REVIEWS OF TOPICAL PROBLEMS

PACS numbers: 95.85.Pw, 98.70.Rz

On the nature of cosmic gamma-ray bursts

B I Luchkov, I G Mitrofanov, I L Rozental'

Contents

Abstract. Current hypotheses of gamma-ray burst origin are analysed. About 30 years after their discovery, it is still unclear where gamma-ray bursts are created (Solar system, Galaxy or Metagalaxy). Nor is the mechanism of their production known. This paper reviews on-going gamma-ray experiments and suggests possible lines of further studies on their origin.

1. Introduction

The American satellite system Vela has been functioning in the space from the beginning of 60s. Originally this system was designed to detect gamma-radiation following nuclear weapon tests in the atmosphere. It included several satellites to provide the global survey and to determine directions of incoming gamma-rays.

After the Soviet-American treaty prohibiting atomic weapon tests in the atmosphere was signed (1963), and the two sides proved to strictly observe their engagements, the system could no longer be used for original applications. However, on July 2, 1967, the satellite Vela 4a detected a short-term (around a few seconds) rises of gamma-rays in the range of 0.1 – 1 MeV [1]. Due to detection of several significant events by the Vela space system later on, the conclusion was drawn that a new astronomical phenomenon has been discovered, named cosmic gamma-ray bursts (GRBs).

Although more than 30 years have passed since the discovery of gamma-ray bursts, there are still no physical arguments that may be regarded as unequivocal evidence of their sources. Moreover, it appears impossible even to conjecture the distance to such sources. Currently, three hypothetical scales of their localisation are considered: Solar system periphery, extended galactic halo, and Metagalaxy.

Present observational data on the GRBs do not allow one to make a simple choice between these three options. Scientific community appeared to be separated into parties in accordance with the preference for one or another concept of GRBs origin. In the April 1995 the Great Debate has been arranged in the Smithsonian Museum between the party of galactic model, which was presented by D Lamb, and supporters of cosmological model, who were presented by B Paczynski. According to a common opinion, neither side evidently dominated at this Debate.

The authors of this paper also do not share a common viewpoint on the GRBs origin. However, they joined to write this review in order to present a current status report on the developments of all three main concepts to the physical community. B I Luchkov and I L Rozental' presented the heliospherical models, which they have developed in their recent papers. Galactic and cosmological paradigms were for the most part reviewed by I G Mitrofanov, who developed recently new tests for direct observational comparison between these two models.

A reader would hardly be able to make a personal choice between all three options based on this review. On the other

B I Luchkov Moscow Engineering Physics Institute
31, Kashirskoe Shosse, 115409 Moscow, Russia
Tel. (7-095) 323-91 94
E-mail: borl@nucl.mephi.msk.su
I G Mitrofanov, I L Rozental' Institute for Space Research, Russian Academy of Sciences 84/32, ul. Profsoyuznaya,
117810 Moscow, Russia
Tel. (7-095) 333-34 89, 333-53 35
E-mail: imitrofa@iki.rssi.ru

Received 6 March 1996, revised 4 April 1996
Uspekhi Fizicheskikh Nauk **166** (7) 743–762 (1996)
Translated by Yu V Morozov, edited by S Danilov

hand, a goal of this paper will be fully achieved, if the reader will take an interest in this mysterious phenomenon.

2. Main characteristics of gamma-ray bursts

A most intriguing characteristic of GRBs is that they cannot be identified with any known astronomical object. Their direction on the celestial sphere is most often determined from the delay t between individual burst records by detectors spatially separated at distance l. The time difference between consecutive burst records by two detectors is ($c = 1$)

$$\Delta t = l \cos\theta \qquad (1)$$

where θ is the angle between the line connecting the detectors and the direction towards the source. By measuring Δt, it is possible to determine a circle on the celestial sphere where the source is located. Recording a burst with three or more detectors allows the source location to be reduced to two or even one 'point' (of course, within an instrumental error; see Refs [2, 3] for details).

Scores of hypotheses on gamma-ray burst sources have been suggested. Notwithstanding numerous experimental studies of this probably most puzzling phenomenon in astrophysics, no solution of this major problem has so far been found even when considered in the light of the results obtained with a wealth of space instruments (GELIOS, SIGNE, KONUS, SMM, LILAS, APEX, GINGA, PHEBUS, BATSE, etc.). The uncertainty remains and has even increased during the last 10 years.

Here is the list of well-established characteristics of gamma-ray bursts.

1. Isotropic angular distribution of gamma-ray burst sources. This fact of fundamental importance for interpreting gamma-ray bursts has been established with all types of measuring devices used, including BATSE, which provides the best sensitivity and the most representative statistical data (over 1500 events). The angular distribution in the galactic coordinates is shown in Fig. 1 [4].

2. Burst length ranges from 10^{-2} to 10^3 s. Loosely, it may be assumed that the mean duration of gamma-ray bursts is 10 s.

Sometimes, it is described by parameters t_{50} and t_{90}. The former parameter is the time interval during which 50% of the recorded burst fluence is accumulated while the latter one (t_{90}) corresponds to the time necessary to accumulate 90% of the fluence. Observations revealed two groups of gamma-ray bursts: short and long ones with $t_{90} < 1.5$ and $t_{90} > 1.5$ s, respectively (Fig. 2) [5].

3. Burst frequency is currently believed to be one per 24 hr (the BATSE detector [6]).

4. The maximum fluence of GRBs near the Earth is $10^{-4} - 10^{-3}$ erg cm^{-2}. The possibility of recording a minimal flux certainly depends on detector sensitivity. The BATSE detector mounted on the GRO orbital station appears to be especially sensitive (about 10^{-7} erg cm^{-2}).

