 1997; Wijers et al. 1997), while the final non-relativistic and adiabatic phase should obey the Sedov (1969) rule, which has well been studied in Newtonian approximation. The key equation (Blandford & McKee 1976; Chiang & Dermer 1999) is

$$\frac{d\gamma}{dm} = -\frac{\gamma^2 - 1}{M}, \quad (5)$$

here m denotes the rest mass of the swept-up medium, γ the bulk Lorentz factor, and M the total mass in the co-moving frame including internal energy U . This equation was originally derived

under the ultra-relativistic condition. The widely accepted results derived under this equation are correct for ultra-relativistic expansion. Accidentally, these results are also suitable for the non-relativistic and radiative case. However, for the non-relativistic and adiabatic case, they will lead to wrong result “ $v \propto R^{-3}$ ” (v is the velocity), while the correct Sedov result should be “ $v \propto R^{-3/2}$ ”, as first pointed out by Huang, Dai and Lu (1999a,b).

It has been proved (Huang, Dai & Lu 1999a,b) that in the general case, the above equation should be replaced by

$$\frac{d\gamma}{dm} = -\frac{\gamma^2 - 1}{M_{ej} + \epsilon m + 2(1 - \epsilon)\gamma m}, \quad (6)$$

here M_{ej} is the mass ejected from GRB central engine, ϵ is the radiated fraction of the shock generated thermal energy in the co-moving frame. The above equation will lead to correct results for all cases including the Sedov limit. This generic model is suitable for both ultra-relativistic and non-relativistic, and both radiative and adiabatic fireballs. As proved by Huang et al. (1998a,b), Wei & Lu (1998a) and Dai et al. (1999a), only several days after the burst, a fireball will usually become non-relativistic and adiabatic, while the afterglows can last some months, the above generic model is really useful and important.

4 Comparison and Association of GRB with SN

Supernova was known as the most energetic phenomenon at the stellar level. SN explosion is the final violent event in the stellar evolution. Dynamically, it can also be described as a fireball, which however expands non-relativistically. After the SN explosion, there is usually a remnant which can shine for more than thousands of years and be well described dynamically by Sedov model (Sedov 1969).

GRB is also a phenomenon at the stellar level. However, it is much more energetic and much more violent than SN explosion! It has been proved to be described as a fireball, which expands ultra-relativistically. The GRB may also leave a remnant which shines for months now known as afterglow.

Their comparison is given in Table I:

Table I

	GRBs	SNs
Burst	Bursting γ-rays	SN explosion
Energy up to	10^{54} ergs	10^{51} ergs
Time Scale	10 sec	Months
Profile	irregular	smooth
Wave Band	γ -ray	Optical
Relic	Afterglow	Remnant
Time Scale	Months	10^3 Years
Wave Band	Multi-band	Multi-band
Understanding		
Fireball Expansion	Ultra-relativistic	Non-relativistic
Mechanism	???	Stellar Core Collapse
Key Process	???	Neutrino process

In April 1998, a SN 1998bw was found to be in the 8' error circle of the X-ray afterglow of GRB 980425 (Galama et al. 1998; Kulkarni et al. 1998). However, its host galaxy is at a red-shift $z=0.0085$ (Tinney et al. 1998), indicating a distance of 38 Mpc (for $H_0 = 65 \text{ km s}^{-1} \text{ Mpc}^{-1}$), which leads the energy of the GRB to be too low, only about 5×10^{47} ergs, 4 orders of magnitude lower than normal GRB.

Later, in the light curves of GRB 980326 (Bloom et al. 1999; Castro-Tirado & Gorosabel 1999b) and GRB 970228 (Reichart 1999; Galama et al. 1999b), some evidence related with SN was found. This is a very important question worth while to study further (see e.g. Wheeler 1999). These two violent phenomena, GRB and SN, might be closely related. They might be just two steps of one single event (Woosley et al. 1999; Cheng & Dai 1999; Wang et al. 1999b; Dai 1999d). It is interesting to note that the first step might provide a low baryon environment for the second step to produce GRB. Such a kind of models can give a way to avoid the baryon contamination.

5 Inner Engine and Energetics

There have been a lot of models proposed to explain the central engine of GRBs (see e.g. Castro-Tirado 1999a; Piran 1999a; Cheng & Dai 1996; Dai & Lu 1998b). All these objects are related with compact stars such as neutron star (NS), strange star (SS), black hole (BH) etc. For example, binary mergers (NS-NS, NS-BH, ...), massive star collapsing, phase transitions (NS to SS) and others have been proposed. To build a successful model for central engine, the most difficult task is to solve the baryon contamination. There seem to be three kinds of ways: 1) based on BH, which can swallow baryons; 2) based on SS, of which baryons are only contained in its crust with mass less than $10^{-5} M_{\odot}$; 3) based on the two-step process pointed out in above section.

A system of a central BH with a debris torus rotating round it may form after compact star merging or massive star collapsing. In this system, two kinds of energies can be used: the rotational energy of the BH and the gravitational energy of the torus. The rotational energy of the BH can be extracted via the B-Z (Blandford & Znajek 1977) mechanism (Mészáros & Rees 1997b; Paczyński 1998). For a maximally rotating BH, its rotational energy can be extracted up to 29% of the BH rest mass, while the gravitational binding energy of the torus can be extracted up to 42% of the torus rest mass. Lee, Wijers and Brown (1999) recently studied the possibility to use these mechanisms in producing GRB.

