Recent Models of Gamma Ray Bursts and Needs for Future Observations

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ABSTRACT

The paper presents the nowadays definition of the phenomenon of cosmic gamma ray bursts, refers to the main alternative models of their origin and proposes three promising domains of new observations in the incoming decade.

Subject headings: gamma ray bursts: phenomenology — models — aims of future observations
1. What is the definition of the phenomenon of gamma-ray bursts?

Today, 30 years after the detection of the first gamma-ray burst in July 2, 1967 (Klebesadel et al. 1973), the definition of the phenomenon has to be adjusted to the present observational data. A lot of new features have been recently discovered, and the phenomenon of *classical gamma-ray burst* (GRB) is becoming to be a rather complex one, which includes a number of different observational features. To explain the origin of bursts one has to build the self-consistent theoretical concept(s), which ought to address to all these features been taken together.

Below I present my insight on the basic observational features of GRBs and on the main theoretical concepts and suggest the directions of further developments in the field.

1.1. Time-related parameters

There are four time-related parameters associated with emission of GRBs. The interval between bursts beginning and end is a *burst duration* $T_d$. One cannot measure the $T_d$ without many biases. Some of them are associated with the difference of triggering conditions for bursts with different time histories, another are related with statistical fluctuations of counts. The best known version of $T_d$ parameter are $T_{50}$ (or $T_{90}$), which equal to time which takes to accumulate from 25% (or 5%) to 75% (or 95%) of the total bursts fluence (Meegan et al. 1996a). The longest bursts are known to have $T_d$ about several hundreds of seconds, the shortest events have $T_d$ about 30 milliseconds (Fishman and Meegan 1995). Therefore, duration of bursts are distributed over more than 4 orders of magnitude.

The bimodal distribution of GRBs was found for duration parameters (Dezalay et al.
1992, Kouveliotou et al. 1993) which probably points out on the existance of different modes of GRBs with different average values of $T_{50/90}$. However, parameters $T_{50/90}$ have different physical senses for bursts with different time profiles: while for single pulse burst they represent the pulse width, for multi-pulse event these parameters represent interpulse separations rather than pulse widths.

The physical interpretation of duration bimodality of GRBs is the important problem of bursts studies. Another options of duration parameter have been proposed to study this problem, which measure either high flux intervals, such as equivalent pulse width $T_{epw}$, or low flux interpulses, such as valley duration $T_{vd}$, (Mitrofanov et al. 1997a). It was found that the bimodality is well seen for the histogram of equivalent pulse width. The two modes have different time histories, and one might suspect that they represent two distinct classes of bursts.

Parameter of flux variations $T_{fv}$ characterizes the shortest time scale of bursts emission. For some fast bursts it is as short as parts of milliseconds (Bhat et al. 1992), for another slow events, like the FRED burst, this time is as long as several seconds (Fishman and Meegan 1995). The shortest physical value of $T_{fv}$ is not resolved yet. The observed limit of $T_{fv}$ is thought to be determined either by 64 ms time resolution of BATSE or by the poor statistics of counts at short time bins. It seems that all large number of short bursts are missed at the time scale shorter then 64 ms.

Quite recently some evidence for the third characteristic time of GRBs was found, which is the time of bursts afterglow $T_{ag}$. This time is between several hours and tens of days (see below).

The longest time scale could be defined, as the possible time of bursts recurrence $T_{rec}$. It is not clear yet, are emitters of bursts really recurrent or not. The most exciting fact was the BATSE detection of four spatially coincident GRBs in October 27-29, 1996 (Meegan et
The rich statistics of \( \sim 2000 \) BATSE bursts allows to find the observational limit for \( T_{\text{rec}} \): the number of possibly repeated bursts cannot be larger than about 7\% (Hakkila et al. 1996). Therefore, for the total time of 5 years of BATSE observations, the lowest observational limit for average \( T_{\text{rec}} \) is about 40 years.

1.2. Photons energy spectra

Classical GRBs have variable photons spectra with peak energy \( E_p \) of the \( \nu F_{\nu} \) curve about several hundreds keV (Fishman and Meegan 1995). Energy spectrum of a burst varies as fast as the total flux, and the time scale \( T_{fv} \) determines the variability of energy spectra also. BATSE bursts have smooth energy spectra with no evidence for line-like features (Briggs 1996a), while lines at low energies \( \leq 100 \) keV are still seen by some another instruments (Aptekar et al. 1996). The problem of no-lines has to be resolved for further progress in the bursts studies.

