Gamma-Ray Bursts: Super-Explosions in the Universe and Related High-Energy Phenomena

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Abstract. The recent progress in studies of gamma-ray bursts, their afterglows, and host galaxies is discussed. The emphasis is given to high-energy phenomena associated with gamma-ray burst explosions: high-energy cosmic rays, neutrinos, gravitational waves. We also show how the relativistic fireball model for GRBs can be used to constrain modern theories of large and infinite extra-dimensions. In particular, in the frame of 5D gravity with the Standard Model localized on 3D brane (Dvali et al. 2000), the very existence of relativistic fireballs of \( \sim 10^{53} \) ergs puts the lower bound on the quantum gravity scale \( \sim 0.1 \) eV.

1 Introduction and short history

A large progress in cosmic gamma-ray bursts (GRB) have been made in recent years, after their precise localizations on the sky have become possible with observations of their soft afterglows. There is a number of modern reviews devoted to the problem of GRB in general (e.g., Piran 1999, 2001, Postnov 1999, Meszaros and Rees 2001), and we here we will not discuss the GRB problem in full detail. Instead, we will try to present information most relevant to the topics of this School.

We start with very brief history of GRB studies, which clearly can be subdivided into three periods. The first period started after serendipitous discovery of cosmic GRB by American military Vela satellites in the end of 60s and ended in 1992 with the launch of Compton Gamma-Ray Observatory. This was a period of data accumulation, with the major contribution made by Konus experiment (Mazets et al. 1981). As there are no means to measure a distance to a poorly localized GRB, it was completely unclear at that time if GRB were local, galactic or remote extragalactic events.

The BATSE era continued until the beginning of 1997, when the first X-ray afterglow from GRB970228 was detected by the Dutch-Italian Beppo-SAX satellite (Costa et al. 1997). Before Beppo-SAX, poor localization (of order degrees) of GRB positions on the sky have prevented their full astronomical investigation from being made, and most valuable BATSE contribution has been the accumulation of a large homogeneous collection of GRBs (more than three thousand), which allowed thorough statistical studies of these objects (Paciesas et al. 1999). These studies (especially, log N-log S counts) provided an indirect evidence that we are dealing with extragalactic events, located at gigaparsec distance scale, so their energetics must be unusually high, of order of \( 10^{52} \) ergs on average. These clues have been confirmed by the identification of the location of more than a dozen GRB afterglows inside high-redshift galaxies, which firmly established the cosmological nature of most cosmic GRBs.

1 Short (\( \sim 2 \) s) GRBs are still unidentified in other wavelengths and might represent a separate phenomenon,
At present, 17 reliable redshift determinations of GRBs or their hosts are known (see Bloom et al. 2001), more or less uniformly distributed between $z = 0.43$ and $z = 4.5$.

\section{Relativistic fireball model}

Of more than 200 GRB models of the mid-80s, the most viable one proved to be the relativistic fireball model, which seems to be confirmed by the bulk of GRB studies in a wide range of wavelengths from radio to gamma-rays (see Piran 1999, 2001 for a comprehensive review) (for an alternative explanation see for example Ruffini et al. 2001). A huge energy ($\Delta E \sim 10^{51} - 10^{53}$ ergs) in gamma-rays ($E_\gamma \sim 100$ keV – 10 MeV), released in a short observed duration of GRBs (typically, $\Delta t_\gamma \sim 10 - 100$ s), with a non-thermal spectrum and varied on ms timescale, leads to the so-called ”compactness problem” (see Blinnikov 2000 for a deep physical discussion). This energy liberated in a small region $\sim 10^6 - 10^7$ cm in size (as implied by the ms variability time scale) would create a photon-lepton ”fireball” with enormous optical depth for pair creation by energetic photons, so a thermal photon spectrum should be observed, unlike actually observed optically thin non-thermal spectra. In addition, high-energy photons (with $E_\gamma > 10$ GeV) detected from some GRBs could not escape such a medium.