5. There is a fine structure of microbursts superimposed on the burst time-scale. One of the best-known gamma-ray bursts recorded on March 5, 1979 (sharp front of 0.2 ms and high peak intensity) yielded 22 pulses for 144 s [7]. In this case, the source location region contained an object emitting soft radiation — the No 49 Supernova remnant in the Great Magellanic Cloud at a distance of 55 kpc [7].

6. The lack of radio and optical bursts concurrent with gamma-ray bursts in terms of time and coordinates.

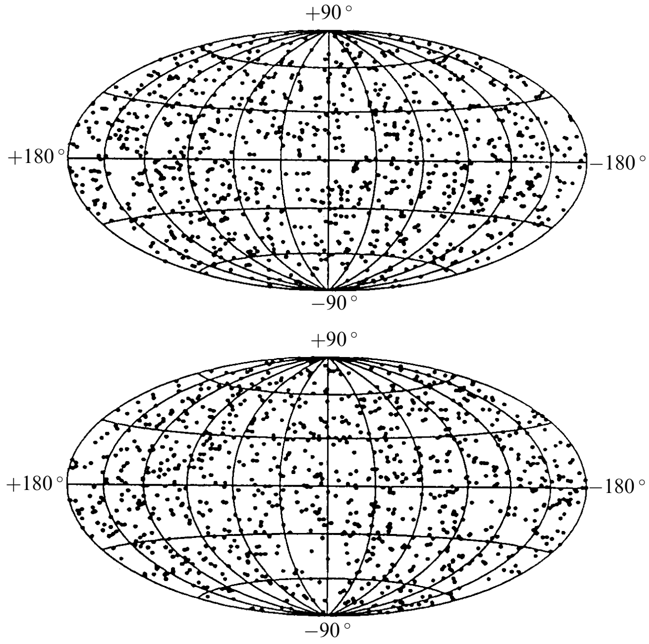

Figure 1. The top panel is the locations in the galactic coordinates of 1005 gamma-ray bursts observed with BATSE. For comparison, the lower panel shows simulation of 1005 isotropic locations [4].

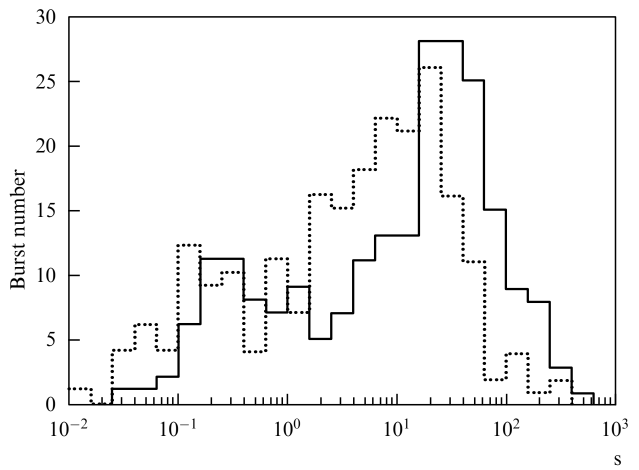

Figure 2. Duration distributions for the 222 BATSE events with t_{50} and t_{90} [5].

7. The problem of gamma-ray burst energy spectrum is more difficult. It is not always possible to unambiguously reconstruct spectra because of their marked variability in individual bursts and low final resolution of measuring instruments. Based on the BATSE measurements, gamma-ray burst spectra can be approximated by two power functions with an inflection at energies of 0.1 – 1.0 MeV (Fig. 3) [8].

8. Flux dependence on the gamma-ray burst number deserves special attention.

For sources with standard luminosity L, the recorded flux is directly related to the distance from the source

$$F = \frac{L}{4\pi R^2} \, . \qquad (2)$$

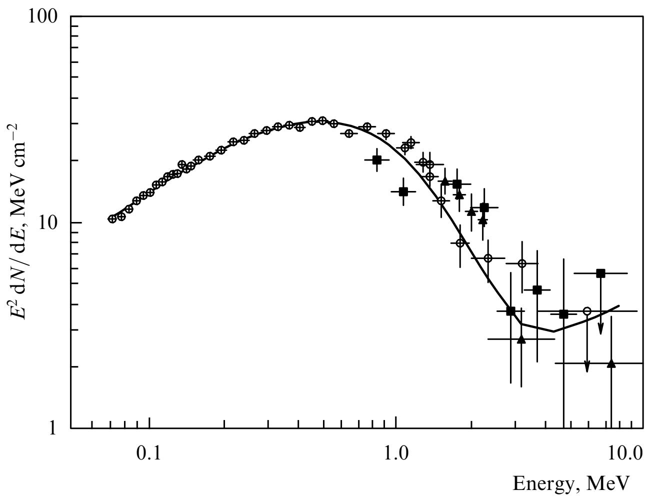

Figure 3. Energy spectrum of the GRB 910601 gamma-ray burst measured in OSSE (○), EGRET (▲) and COMPTEL (■) experiments of the Compton observatory [21].

If the sources are homogeneously distributed with concentration n, the number of gamma-ray bursts with the flux $> F$ from a region with radius R is

$$N(>F) = \frac{4\pi}{3}\, nR^3 = \frac{1}{6}\,\pi^{1/2} n \left(\frac{L}{F}\right)^{3/2}. \tag{3}$$

Therefore, if dependence $N(>F)$ obeys the '-3/2 power law', this suggests homogeneous spatial distribution of gamma-ray burst sources. It is known, however, that the measured distribution deviates from the '-3/2 power law' (Fig. 4). Hence, source density is inhomogeneous.