A group of BATSE bursts was separated, as high emission (HE) bursts. They have significant flux at high energies above \( \sim 300 \) keV. A complementary group was named, as no high emission events (NHE), because they do not have a significant emission at this range (Pendleton et al. 1997). Correspondingly, some BATSE bursts have energy spectra with exponential cut-off above \( \sim 300 \) keV, while some another events have the power low spectra at high energies (Band 1996). Using the data of instruments COMPTEL and EGRET, the significant high-energy emission component was found for 5 bright BATSE bursts with energies as high as several GeV (Dingus 1995, Hurley et al. 1994).

On the other hand, the excess of soft X-rays at 5-10 keV was found for \( \sim 10\% \) of bright bursts (Preece et al. 1996). It is well seen above the level of spectral interpolation from the medium energy range, and it could be interpreted as a separate emission component.
Further studies has to be done to find any correlation between emission at different spectral ranges.

1.3. Afterglow emission

The first evidence for afterglow emission was found at high energy gamma rays, when GeV photons were detected during $\sim 5000$ s after the end of GRB 940217 time profile (Hurley et al. 1994). Recently the afterglow in X-rays was found for several bursts due to rapid follow-up observations with high sensitivity (e.g. Costa et al. 1997, Piro et al. 1997a,b, Marshall et al. 1997). The high accuracy of locations of X-ray transients allowed to find the possible optical and radio counterparts of GRBs. They had decreasing luminosity, and could be associated with afterglow of bursts in visual light and in radio waves (Groot et al. 1997, Bond et al. 1997, Frail et al. 1997a).

The fading time of afterglow $T_{ag}$ is about several hours in X-rays and about days or tens of days in optics and radio. It is not clear yet, does the afterglow emission accompanies some distinct group of bursts, or is it a common signature for all bursts. However, it seems that some bursts (e.g. GRB 970111) have not afterglow (Frail et al. 1997b).

The most exciting recent result is associated with the optical counterparts of GRB 970228 and GRB 970508. In the second case the red-shifted absorption lines have been resolved in the optical spectra of a fading object with $Z_{ab} = 0.835$ (Metzger et al. 1997). If this object is indeed the burst afterglow, one gains the conclusive identification of the burst with a cosmological source with $Z_{em} > 0.835$. On the other hand, five GRBs with the smallest known error boxes were recently examined with HST. No optical objects were found inside them, which would be similar to that proposed as a counterpart of GRB 970228 (Scharfer et al. 1997). So, either a burst GRB 970228 has the unusual afterglow
counterpart, or this identification needs some further approvals.

1.4. Bursts on the sky map and on the brightness scale

All detected bursts are known to lie on the sky with the perfect isotropy (Fishman and Meegan 1995). No groups of bursts could be selected among them which would manifest any significant deviations from it (Briggs et al. 1996b). However, another test of a bright sample of bursts led recently to the conclusion that they are concentrated toward the Galactic Plane and the Center (Link and Epstein 1997). Further studies are necessary in this direction.

The peak fluxes $F_{\text{max}}$ of classical bursts varies in more than 4 orders of magnitude from $\geq 10^{-3}$ erg cm$^{-2}$ down to $\leq 10^{-7}$ erg cm$^{-2}$. The brightness distribution $\log N / \log F_{\text{max}}$ of the largest sample of 3B catalog (Meegan et al. 1996a) significantly deviates from the -3/2 slope, which corresponds to homogeneous distribution of sources in the three-dimensional Euclidean space. This deficit of dim bursts is also seen as decrease of the average parameter $< V/V_{\text{max}} >= 0.33 \pm 0.01$ in respect with the value 0.5, which is expected for the homogeniouse case (Meegan et al. 1996a).