These problems can be circumvented if the fireball expands relativistically, with a Lorentz-factor $\Gamma > 100 - 200$ (Ruderman 1975). Indeed, the size of the rapidly expanding volume, as derived from the emission time variability, is $\Gamma^2$ as large as of the stable one. This and other relativistic effects decreases the optical depth by a factor of $\Gamma^{7...8}$ or even more (depending on geometry and other parameters), which solves the compactness problem of the fireball, but of cause leaves open the question how such a fireball could be formed. But this is a question to the ”central engine” of GRBs.

Setting this explosion in tenuous interstellar (or intergalactic) medium results in the formation of (collisionless) relativistic shocks (Rees and Mészáros 1992). In this model, thermal energy of the initial photon-lepton fireball with small baryon contamination ($\Delta M_b \sim 10^{-5}M_\odot$) to ensure a relativistic expansion with the required high Lorentz factor) is transformed into the kinetic energy of baryons, which subsequently is thermalized in the relativistic shocks. It is this energy that is eventually converted into X-ray photons (in the comoving frame) via synchrotron and/or inverse Compton processes in the shocks, which are detected as gamma-ray photons in the observer’s frame.

In the currently most elaborated internal shock model (Narayan et al. 1992, Rees and Mészáros 1994), the GRB itself is produced when consecutive internal shocks, which are assumed to be generated by a (still unknown) ”central engine” during the time $\Delta t_\gamma$ with slightly different Lorentz factors, collide with each other at a characteristic distance $r_c \sim \delta t \Gamma^2 \sim 10^{12}$ cm ($\delta t \sim 10$ ms is a typical GRB variability time scale). An external shock is formed at the collision site with the ambient medium ($\sim 10^{14} - 10^{16}$ cm away from the explosion site). The observed X-ray and optical afterglows are thought to be produced however their spectral characteristics are very similar to those of long cosmological GRBs (Frederiks et al. 2001).

\footnote{We will not consider still controversial case of GRB980425 possibly associated with supernova explosion SN1998bw in a nearby galaxy.}
by the external shocks when it decelerates in the surrounding gas (in this respect GRB afterglows are just relativistic analogs of the conventional supernova remnants, i.e. are essentially environmental effects of powerful explosions).

Basically, the model has only 6 free parameters: the initial energy of the explosion $\Delta E$, the initial expansion Lorentz factor $\Gamma$ (or, equivalently, the fireball baryonic load $\Delta M_b$), the ambient gas density $n$, the fraction of the shock thermal energy in the electronic component $\xi_e$, the fraction of the shock thermal energy in the enhanced magnetic field energy behind the front $\xi_b$, and the spectral index $p$ of accelerated relativistic electrons in shocks, $dN/d\epsilon \sim \epsilon^{-p}$ (here $\epsilon$ is the electron energy).

The afterglow studies provide some evidence for possible beaming of gamma-ray emission in GRBs (e.g. Frail et al. 2001, and references therein). The angular beaming inferred is of order $\theta \sim 0.1$ rad. It is still unclear if a standard energy is released in GRBs or they have a broad luminosity function (the latter seems more probable and seems to be required by extensive statistical studies, e.g. Stern et al. 2001). For GRBs with known redshifts, $\Delta E$ can be directly derived from observed flux assuming one or another GRB beaming factor. Typical values are on average around $10^{53}$ ergs (assuming GRB emission isotropy), but can be smaller by two orders of magnitude if the beaming factor (model-dependent estimate) is taken into account (Lipunov et al 2001, Frail et al. 2001).

Multiwavelength studies of GRB afterglows allow to determine the fireball model parameters, and show a broad consistence with GRB being superexplosions in the galactic environment (Mészáros 2001, Mészáros and Rees 2001).

3 Central engine

Much less is known about central engine of GRBs. Small time-scale variability and large energy release suggest the presence of a stellar-mass compact object. Gamma-ray beaming suggests the presence of rotating magnetized plasma. Any viable mechanism for GRBs should be able to produce a relativistically expanding fireball with small baryon contamination operating during time intervals $\Delta T_{GRB} \sim 100$ s, which is much longer than the dynamical time scale for compact objects and the observed time variability scale (1-10 ms).