To obtain a more reliable verification of inhomogeneous gamma-ray burst distribution, the special test has been proposed which is based on the mean $V/V_{\max}$ ratio. Volume

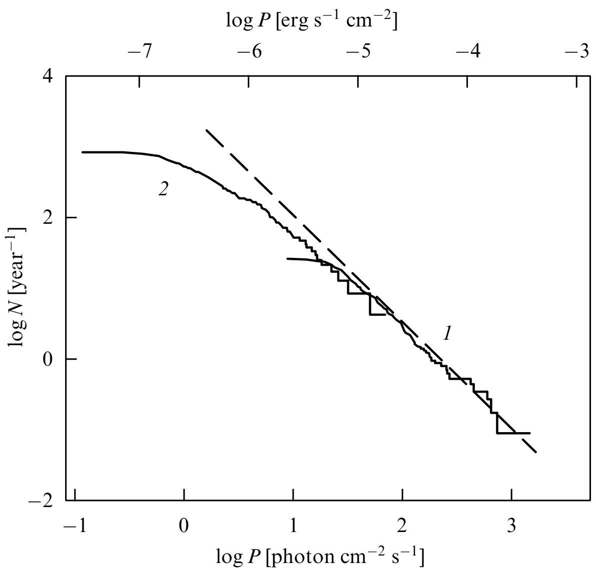

Figure 4. Statistics of gamma-ray burst distribution with fluxes above the selected value for events observed with PVO (*1*) and BATSE (*2*) [81]. The dashed line shows the -3/2 slope.

$V_{\max}$ corresponds to the entire observable region for a given instrument under given background conditions and depends on the sensitivity for burst detection $F_{\rm thr}$. Volume V corresponds to the estimated distance to the source generating a burst with the measured flux F. The volume ratio

$$\frac{V}{V_{\max}} = \left(\frac{F_{\rm thr}}{F}\right)^{3/2} \tag{4}$$

is independent of intrinsic luminosity of the source. The $V/V_{\max}$ ratio needs to be calculated for each individual burst. The distribution of gamma-ray bursts by $V/V_{\max}$ characterises spatial distribution of their sources. For standard sources of homogeneous density, it corresponds to the flat distribution with values from 0 (upper brightness limit) to 1 (sensitivity threshold level). The mean value for a uniform ensemble must be around $\langle V/V_{\max}\rangle = 0.5$. The measured value for 601 bursts in the BATSE experiment is $\langle V/V_{\max}\rangle = 0.328 \pm 0.012$ [4]. This suggests an excess of bright gamma-ray bursts ($V/V_{\max} < 0.5$) or deficit of dim ones (> 0.5), i.e. a deviation from uniformity.

A most important (and puzzling) fact about GRBs is their eight feature. In accordance with No 1, burst sources must be isotropically distributed over the celestial sphere. But this immediately rules out their most natural position — in the galactic disk, because in this case inhomogeneous distribution of sources should be accompanied by their concentration on the sky to the galactic equator. Therefore, there are only four logically conceivable options:

1. Sources at the Solar system periphery (>100 AU).
2. Galactic sources at distances smaller than transverse thickness of galactic disk in the vicinity of Solar system (<100 pc).
3. Galactic sources in extended spherical halo with distances scale >100kpc.
4. Metagalactic (cosmological) sources at distances $>10^3$ Mpc.

In the latter case, distances are normally measured in terms of cosmological redshift in source spectra.

Naturally, the choice between these options is not enough to ultimately resolve the problem, but it is likely to restrict the number of hypotheses and could even contribute to the final solution provided some additional measurements are available. Such additional characteristics were obtained in the 1980s in the KONUS experiment which revealed the presence of lines in burst spectra, in the first case, a line with energy of 420–430 keV [8, 9]. The presence of this line in conjunction with the periodic burst structure (period ~ 8 s) on March 5, 1979 was a conclusive demonstration that old neutron stars can be burst sources [3]. In this case, the 420 keV line may be interpreted as annihilation radiation (511 keV) shifted by almost 100 keV under the influence of the stellar gravitational field. Also, KONUS [8] and GINGA [10] experiments provided evidence of absorption lines at electron cyclotron frequency (20–50 keV). The strength of the magnetic field responsible for cyclotron lines coincides with the expected strength of the neutron star magnetic field $H \simeq 10^{13}$ Gs. Evidently, such an interpretation unequivocally supports the hypothesis that old neutron stars are sources of gamma-ray bursts. However, the most representative data recently obtained in the BATSE experiment appear to disprove this inference.

First publications on the results of the BATSE experiment reported no lines in gamma-ray burst spectra and brought the problem of source localisation back to uncertainty: distances to the sources (hence their nature) remained undetermined as before.

A recent publication [11], however, discusses difficulties encountered in spectral line identification in gamma-ray bursts using limited statistical data. In view of conflicting opinions, one may not argue that the lines are totally absent, though in this review we follow this supposition.

While the presence of spectral lines (especially lines at 420 keV energy) unambiguously relates generation of GRBs to the activity of neutron stars, it is difficult to distinguish between the solar and galactic hypotheses without additional characteristics. New direct and indirect data are needed, e.g. about correlation of burst characteristics and frequencies with solar activity, which requires long-term observations.

Studies to confirm or disprove cosmological origin of GRBs appear to be more promising. They are based on the relationship between the distance R to cosmological sources and frequency ν of recorded gamma-rays. It is known that $\Delta\nu \sim R$, in agreement with the Friedmann – Hubble cosmology [12]. This analysis is underlain with rather a strong assumption that burst characteristics in a system connected with the source do not depend on R.

Therefore, a feasible observational test of the cosmological hypothesis is based on the redshift of GRBs with a concomitant decrease in burst intensity (this issue is discussed at greater length in Section 5). Here, we shall focus on the physical sense of the anticipated effect. The greater the distance between burst sources the weaker they are, their total energy decreasing with increasing Z. Let sources of bright and dim GRBs have redshifts $Z_{\rm bright}$ and $Z_{\rm dim}$, respectively. Then, gamma-rays at the same frequency ν_0 will be seen for bright and dim bursts at frequencies ν_1 and ν_2, which are related as $\nu_1/\nu_2 = (1 + Z_{\rm dim})/(1 + Z_{\rm bright})$ (see Section 5.4).