1.5. Average signatures of bursts emission

The large number of $\sim 2000$ BATSE bursts allows to find the generic signatures of bursts, which represent the basic properties of their emitters. The first found signature was the hardness-brightness correlation (Mitrofanov et al. 1992a,b, 1996; Paciesas et al. 1992): brighter bursts were found to be much harder than dimmer events. This effect was also well seen, as a strong correlation between bursts peak fluxes $F_{\text{max}}$ and spectra peak energies $E_p$
The recent statistical studies of energy spectra of BATSE bursts have shown that
groups of bright and dim bursts have similar evolution trends on the plane of power index
$\alpha$ and peak energy $E_p$, but the trend for the dim group is shifted to larger power indexes
$\alpha$ and smaller $E_p$ values relative to one for the bright group. Therefore, the difference of
average spectral parameters between bright and dim samples is found to be more complicate
than the simple correlation between $E_p$ and brightness (Mitrofanov et al 1997b).

The effect of duration-brightness anti-correlation was discussed by several authors
with quite contradicting conclusions (Norris et al. 1994, Mitrofanov et al. 1996). Bursts
are known to have very different time histories, and one could not test the effect by the
direct comparison between particular events. Special average signatures were implemented
to make the comparison, such as the average emissivity curve (Mitrofanov et al. 1996),
or average autocorrelation function (in’t Zand and Fenimore 1996). The 3$\sigma$ upper limit of
stretching factor of dimmer bursts in respect with the bright sample was recently estimated
as $\leq 1.5$ (Mitrofanov et al. 1997c).

2. Origin of GRBs

The time of bursts variability is so small, the energy of bursts’ photons are so high and
estimated emission energy is so large, that practically all theoretical models identify bursts
with cataclysms on compact relativistic objects of stellar masses. The difference between
models is in the nature of these cataclysms.
2.1. The Cosmological paradigm

Studies of binary radio pulsars led to the conclusion that close relativistic binaries of compact stars at the late stage of evolution lose the bound energy and finally fall into the merging stage, when two compact objects coalesce into a black hole with emission of $E_{\text{mer}} \sim 10^{53}$ erg of energy (e.g. Paczynski 1986, Piran 1992). For a spiral galaxy like Milky Way the rate of merging is about $\sim 10^{-4} - 10^{-6}$ yr$^{-1}$ (Narayan et al. 1991, Jorgensen et al. 1995). This rate and the total energy release agree with the needs of the cosmological model of GRBs, which put mergers at cosmological distances with the red-shifts for the most distant objects $Z_{\text{out}} = 2 - 6$.

A burst is thought to be emitted by the relativistic fireball, which expands into the interstellar medium from a place of energy release. The Lorentz factor of fireball expansion is about $\Gamma \sim 100 - 1000$. The forward shock wave propagates outward and interacts with the interstellar medium. It is accompanied by reversed wave coming inward (Meszaros and Rees 1993). The prompt emission of gamma ray bursts is thought to be emitted either by the synchrotron radiation or by the inverse Compton scattering at the external shock wave regions. Lorentz transformation makes this emission as hard as observed gamma rays $\sim E_p$ and squeezes it into a time interval as short as bursts time duration $\sim T_d$. At the late stage of expansion the blast wave is substantially decelerated by accumulated interstellar matter, which gives rise to continues afterglow emission. It shifts from X-rays down to optics and radio, and takes a time of about $T_{ag}$ for the full disappearing.

The simple model of external shock wave has the well known difficulty in explanation of the complexity of bursts time profiles, which is manifested by fast and sharp variations $\sim T_{fv}$ between pulse and interpulse intervals. The alternative model has been implemented to solve the problem, which attribute pulse structure with emission from internal shocks waves inside a fireball (Rees and Meszaros 1994). They are thought to be ignited by
explosions of energy source, which sporadically take place during a time of burst duration $\sim T_d$.

According to the modern cosmological models, the *internal shock* wave is responsible for the prompt bursts emission, while the *external shock* waves are more likely associated with the afterglow emission (Katz and Piran 1997).

### 2.2. The Galactic Paradigm

The galactic paradigm associate GRBs with sporadic outbursing activity of high velocity neutron stars (NSs) in the extended galactic halo with a distance scale of about $\sim 100 – 300$ kpc (Shklovskii and Mitrofanov 1985, Li and Dermer 1992). High velocity neutron stars are known to exist (Line and Lorimer 1994), and they have to escape the disk and to income into the extended halo. Either starquakes or comets accretion are thought to be energy resources of outbursts (for recent review see Woosley 1996). And, each emitter has to provide a set of about $\lesssim 10^4$ bursts with the average energy $\sim 10^{42}$ erg at each event.