There is a growing evidence that GRBs are associated with star forming regions in galaxies (Piro et al. 2000, Sokolov et al. 2001), so their progenitors could be massive stars ("failed supernovae" – Woosley 1993, MacFadyen and Woosley 1999, "hypernovae" – Paczyński 1997, "supranovae" – Vietri et al. 2000, WR-stars – Postnov and Cherepashchuk 2001).

Currently, two types of progenitors are considered: collapse of massive stars (as suggested by Woosley 1993), or coalescence of binary compact objects (neutron stars or black holes) (as first suggested by Blinnikov et al. 1984). Although strong association of optically identified GRBs with star forming regions favors the collapsar model, binary compact star coalescences can not be totally discarded (for example, a significant fraction of binary compact stars is expected to coalesce in a short time after a star formation burst (Lipunov et al. 1995) so they, too, will be apparently associated with star forming regions in galaxies). The collapsar model also suggest possible connection with supernova explosions, and indeed, apart from possible direct association of GRB980425, one can find some evidence of this in optical afterglow behaviour monitoring (bumps in the afterglow light curves, e.g. Sokolov 2001 and
refs. therein), yet other explanations to these features exist (Esin and Blandford 2000).

Certainly, the relativistic fireball model of GRBs have some problems (see e.g. Piran 2001) and only new astronomical observations can resolve all the GRB puzzles, but for our discussion here we will rely upon the relativistic fireball model as mostly confirmed by the existing observations.

4 High-energy phenomena associated with GRB

The large energy release and relativistic expansion velocities implies that various high-energy phenomena can be associated with GRBs. The relevant quantity derived from observations is the average energy production rate of cosmic GRBs. A simple estimate is straightforward: the observed GRB rate is about $\mathcal{R}_{\text{GRB}} \sim 10^{-7}$ per year per galaxy (assuming GRB isotropy), i.e. $\sim 10^{-9}$ per year per Mpc$^3$. With the average isotropic energy of one GRB $10^{53}$ ergs we arrive at $dE/dt/dV \sim 10^{44}$ ergs per year per cubic Mpc. Notably, this estimate does not depend on the GRB beaming factor: with beaming, decrease in energy exactly compensates for increase in rate.

4.1 Particle acceleration and ultra high-energy cosmic rays

Fermi acceleration in relativistic internal shocks is likely to accelerate protons to high Lorentz factors (Vietri 1995, Waxman 1995), so it is temptative to compare the above estimate with rough energetics of ultra-high energy cosmic rays (see Waxman 2001 for extensive discussion). Waxman shows that ultra-high energy cosmic rays indeed could be produced by cosmological GRBs in the observed amount (with unavoidable GZK-cutoff above $10^{19.7}$ eV).

According to this model, there are clear predictions potentially checkable by observations if GRBs indeed provide a significant contribution to the observed flux of UHECR. Namely, because of different time delay for protons with different energies in the intergalactic magnetic field, bursting UHECR sources should have narrowly peaked spectra, with the brightest sources being different at different energies. This feature is distinctive from steady sources where the brightest sources at high energy should be brightest at low energies as well.

But in view of difficulties for any model involving population of sources at cosmological distances to explain the observed UHECR properties (especially the observed clustering at different energies) (Teshima’s lecture, this volume; see also a detailed discussion in Dubovsky 2001, this volume), GRBs can hardly be considered as primaries for most energetic cosmic rays.

4.2 Neutrino emission from GRBs

In the framework of the relativistic fireball scenario, GRB also become copious sources of high-energy neutrinos (Waxman and Bahcall 1997,1999). Indeed, protons accelerated in the fireball lose energy via photo-meson interaction with fireball photons, mediated by $\Delta$-resonance $\uparrow$: $p = \gamma \rightarrow \Delta \rightarrow p + \pi^+$. High energy neutrinos then result from the charged pions.