Another feasible test associates with a search for a consistent stretching of dim GRBs due to the Doppler time dilation for sources at cosmological distances (see Section 5).

Unfortunately, both tests are based on the assumption that burst sources are standard candles and therefore they cannot be interpreted unambiguously. We belive that it is more promising to seek for the solution of the gamma-ray burst problem by improving sensitivity of measuring instruments and looking for burst analogues in other electromagnetic wave-bands (optics, radio-waves, soft X-rays). Determining the nature of optical and radio sources and especially distances to them is much easier than doing the same for gamma-ray burst sources. However, relevant studies have so far yielded no convincing data [13, 14].

3. Heliospherical gamma-ray burst models

Specific spectral features of some bursts in the KONUS [15] and GINGA [10] experiments suggested the presence of absorption lines in the 20 – 50 keV range and an emittance line with the energy of 0.4 MeV. These spectral characteristics were interpreted as red-shifted resonant lines of absorption of gamma-rays by electrons in a strong magnetic field and lines of electron-positron annihilation. It was concluded that gamma-ray bursts are produced by neutron stars with strong magnetic fields. This inference became the basis for further long-term studies. Nowadays, however, the validity of this approach is questioned in the light of numerous TGRS [16] and BATSE [17] data that provided no statistical evidence of either absorption lines at 20 – 50 keV range or emission lines with the energies at 0.40 – 0.45 MeV.

The absence of lines in GRBs spectra dramatically changes the situation. Now, neutron stars have to be considered as a possible but not the sole source of gamma-ray bursts, the main criterion being isotropic distribution of sources over the celestial sphere and their inhomogeneous spatial density associated with the deficiency of faint bursts. This experimental finding indicates that the sources occupy a limited space while sensitivity of modern detectors allows recording the most distant of them localised at the periphery of this space.

It is therefore appropriate to assume that such objects with inhomogeneous density, confined spatially and isotropic with respect to an observer, are localised in heliosphere the outer boundary of which is usually taken to be at half the distance to the nearest stars, that is about 1 pc $= 2 \times 10^5$ AU (1 AU $= 1.5 \times 10^{13}$ cm is the mean radius of the Earth's orbit).

3.1 Heliospherical (solar) gamma-ray burst models

An obvious advantage of the model of heliospherical gamma-ray burst sources is relatively low energy yields requiring planetary and even meteorological rather than stellar energy stores. Such gamma-ray bursts have recently been reported to occur in the upper atmosphere during thunderstorms [18]. They were observed at low latitudes (0–30°), allegedly resulting from electric discharges between the top cloud layer and ionosphere. The total energy released during such an event and the source's luminosity were $E = 10^9$ erg and $L = 10^{12}$ erg s^{-1}, respectively. Characteristic features of atmospheric bursts are short duration (milliseconds) and hard spectra distinguishing them from the bulk of cosmic bursts which are normally longer and softer. Their temporal profiles are very similar. The discovery of gamma-ray flares in the Earth's atmosphere points to the actual existence of nearby sources of gamma-rays and to mechanisms of short-term generation of gamma-quanta in rarefied (noncompact) objects.

First reports on gamma-ray burst sources in the Solar system appeared very soon after their discovery [2] but were not supported by further studies because they disagreed with experimental data. A V Kuznetsov [19, 20] noted the dependence of the number of bursts on heliolatitude. He constructed the distribution for 182 bursts whose coordinates were found with an accuracy of $\leqslant 10°$. The author singled out a group of repeating events that occurred at the same northern and southern heliolatitudes. However, the significance of this recurrence proved to be low and was not confirmed in other studies including the BATSE experiment. The same author [20] developed a model of burst production by solar coronal discharges (SCD), i.e. plasma blobs with mass of $\sim 10^{16}$ g carrying energy of $\sim 10^{32}$ erg, largely of magnetic origin. According to this model, bursts are generated during the interaction between SCD and interplanetary magnetic field. Because there is no direct evidence of SCD in the heliosphere in any wavelength range, the model is speculative. Solar activity responsible for SCD is markedly anisotropic, which is in conflict with a high degree of gamma-ray burst isotropy.

Burst isotropy, a potential bias from which does not exceed a few percent (in agreement with the recent BATSE data concerning 1,200 events [21]), is a strict criterion to verify heliospherical models. It appears that any model which associates gamma-ray bursts with the observed solar activities should be considered irrelevant. Anisotropic nature of solar activity is imprinted on a variety of its manifestations, e.g. blast waves of solar flares, SCD, solar wind, etc. However, the situation is different with respect to magnetic field inhomogeneities and density at large distances from the Sun (> 100 AU). Collisions of inhomogeneities may result in their isotropisation.

Rozental' [22] considered the problem of gamma-ray burst origin in relation to the collision and annihilation mechanism for magnetic clouds as suggested by Trubnikov et al [23 , 24], in the framework of galactic models. Bursts are supposed to result from annihilation of magnetic clouds that break into cylindrical pinches giving rise to fast electrons which in turn produce, through retarded radiation, a flux of gamma-rays with the observational spectrum. However, the 'galactic' variant of the model (for magnetic clouds 10 pc in size at particle density 10^{-2} cm^{-3} encounters serious difficulties in explaining the burst time patterns and energetics. The difficulties are removed if the same ideas are applied to magnetic clots that occur in the Solar system. One of the 'solar' variants implies blast wave collision at distances of 1 to 100 AU. This variant can hardly meet the criterion for burst isotropy, not with standing its seeming validity. More preferable is another variant dealing with chaotic magnetic inhomogeneities that fill up the entire Solar system. If the inhomogeneities are relics preserved from the moment of its creation, they are likely to retain the former isotropy. The total number of clots is estimated to be 10^4–10^6, with their size ranging from 10^7–5×10^{11} cm at a particle concentration of 10^{-4}–1 cm^{-3}. The problem is whether such residual magnetic inhomogeneities still occur in the heliosphere. Experimental data concerning inhomogeneities in the Solar system account for all known properties of gamma-ray bursts.