During a burst duration $\sim T_d$, the relativistic ejection of a hot plasma occurs from a surface of NS into the magnetosphere, which radiates a pulses of gamma-rays with energies $\sim E_p$ and with duration from milliseconds up to several tens of seconds. After a *burst* stage, a NS could go into a *relaxation* stage, which could be as long as a post-glitch relaxation of radio pulsars. It is known to be about several days (Cordes 1983). The energy release at this stage could be much smaller than the total energy of the burst stage. At the relaxation stage high energy photons could be radiated with energies up to several GeV, and the surface of NS could be heated up to $\sim$keV temperatures by discharges of sparks in the magnetosphere. The post-burst relaxation stage might result to afterglow emission as long as several days.
3. Testing the cosmological and galactic paradigms

Different tests for both paradigms were proposed. Some of them are decisive tests, which would provide the ensure conclusion about the origin of GRBs. Another tests could give more or less preference to one or another model.

3.1. Direct astronomical identification of bursts emitters

It would be distinctively positive for cosmological models, if no-host problem will be resolved by direct measurements of optical counterparts with cosmological red-shifts (see Metzger et al. 1997). On the other hand, it would be distinctively positive for galactic models, if proper motion of the optical counterpart will be confirmed (Caraveo et al. 1997), or some another direct identification with the galactic object will be performed. Astronomical identification is the most conclusive test to make a choice between two alternative models.

3.2. Bursts repetition

The fact of bursts repetition, provided it would be found, should be distinctively negative for cosmological models because cosmological sources can not be recurrent, and it would distinctively points out on the galactic halo emission. The events like the set of four bursts of October 27-29, 1996 (Meegan et al. 1997b), have to be studied in more details for the repetition test.
3.3. Spectral line-like features

The finding of spectral line-like features would be distinctively negative for cosmological models because fireball emission can not have any narrow spectral lines. The presence of lines would be positive (or neutral) for models which put bursts in the extended halo.

3.4. Isotropy on the sky

The perfect isotropy on the sky is very strong argument for the cosmological model, but any significant deviation from the isotropy would lead to rejection of this paradigm at all. The galactic model predicts small dipole and/or quadruple effects due to perturbations from the Milky Way and the Andromeda. The detection of the extended halo around the Andromeda would be the distinctively positive test for the galactic model.

3.5. Afterglow emission

Detection of bursts afterglow is the positive argument for the cosmological model, provided the afterglow decrease would be confirmed like $\sim t^{-1}$. For GRB 970508 some groups see these kind of decay (Djorgovski et al. 1997), but some another detects more rapid exponential decay (Kopylov et al. 1997). On the other hand, the models of extended halo can explain the afterglow, as the post-burst relaxation stage of neutron star.

3.6. Time stretching of dim bursts

All cosmological models predicts time-stretching of dim bursts due to expansion of the Universe, and, therefore, detection of time stretching would be a strong argument
for these models. However, one has to be sure that a found effect of duration-brightness anti-correlation is actually resulted from the cosmological time stretching.

Internal evolution of sources might lead to this effect too. The distinctive detection of cosmological time-stretching should be based on several physically independent clocks of bursts, which would manifest the same time-dilation when compared between bright and dim bursts. On the other hand, some internal correlation between luminosity and time of emission could easily explain time stretching effects for sources in the galactic halo, and one cannot consider this effect, as the conclusive test between two models.

3.7. Red shifting of dim bursts

The effect of hardness-brightness correlation of GRBs could be interpreted as the evidence for cosmological red-shifting. However, the groups of bright and dim bursts were found to have quite similar trends of \((\alpha, E_p)\) evolution, but the evolution curve for dim group is shifted to larger \(\alpha\) and smaller \(E_p\) values. It seems that the difference between dim and bright bursts cannot be explained by a cosmological transformation of standard candles, and some spectral evolution of sources is required. On the other hand, the effect could be easily explained by the galactic model also, provided the evolution of emitters would be assumed (Mitrofanov et al. 1997d). Therefore, one might conclude that the effect of hardness-brightness correlation does not allow to make a distinct choice between cosmological and galactic models, but leads to the conclusion that emitters cannot be treated as standard candles.
4. Potential developments in the Next Decade

There are three main directions of potential development of burst studies which could be predicted in the Next Decade.