$\uparrow$If not only $\Delta$-approximation contributes to photo-meson interaction, the results does not change significantly (Waxman 2001)
decays: $\pi^+ \rightarrow \mu^+ + \nu_\mu \rightarrow e^+ + \nu_e + \nu_\mu + \bar{\nu}_\mu$. The relation between the proton and neutrino energies is dictated by the $\Delta$-resonance condition $\epsilon_\gamma \epsilon_p = 0.2(\text{GeV}^2)\Gamma^2$. For typical $\epsilon_\gamma \sim 1$ MeV and $\Gamma \sim 300$ protons with energies $\epsilon_p \sim 10^{16}$ eV are capable of producing neutrinos. It can be shown that pion-decay produced neutrinos carry about 5% of the proton energy, so the production of $\sim 10^{14}$ eV neutrinos are expected.

The GRB neutrino flux can be evaluated using observed gamma-ray fluences $F_\gamma$. Flux of pions is proportional to the proton flux, which is $f_\pi \times F_\gamma / \xi_e$. Each neutrino carries $\sim 1/4$ of the pion energy, so the net result is $\epsilon_\nu^2 dN_\nu / d\epsilon_\nu \sim 0.25 (f_\pi / \xi_e) F_\gamma / \ln(10)$ (the factor $\ln 10$ accounts for the fact that synchrotron radiating electrons span a decade in energies, as inferred from the observed GRB spectra). The average neutrino flux per unit time per solid angle is obtained by multiplying the single burst fluence with the GRB rate per solid angle, which is $\sim 10^9$ bursts per year per $4\pi$ steradian. With a typical GRB fluence of $\sim 10^{-5}$ erg cm$^{-2}$ we arrive at a muon neutrino flux $\epsilon_\nu^2 \Phi_\nu \sim 3 \times 10^{-9} (f_\pi / \xi_e)$ GeV cm$^{-2}$s$^{-1}$sr$^{-1}$. Other neutrino flavors flux is comparable. The expected high-energy muon neutrino flux can be detected by a km$^2$ neutrino detector with a rate of $\sim 10$ events correlated with GRBs.

The model allows the possibility to produce $\sim 10^{18}$ eV neutrinos in interaction of the reverse shock driven into the fireball ejecta at the initial stage of interaction of the fireball with the ambient medium. This takes place $\sim 10$ s after the initial explosion, which is comparable with the fireball duration itself. In this scenario, optical and UV-photons radiated by electrons accelerated in shocks propagating backward into the ejecta may interact with accelerated protons of the ejecta. A burst of $10^{17} - 10^{19}$ eV neutrinos is then expected via photo-meson interactions (Waxman and Bahcall 2000). The estimated flux (somewhat more model-dependent) is about $10^{-10}$ GeV cm$^{-2}$s$^{-1}$sr$^{-1}$, which can be more difficult to detect.

Detection of high-energy neutrinos from GRB will test the shock acceleration mechanism and the key suggestion that GRBs are the sources of the ultra-high energy protons ($> 10^{16}$ eV to produce $> 10^{14}$ eV neutrinos and $> 10^{19}$ eV to produce $> 10^{16}$ eV neutrinos).

In addition, inelastic $p - n$ collisions during the fireball acceleration stage may produce $\sim 10$ GeV neutrinos with a fluence of $\sim 10^{-4}$ cm$^{-2}$ per burst. Such neutrinos can be potentially detected in a 1 km$^3$ neutrino telescope with a rate of $\sim 10$ events per year. There detection will constrain the fireball neutron fraction and hence the GRB progenitor model.

### 4.3 Gravitational waves production in GRBs

The production of gravitational wave in GRB is much more model-dependent since it require some model for the GRB progenitors. If compact binary coalescences underly GRBs, gravitational waves will be copiously generated before GRB, at the binary inspiral phase and at the merging phase. Binary mergings are expected to be primary targets for the gravitational wave interferometers like LIGO, VIRGO or GEO-600, with the expected event rate a few per year from some types of compact binaries (see Grishchuk et al. 2001 for a recent review). Simultaneous detection of GW signals from binary mergings with GRBs would be a proof of the binary merging model for GRB.

If GRBs are related to massive star core collapses, the situation is less optimistic, since rather weak GW signals are expected to be associated with collapses as both Newtonian and relativistic numerical simulations show (see Dimmelmeier et al. 2001 and references therein).