3.2 Heliospherical (cometary) gamma-ray burst models

The primeval heliosphere left memory of itself in the form of the Oort cloud [25, 26] which most astrophysicists, beginning from Oort himself, used to consider to be a spherically symmetric structure filling the periphery of the Solar system (10^3–10^5 AU), a store of comets from which they are released by gravitational perturbations of stars and gas clouds. The estimated total number of comets in the Oort cloud is 10^{11}–10^{15}. Not surprisingly, they have recently aroused great interest as possible sources of gamma-ray bursts.

White [27] considered a variant of cometary collisions in a spherical layer 35 – 600 AU from the Sun. According to this author, contracting magnetic fields of the comets induce betatron acceleration of electrons which give rise to a gamma-ray burst. Mean luminosity of a burst created at a distance of 100 AU is 3×10^{26} erg s^{-1}, i.e. 100 times lower than the collision energy. However, the probability for the comets to collide is very low and does not account for the observed burst frequency (around one per day).

Maoz [28] investigated the correlation between celestial distributions of comets and gamma-ray bursts. The positions of comets were deduced from the aphelia of their orbits, that is from their largest distances from the Sun (the Marsden Catalogue [29]). Coordinates of 260 bursts were used (1st BATSE Catalogue [30], angular precision 4°–13°). Although the comet distribution appears to be highly anisotropic, statistical tests can not yet exclude its correlation with the observed isotropy of gamma-ray bursts. Greater statistics and more accurate burst location are needed. In fact, both studies analyse a small fraction of the comets, rather than the Oort cloud itself, which are released from the cloud affected by stellar and galactic perturbations and occasionally enter the interior of the Solar system (the so-called historical comets). Is a sample of historical comets representative of their total amount in the heliosphere? The problem of comet selection for the purpose of observation and measurement of their orbits (especially in the past) is not completely resolved although it may be critical in terms of final results of the analysis.

Studies of Clarke et al. [31] and Horak et al. [32] are directly related to gamma-ray bursts supposed to originate from comets in the Oort cloud. Parameters of the cloud are deduced from its creation scenario as described by Duncan et al. [33]. In the framework of this model, gamma-ray bursts are emitted by the inner Oort cloud at 3×10^3 – 2×10^4 AU which is less sensitive to stellar perturbations and contains 80% or more of all the comets [34, 35]. The observed (historical) comets released from the outer Oort cloud (2×10^4 – 2×10^5 AU) subject to stronger gravitational perturbations have completely different orbit characteristics and were not considered as burst sources in the above papers. Therefore, models [31, 32] are also speculative as having to do with unobserved objects (comets of the inner Oort cloud), and the results they yielded are not reliable. Burst energy was estimated to be $10^{26} - 10^{27}$ erg. The authors were unable to identify a cometary process that could release such energy in the form of gamma-rays. The expected distribution of burst sources over the galactic latitude b (for the overwhelming majority of comets, with the large semiaxis in the range of 3×10^3 AU $< a < 3 \times 10^4$ AU) is shown in Fig. 5, based on the analysis of 10^5 and 10^6 cometary orbits with excentricitets $e = 0.95$ and $e = 0.997$. The shape of the distribution is determined by the galactic tidal forces which are responsible for marked quadrupole deformation of the cometary cloud with a concentration towards the galactic poles ($\sin|b| = 1$) and the plane ($\sin b = 0$), respectively. There is also a small singularity at an angle of 60.2° to the ecliptic plane due to

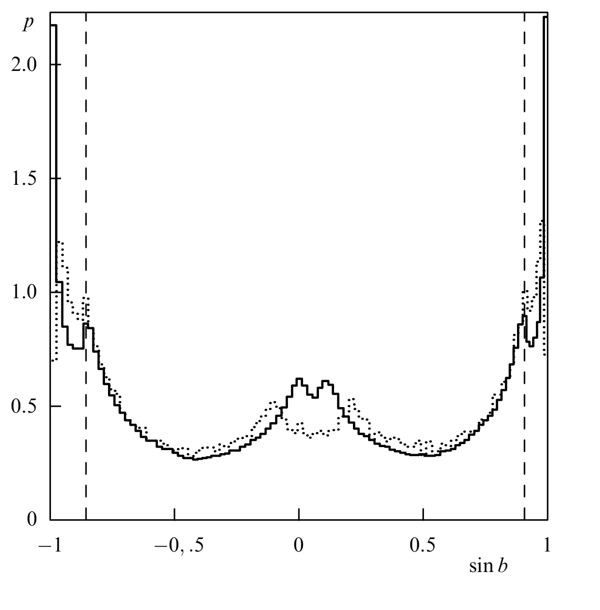

Figure 5. Monte-Carlo simulation of gamma-ray burst probability distribution along the galactic latitude b in the cometary model [31] for orbit excentricities $e = 0.997$ (solid curve) and $e = 0.95$ (dotted curve); the vertical dotted line shows the angle between ecliptic and galactic planes.

effects of the Sun and planets. The anisotropic distribution thus obtained does not agree with the measured gamma-ray burst distribution (correlation probability 3×10^{-4}). The isotropic distribution is inherent in comets with large semiaxis $a > 3 \times 10^4$ AU, but their number in the Oort cloud does not exceed 10%. Therefore, the inner Oort cloud cannot serve as a source of observable gamma-ray bursts.

Horak et al. [32] arrived at a similar conclusion after they compared calculated burst number distributions in the peak flux with those obtained in the BATSE experiment. It appears impracticable to correlate the total of bursts, both bright and faint, in the framework of one approach.