4.1. New places in the space

If classical bursts are cosmological, the largest red-shifts of dimmest bursts $Z_{\text{out}}$ has to become resolved by future measurements. These data will provide the unique way for direct studies of stars evolution at the early Universe.

The sample of the brightest bursts with accurate positions has to be used to combine the collective sky map of X-ray, optical and radio objects around the bursts locations. Enhancement of any particular objects at the collective map could point out the best candidate for bursts identification. On the other hand, the absence of any counterparts will provide the upper limit $Z_{\text{in}}$ for the distance scale of the most close emitters.

If classical bursts have the galactic origin, they are emitted from the extended galactic halo. The similar extended halo should be found around the Andromeda by more sensitive instruments of the Next Decade. Direct comparison between bursts from both halos will test bursts emission models. Large part of high velocity neutron stars has to escape from the extended halo around galaxies and give rise to the Local group halo around the Local Group (Schaefer 1996). Very sensitive instruments could detect bursts from neutron stars of supergalactic halo provided they are still active having such a large age.

The future instruments are necessary with much higher sensitivity for bursts detection down to $\sim 10^{-9}$ ergs/sm$^{-2}$ and with much better angular resolution up to arc seconds. To achieve this requirements, the X-ray all- sky cameras would be the best facilities to perform
the continues observations, which could provide the on-board triggering for each angular pixel of the imaging sky map.

4.2. New domains in the time

Both for galactic and cosmological paradigms, the bursts energy is thought to be released within the small volume of neutron star or stellar black hole with the length of $R_{\text{min}} \sim 10^6 \text{ cm}$. Therefore, the physical limit for bursts time scale is $t_{\text{min}} \sim R_{\text{min}}/c \sim 30 \mu\text{s}$.

Present instruments do not see any bursts shorter than tens of milliseconds. On the other hand, the distribution of bursts over parameter $T_{\text{epw}}$ shows that there could be a large number of short events with $T_d < 64 \text{ ms}$.

The future instruments are necessary with fast time resolution up to microseconds. They probably should use the segmentation of detectors and the logic of coincidence to detect events at microseconds time scale.

4.3. New ranges of photons energy

There are about 80 high energy photons which were detected by EGRET from 5 bright BATSE GRBs at high energy range from tens of MeV up to several GeV (Dingus 1995). The emission was seen from $\sim 400 \text{ s}$ before burst, as for GRB 910601, up to $\sim 5000 \text{ s}$ after it, as for GRB 940227. The key questions arises, how broadly is high energy emission spreaded around a burst itself? Is emission associated with the brightest bursts only, or with all of them?

Recent discoveries of the X-ray, optical and radio afterflow emissions of GRBs gave very high priority to observations at the low energy domain. The key question has to be
responded, could the low energy emission be seen before and during bursts, as well as it is seen after them? Bursts with afterglow do not have the same ratio between the fluence at gamma-rays and intensity at another spectral ranges, so one needs to estimate the generic relationship between fluence at different spectral ranges.

The correlative program of future space/ground observations is necessary with the fastest follow-up measurements at different energy ranges. The BeppoSAX mission has started this program, and the Compton/Rossi duet is performing it now. The future missions should be developed taking into account the ability to participate in these correlative programs.

5. Conclusion

The studies of a particular burst could lead to understanding of the phenomenon, only provided each event represents the all set. I think that in the case of GRBs the situation could be quite different: there is a broad variety of individual events which have physically different, sometime even conflicting properties.

As well as quasars would not be selected within ordinary stars using the optical plates only, new observations of gamma-ray bursts are necessary, as suggested above, to fix the basic properties of bursts, as the necessary and sufficient conditions to identify the phenomenon. In parallel, a distinct groups of bursts could probably be resolved with different, even inconsistent basic properties.

Taking into account well-known contradictions in the observational properties of individual bursts, as presented above, one could expect that in the future studies the existence of two or more distinct groups of bursts could probably be approved. The concepts of typical emitters of bursts would be developed for these groups, and theoretical models
could be suggested to explain the origin of separate classes of events.

I think that it would be the main direction of studies of GRBs for the Next Decade.

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