The phase transition from neutron star to strange star can release huge energy to account for GRB. As an estimate, we can reasonably assume that about 20-30 MeV is released per baryon during the phase transition. Total energy released this way can be up to about $(4 - 6) \times 10^{52}$ ergs. Strange star is the stellar object in the quark level. Whether it exists or not is a fundamental physical/astrophysical problem. Its main part is a quark core with large strangeness (known as strange core). There could be a thin crust with mass of only about $\sim (10^{-6} - 10^{-5})M_{\odot}$ (Alcock et al. 1986; Huang & Lu 1997a,b; Lu 1997; Cheng et al. 1998), all baryons are contained in the crust. It is interesting to note that this baryonic mass is low enough to avoid the baryon contamination. Kluźniak and Ruderman (1998) proposed differentially rotating neutron stars as an origin of GRBs. Dai and Lu (1998b) used this mechanism to the case of differentially rotating strange stars and proposed a possible model for GRB without baryon contamination.

6 New Information Implied by the Deviations from the Standard Model

The standard model described above is rather successful in that its physical picture is very clear, it gives results very simple, and observations on GRB afterglows support it at least qualitatively but generally. However, various quantitative deviations have been found. They indicate that the simplifications made in the standard model should be improved. These deviations may reveal important new information, such as non-uniform environment, additional energy injection, beaming effects of radiation and others.

Wind environment effects: Dai and Lu (1998c) analysed the afterglows of GRB970616 and others. They studied the general case of $n \propto R^{-k}$ for the non-uniform environment density

(here n is the number density of the environment medium) and found that the X-ray afterglow of GRB970616 can well be fitted by $k = 2$, and pointed out that this non-uniformity may be due to the existence of a stellar wind. After the detailed studies by Chevalier & Li (1999a,b), the stellar wind model has become widely interested. People are aware that it may contain many implications about the progenitors of GRBs and provide strong support to their massive star origin.

Additional energy injection: The optical afterglows of GRB 970228 and GRB 970508 had some complexities, showing down-up-down variation in their light curves. These features can be explained by long time scale energy injection from their central engines (Dai & Lu 1998a,b; Rees & Mészáros 1998; Panaitescu et al. 1998). For example, a milli-second pulsar with super-strong magnetic field can be produced at birth of GRB. As the fireball expands, the central pulsar can continuously supply energy through magnetic dipole radiation. Initially, the energy supply is small enough, the afterglow shows declining. As it becomes important, the afterglow shows rising. However, the magnetic dipole radiation should itself attenuate later. Thus, the down-up-down shape would appear naturally. Dai and Lu (1999c) analysed GRB 980519, 990510 and 980326, and obtained the results agreeing well with observations.

Additional radiations: Though the synchrotron radiation is usually thought to be the main radiation mechanism, however, under some circumstances, the inverse Compton scattering may play an important role in the emission spectrum, and this may influence the temporal properties of GRB afterglows (Wei & Lu 1998a,b).

Later data in the afterglows of GRB 970228 (Reichart 1999; Galama et al. 1999b) and 980326 (Bloom et al. 1999; Castro-Tirado & Gorosabel 1999b) may show the deviations as additional contributions from supernovae.

Beaming effects: GRB 990123 has been found very strong in its γ -ray emission, and the red shift of its host galaxy is very large ($z=1.6$) (Kulkarni et al. 1999a; Galama et al. 1999a; Akerlof et al. 1999; Castro-Tirado, et al. 1999a; Hjorth, et al. 1999; Andersen, et al. 1999). If its radiation is isotropic, the radiation energy only in γ -rays is already as high as $E_\gamma \sim 3.4 \times 10^{54}$ ergs, closely equals two solar rest energy ($E_\gamma \approx 2M_\odot c^2$)! As the typical mass of the stellar object is in the order of $\sim 1M_\odot$, while the radiation efficiency for the total energy converting into the γ -ray emission is usually very low, such a high emission energy is very difficult to understand (Wang, Dai & Lu 1999a).

A natural way to relax the energy crisis is to assume that the radiation of GRB is beaming, rather than isotropic. Denote the jet angle as Ω , then the radiation energy E will be reduced to $E\Omega/4\pi$. At the same time, the estimated burst rate should increase by a factor of $4\pi/\Omega$. Are there any observational evidences for the jet in GRB and its afterglow? Pugliese et al. (1999), Rhoads (1997, 1999), Sari et al. (1999) and Wei & Lu (1999a,b) have discussed this question. Kulkarni et al. (1999b) observed that two days after the burst, the decaying was getting more steepening, appearing as a break in the light curve of GRB 990123, and they regarded this as the evidence for jet. Recently, Huang et al. (1999c) calculated the influences of various parameters on the jetted emission of GRB, showed that a break in the light curve may appear in the case of narrow jet and for small electron energy fraction and small magnetic energy fraction.

Dense environment effects: However, Dai and Lu (1999b) pointed out that a shock undergoing the transition from a relativistic phase to a non-relativistic phase may also show a break in the light curve, if there are dense media and/or clouds in the way, this break may happen earlier. This model could also give an explanation for the observed steepening. Recently, Wang et al. (1999c) proved that the dense environment model can also explain well the radio afterglow of GRB 980519 (Frail et al. 1999). Thus, we should study the break appearing in the light curve further to take both beaming and dense environment effects into account.

7 Conclusion

The standard internal-external shock model, which is built under many simplifications, has been proved to be well fitted by observations qualitatively but generally. Based on the success of this model, it should be very important to study the deviations from the standard model, which indicate that the simplifications should be relaxed in some aspects. Hence, the deviations contain important new information and have been a fruitful research area.

In contrast to the rapid progress in understanding the nature of afterglows, GRB itself has not yet been clear. However, this is a very important problem. The solution about the origin of GRB is related with most fundamental questions in physics and astrophysics, such as black holes, stellar objects from quark level, physics and properties of the farthest stellar phenomena and others. It may also give new and important information for cosmology. Within five or ten years, there should still be a lot of further surprising achievements about these most violent events.

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