Another aspect of the comet model was investigated by Luchkov and Polyashova [36, 37] who examined historical comets largely 'turn out' from the outer Oort cloud (10^4 – 10^5 AU). Considering these comets to be burst sources agrees with their celestial isotropy as was shown in [31]†.

What is the cause of cometary activity leading to gamma-ray bursts? In an attempt to elucidate the mechanism of such activity with due regard for experimental findings, the spatial distribution of long-period Catalogue comets ($P > 200$ years) [38] was calculated. To fill up the entire space of $r = 2 \times 10^4$ AU with historical comets, each was 'launched' many times. Their orbit characteristics remained unaltered while the time of the passage through the perihelion (the minimum distance from the Sun) shifted to the past with $\Delta t = 600$ years. Thus, a comet had had time to move off even further from the Sun every time before it was recorded again. From the comet spatial distribution patterns thus obtained, it was possible to deduce the burst distribution in the flux, based on the assumed 'burst activity' mechanism.

There are three possible variants:

(1) an internal source of energy for all the comets (in this case, the number of burst sources N_b is proportional to the number of comets N_c);

(2) activation of a comet upon its interaction with the medium (gas, dust, meteorites) in which it travels, leading to the accumulation of an electric charge in the surface layer of its nucleus followed by a discharge [39] (on attaining a threshold potential), acceleration of electrons, and their retarded radiation in the surrounding matter (in this case, the number of sources $N_b \propto N_c v$, where v is the comet's speed;

(3) activation of a comet by the solar wind (due to quadratic decline of its intensity with r, the number of sources $N_b \propto N_c / r^2$). Figure 6 presents the results of the calculation (S is the flux in relative units, on the assumption of equal luminosity of all the bursts).

Comparison with the experimentally found dependence [8] indicates that distributions *1* and *3* disagree with the observed patterns whereas curve *2* fits them perfectly well following normalisation as shown in Fig. 6. The normalisation relates the experimentally measured flux to the distance from the source which allows mean luminosity of a burst to be calculated as $L = 10^{22}$ erg s^{-1}, when burst duration is 10 s and angular divergence 10^{-3} rad. The discussed mechanism essentially resembles the one leading to atmospheric gamma-ray bursts [18], but energetics in the comet model is ten orders of magnitude higher. The overall bursting rate is 4×10^6/day at the observed 1 burst/day and the angular direction 10^{-3} rad (a large number of bursts pass

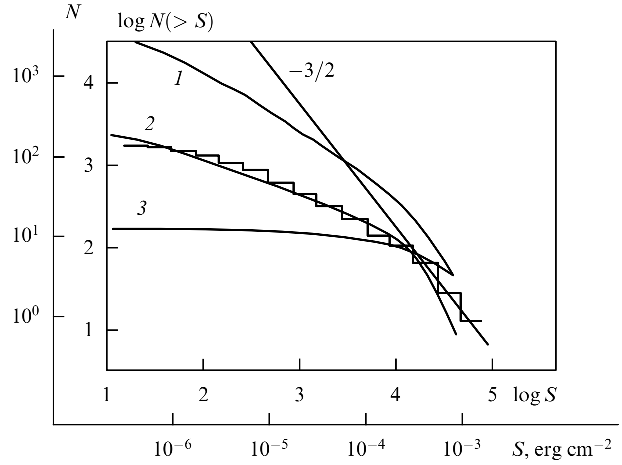

Figure 6. Estimated gamma-ray burst distributions $N(> S)$ from the flux S in the cometary model [37] for different sources of cometary activity: (*1*) internal energy resource; (*2*) interaction between the comet and the environment; (*3*) solar wind. The histogram shows experimental distribution [8].

undetected by the observer) which is not very high taking into consideration the total number of comets in the Oort cloud (10^{11} – 10^{15}). Unfortunately, we do not know enough about possible burst sources even though we deal with real historical comets. The comets that moved of from the Sun farther than $r > 10^3$ AU should be regarded as prehistorical ones while those as far from the Sun as $r > 10^4$ AU appear to have passed perihelion millions of years ago, and neither their number nor orbital characteristics are known (results of astrogeological studies suggest that the intensity of comet showers was much higher at that time [34, 40]). We have no information whatever about comets still bound for the Sun‡.

3.3 Check tests and observations

Comets are relatively close to us, and several tests are available to measure their distances from the observer. In the first place, bright gamma-ray bursts are checked (10^{-4} – 10^{-3} erg cm^{-2}). Given a burst emitted from a distance of 10 – 100 AU, one may attempt to identify it with a known historical comet both individually and using correlation analysis. A burst from a nearby comet will have parallax 10^{-2} – 10^{-1} which is possible to measure by widely separated spacecraft sensors (2 – 5 AU) provided each has the angular resolution not less than 1°. Recurrent bursts from a nearby comet (10 AU) will undergo a shift of several angular minutes per year which is also possible to measure using improved instrumentation. However, it should be recognised that identification of a gamma-ray bursts with a comet is a difficult and inefficient procedure because of the narrow angular direction of a burst and small probability of its production by a single comet.

More promising is a search for optical counterparts of gamma-ray bursts using a fast detector system which may incorporate high-resolution optical telescopes with

† However, it was shown [67] that these cometary models do not agree with the recent data on the isotropy of 1005 BATSE bursts (comment by I G Mitrofanov).

‡ Unfortunately, the latest observational data on the statistics of GRBs with different intensities ([81], Fig. 4) were not employed to test this model. Besides, one needs to explain the discrepancy between predictions of cometary models and the recent data on GRBs isotropy [67] (comment by I G Mitrofanov).

enhanced angular precision. As regards comets, such a search proceeds from the assumption that the brightness of a comet increases after it emits a gamma-ray burst, and it can be identified as a variable object with the characteristic time of a few hours to several days. Recently, the BACODINE system (BATSE Coordinates Distribution Network) has been established [41] which allows all interested observation settings to record a burst with a 4 – 7 s delay between its arrival at the BATSE detector and the reception of a signal of its celestial coordinates. A search for optical signals (as well as other forms of emission differing in terms of wavelength) is currently underway in several centres [42, 43] including the FOCSE (Fast Optical Comet Search Experiment) supervised by E Shoemaker. These and other on-going comet studies are expected to demonstrate in the near future the role of these objects in the creation of cosmic gamma-ray bursts.