If relativistic fireball is beamed, as we discussed above, there is a robust lower limit on
the amount of gravitational waves emitted due to the acceleration to relativistic velocities of the fireball’s baryons \( m_b = \Delta E_\gamma / \Gamma c^2 \) (Piran 2000). A broad-band signal is expected up to a maximal frequency \( \omega_{\text{max}} \sim 2\pi / \delta t \), with a total amount of GW energy of \( \Delta E_{GW} \sim 2Gm_b^2 \Gamma c^2 / (c\pi \delta t) \). At the maximum frequency \( \nu_{\text{max}} \sim 100 \text{ Hz} \) this would correspond to

\[
h \sim Gm_b \Gamma^2 / c^2 d \approx 3 \times 10^{-25} (\Delta E_\gamma / 10^{51} \text{ erg}) (\Gamma / 100) (d / 100 \text{ Mpc})^{-1},\]

which is still too low for direct detection even by the enhanced LIGO II interferometer.

The situation may be not so hopeless, however, if one appropriately uses correlation of GRB and GW (and possibly neutrino) signals. At present, some joint data analysis algorithms are under construction (e.g. Rudenko et al. 2000).

### 4.4 GRB and theories of large and infinite extra dimensions

A huge energy release in a compact region in GRB implies very high energy densities resembling to certain stages in the radiation-dominated era of the evolution of the Universe. With characteristic energy \( E_{53} = \Delta E_\gamma / 10^{53} \text{ erg} \) and the initial size \( r_6 = r_0 / 10^6 \text{ cm} \) the initial temperature of the optically thick fireball is

\[
T_f \simeq 116 (\text{MeV}) E_{53}^{1/4} r_6^{-3/4},
\]

which is similar to that in the Universe as early as \( \sim 10^{-4} \text{ s} \) after the beginning of expansion. The photon number density (as well as of relativistic leptons) is

\[
n_\gamma \simeq 4.3 \times 10^{37} (\text{cm}^{-3}) (T/100 \text{ MeV})^3
\]

and diverse photon-photon and photon-lepton processes intensively occur. Thus the GRB fireballs can be potentially useful to test high-energy physics at MeV scales.

We wish to consider constraints the very existence of GRBs imposes on some modern theories of gravity. As example, we examine the theory of multi-dimensional gravity with quantum gravity scale at TeV energies (Arkani-Hamed, Dimopoulos, Dvali 1998, hereafter ADD), and more recent 5D gravity of infinite-volume flat extra space with \( 10^{-3} \text{ eV} \) quantum gravity scale (Dvali, Gabadadze, Porrati 2000, Dvali et al. 2001, hereafter DGP). These theories assume that the Stabbdard Model particles are localized in a 3D “brane” embedded in compactified space with large (or infinitely large) extra dimensions. The state-of-the-art in modern brane-world theories has been extensively discussed in this conference (Yu.Kubyshin’s talk), and in the literature (Rubakov 2001, and references therein).

In these theories, the fundamental gravity scale is no more the conventional Planck mass \( (M_P \sim 10^{18} \text{ GeV}) \), which determines the observable weakness of the Newton gravitational constant \( G_N \). The latter turns out to be defined by the quantum gravity scale \( M_\ast \) of the corresponding theory. In such a frame, one of the phenomenological manifestations of the existence of large (or infinite) extra dimension(s) is an additional cooling of hot plasma due to emission of Kaluza-Klein massive gravitons into the bulk (ADD model) or excitation of stringy Regge states (DGP model).

In the ADD scenario, the 4D Planck mass is related to the compactification radius \( r_n \) and fundamental gravity scale \( M_\ast \) as \( M_P \sim r_n^n M_\ast^{n+2} \), where \( n \) is the number of extra dimensions.
The emission of KK-gravitons in the bulk in photon-photon interactions (relevant to GRB fireballs) has a cross section (Arkani-Hamed et al. 1998)

$$\sigma_{\gamma\gamma} \sim \frac{1}{16\pi} \left( \frac{T}{M_*} \right)^n \frac{1}{M_*^2}$$

i.e. the KK-luminosity becomes

$$(dE/dt)_{KK} \sim n_\gamma^2 \sigma_{\gamma\gamma} c \epsilon_{KK} \propto T_f^{7+n} / M_*^{2+n}$$

(Here $\epsilon_{KK} \sim 2.7T_f$ is the typical KK-graviton energy).

If the emission of KK-gravitons effectively would cool down the fireball before its initial thermal energy is converted into the kinetic energy of the baryons, the required high Lorentz factors would not be attained, and no GRB with the observed properties would be produced. This implies that the emission of KK-gravitons in the fireball should meet the condition

$$r_0/c < \Delta E_y / (dE/dt)_{KK}.$$ 

Putting all quantities together, we arrive at the following constraints:

$$n = 2: \quad M_* > 2(\text{TeV}) E_{53}^{5/16} r_6^{-11/16},$$

$$n = 3: \quad M_* > 0.25(\text{TeV}) E_{53}^{3/10} r_6^{-7/10}.$$ 

These are weaker than limits inferred from SN1987a neutrino burst ($M_* > 30$ TeV for $n=2$) and from cosmological considerations (Arkani-Hamed et al. 1998; Hannestad, Raffelt 2001).

More interesting is the case of DGP model. In this framework, the weakness of an observable gravity is explained by the high cut-off of the Standard Model $M_{SM}$ localized on the brane. In contrast to the ADD model, the large value of the observable $M_P$ is determined by $M_{SM} \gg M_*$ rather than $M_*$. Now the emission of massive KK-gravitons into the bulk is strongly suppressed. Instead, the possibility to produce an exponentially large number of Regge states at very low energy appears. At $T \ll 1$ TeV, the total rate of the production of stringy Regge states is determined by the 2-d mass level and is (Dvali et al. 2001)

$$\Gamma_2 \sim E \frac{E^4}{M_*^2 M_P^4}$$

(here the mean energy particle $E \sim 2.7T$). This gives rise to the total Regge state emission rate in the GRB fireball

$$(dE/dt)_R \approx 10^{55} (\text{erg/s}) E_{53}^{9/4} r_6^{-15/4}$$

and the fireball acceleration constraints would be

$$M_* > 0.5 \text{ (eV)} E_{53}^{5/8} r_6^{-11/8}$$

This is by about two orders of magnitude higher than original lower bound $10^{-3}$ eV discussed in Dvali et al (2001). If this limit is true, deviations from the Newton gravity are expected at distances smaller than $r < 1/M_* \simeq 10^{-3} \text{ mm}$.
5 Conclusion

After about 30 years of studies, the cosmic GRB phenomenon seems to be finally understood, at least in principle. It is an enormous energy release in a compact region, most plausibly due to either core collapse of a massive rotating star into a black hole, or binary compact star merging, or both, in remote galaxies. This energy is in the form of photons and leptons, with a small amount of baryons involved (a photon-lepton fireball). The fireball rapidly expands, forming relativistic shock waves in the surrounding medium. The kinetic energy thermalized in the shocks produces the observed electromagnetic radiation of the GRB itself and its afterglows in softer bands. The nature of the central engine and generation mechanism of the (beamed) relativistic ejecta forming the fireball remains one of unresolved issues of the model.

In this framework, cosmic GRBs can be good accelerators of high-energy particles and thus contribute to the high-energy cosmic rays. They also can be copious sources of high-energy neutrinos, which can be detected in the forthcoming experiments. If binary compact star mergings underly some GRBs, a time correlation with chirp gravitational wave signals is expected, otherwise GRBs appear to be rather weak sources of gravitational waves.

At last, a huge energy density in relativistic fireballs can be used as an independent tool to test modern theories of quantum gravity.

To conclude, we stress the need for both astrophysical multivawelength studies of the GRB phenomenon (which proved to be extremely successful in the last years) and high-energy particle observations from GRBs. These observations would provide independent tests for modern GRB theories and can be used to study high-energy particle properties.

Acknowledgements. The author thanks V. Rubakov, Yu. Kubyshin, V. Rudenko, S. Dubovsky for useful discussions. Special thanks to D. Kosenko for help in some estimations. The work was partially supported by RFBR grants 99-02-16205, 00-02-17884a, and 00-02-17164.

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