4. Galactic gamma-ray burst models

4.1 Models with neutron stars in the galactic disk

According to the simplest galactic models [44, 45], gamma-ray bursts originate from neutron stars in the galactic neighbourhood of the Solar system. The neutron star concentration in this region is $n_{\rm NS} = 10^{-3}$ pc^{-3} [46]. Assuming that gamma-ray bursts are generated by a fraction of neutron stars δ, the distance to the nearest burst sources is estimated to be

$$D_{\min} = 4\delta^{-1/3} \text{ pc}. \tag{5}$$

Sources of the brightest gamma-ray bursts with intensities $S_{\max} \sim 10^{-3}$ erg cm^{-2} must be positioned at distances of $\approx D_{\min}$; hence, their luminosity is

$$L_{\rm disk} = 10^{36}\delta^{-2/3} \text{ erg s}^{-1}. \tag{6}$$

The dimmest gamma-ray bursts with intensities $S_{\max} \sim 10^{-7}$ erg cm^{-2} must be localised at distances $D_{\max} \sim 100 D_{\min} = 400\delta^{-1/3}$ pc.

A homogeneous disk in the vicinity of the Sun must necessarily be oblate at distances exceeding its thickness h_0. Therefore, at $D_{\max} > h_0$, burst sources must be deficient at high galactic latitudes. Indeed, there is the deficiency of weak sources as was previously observed (see Section 2, Fig. 4), but it does not result in the concentration of their distribution towards the galactic equator (Fig. 1). It is therefore concluded that the simplest model of standard sources in the nearest galactic disk neighbourhood is inconsistent with the experimental findings.

The discovery of angular correlation between bright and dim GRBs from the 1st BATSE Catalogue, in conjunction with concentration of medium bursts towards the galactic disk and centre, facilitated the development of a more sophisticated disk model [47]. According to this model, sources can give rise to large and small flares. Bright gamma-ray bursts are thought to be in fact large flares from nearby sources. Their full luminosity is estimated from (5). Dim GRBs could be associated with small flares, and their full luminosity is 3 – 4 orders of magnitude lower than (5). The bright to dim burst ratio (1/1000 or more) reflects the large to small flare frequency ratio in a source. Medium GRBs with apparent anisotropy are large flares from distant sources whose small flares fail to be recorded.

The main difficulty with this model is that the data of the 2nd and 3d BATSE Catalogues [48, 49] do not confirm either of the effects: angular correlation for bright and dim GRBs and galactic anisotropy for medium ones. This is a serious drawback because recent Catalogues include reconsidered data from the 1st BATSE Catalogue and have much larger statistics. It may be inferred that the model of the galactic disk sources producing two types of flares is at variance with the recent observational data.

One more attempt to associate gamma-ray bursts with sources in the galactic disk was made in Ref. [50] where these objects are considered as belonging to two different populations. It is supposed that nearby sources emit dim bursts with luminosity of $(10^{32} - 10^{33})\,\delta^{-2/3}$ erg s^{-1}, while very distant sources in the extended halo emit bright gamma-ray bursts and have luminosities around $L_{\rm halo} = 10^{45}$ erg s^{-1}. Evidently, the opposite variant of the two-component GRBs model, with bright gamma-ray bursts identified with nearby sources and dim ones with distant sources of the extended halo, is impossible because it suggests that distant sources of the disk must also be seen as dim bursts, thus contributing to anisotropy along the galactic equator.

A major inconsistency of the two-component galactic model is the absolute identity of averaged emission curves for bright and dim GRBs (Fig. 9). This similarity is difficult to explain for the sources in which the difference in energy yields amounts to 12 – 13 orders of magnitude and which must seemingly produce bursts of different nature.

4.2 Extended halo models

The main advantage of the extended halo model is the simplicity of accounting for the observed isotropy of sources on the celestial sphere (Fig. 1) and the deficiency of dim events in the statistical burst distribution by intensities (Fig. 2). Generally speaking, the sky distribution of GRBs from standard sources of an extended halo must include two anisotropic components. First, bright GRBs must have dipole anisotropy in the centre–anticentre direction because these sources must experience the effect of the shift of the Solar system from the centre of the Galaxy. Second, dim GRBs must manifest the additional contribution from the extended halo around the neighbouring spiral galaxy M31 (Fig. 7).

Biased isotropy cannot be statistically detected using the known localised BATSE sources, which makes it impossible at present to either confirm or disprove the model of standard sources in the extended halo. However, the data available allow the range of parameter values in the extended halo model to be restricted (Fig. 7) [51] and show that it will contract with further accumulation of recorded events. As soon as more than 2,000 GRBs will be accumulated (hopefully by 1998, if the BATSE will operate as efficiently as before), these anisotropic effects for the model of an extended halo with standard sources will be possible to observe. Otherwise, the simplest extended halo model will have to be discarded.

Similar to other galactic models, extended halo models propose high-velocity neutron star flares as burst origins. A model of an extended halo formed by high-velocity neutron stars was first suggested in Ref. [52] as an alternative to the then generally accepted disk model. It was postulated that high-velocity neutron stars able to leave the galactic disk generate gamma-ray bursts in the extended galactic halo. From the very beginning, this model was taken in with a large

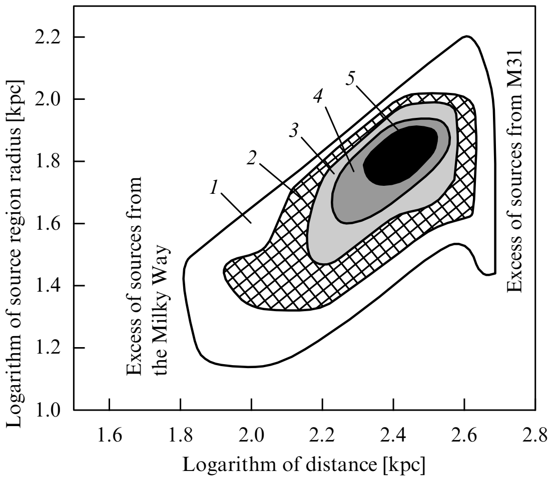

Figure 7. The range of permissible parameters of the extended galactic halo [51]. *1*, *2*, *3*, *4*, and *5* correspond to 100, 200, 400, 800, and 1600 bursts, respectively.

deal of scepticism because estimated intrinsic velocities of galactic neutron stars (radiopulsars) were about 100 km $s^{-1]}$, and it was believed that only a small fraction of these objects were able to escape from the disk [53].

An attempt of a straightforward answer to the question of source origin in an extended halo was made in Ref. [54] where neutron stars were postulated to be born in the halo together with the Galaxy itself and remain qualitatively different from neutron stars in the extended disk which arise continuously during supernova flares.

The situation has drastically changed by now. The recent re-evaluation of radiopulsar intrinsic velocities has demonstrated that their average value is about 500 km s^{-1} [55]. This means that about half of the galactic neutron stars have a great chance to abandon the galactic disk and either remain within the galactic halo or leave the galactic neighbourhood forever. Therefore, there can be no doubt now as to the presence of a galactic subsystem of neutron stars in the extended halo. However, there is another fundamental question to be answered to validate the burst origin model: why do not high-velocity neutron stars remaining in the disk generate GRBs ?

First extended halo models were based on the assumption that nearby and distant standard sources generate bright and dim GRBs respectively (see, for instance, Ref. [52]). Up-to date instruments like BATSE make records of practically all galactic gamma-ray bursts in agreement with the extended halo models with standard sources. Since there is no excess of faint gamma-ray bursts in the sky in the vicinity of the Andromeda galaxy, the outer boundary scale of the halo is about $D_{\max} = 100-300$ kpc [51]. Assuming that the difference of four orders of magnitude between gamma-ray burst fluxes is associated with the difference of two orders of magnitude between $D_{\min}$ and $D_{\max}$ distances to standard sources, it is estimated that the minimum distance $D_{\min} = 1-3$ kpc and characteristic luminosity

$$L_{\text{halo}} = 10^{41} - 10^{42}\ \text{erg s}^{-1}. \tag{7}$$

Suppose that gamma-ray bursts in a halo originate from neutron stars escaped from the galactic disk. The disk is abandoned by a fraction δ_0 of all the newly-born neutron stars, a fraction δ_1 of stars remain within the halo while a fraction δ_{GRB} of escaped stars might spontaneously generate bursts. Then, assuming the birth rate of galactic neutron stars to be around $\dot{R}_{\text{NS}} \sim 10^{-2}$ year^{-1}, it is possible to estimate the number of them that for the first time escape from the disk to move away towards the galactic periphery. The velocity of 1,000 km s^{-1} corresponds to 1 kpc Myr^{-1}; hence, the age of the stars leaving the disk for the first time is $t_{\text{age}} < 300$ Myr. Their number is

$$N_1 = 3 \times 10^6\, \delta_0 \delta_{\text{GRB}}\,. \tag{8}$$

The total number of neutron stars in the halo that must have been accumulated during the life of the Galaxy (about 10 milliard years) is

$$N_2 = 10^8\, \delta_0\, \delta_1\, \delta_{\text{GRB}}\,. \tag{9}$$

In the framework of the extended halo model, cases of single pass and accumulation should be considered separately (see [56]).

The overall birth rate of halo bursts is

$$\dot{R}_{\text{GRB}} = \frac{N}{t_{\text{rec}}} = \dot{R}_{\text{NS}}\, \frac{t_{\text{age}}}{t_{\text{rec}}}\,. \tag{10}$$

The detection rate by the BATSE is about 1,000 events per year for the entire celestial sphere. Hence, the estimated average recurrence times t_{rec} in models for the single pass and accumulation of halo sources are

$$t_{\text{rec}}^{(1)} = 3 \times 10^3 \delta_0\, \delta_{\text{GRB}}\ \text{years}, \tag{11}$$

$$t_{\text{rec}}^{(2)} = 10^5 \delta_0\, \delta_1\, \delta_{\text{GRB}}\ \text{years}, \tag{12}$$

respectively. It follows from (9), (10), and (11) that the mean number of bursts emitted by each source in the halo is

$$Q = \frac{t_{\text{age}}}{t_{\text{rec}}} = \frac{10^5}{\delta_0 \delta_{\text{GRB}}} \times \begin{cases} 1 & \text{(for the single recession model)}, \\ \delta_1^{-1} & \text{(for the accumulation model)} \end{cases} \tag{13}$$

and is practically independent of whatever variant of the model is preferred. At $\delta_1 \approx 0.5$, the difference between the estimates for them may be neglected.

Hence, the estimated total energy emitted in gamma-ray bursts of the mean 10 s duration t_{GRB} is

$$E_{\text{tot}} = L_{\text{halo}} Q t_{\text{GRB}} = (10^{47} - 10^{48})\, (\delta_0\, \delta_{\text{GRB}})^{-1}\ \text{erg}. \tag{14}$$

Assuming that efficiency of transformation ε of the total energy into gamma-rays in burst sources is several percent, the estimated total energy necessary for a neutron star in an extended halo to emit all its gamma-ray bursts is

$$(10^{49} - 10^{50})\, \frac{1\,\%}{\varepsilon}\, \frac{1}{\delta_0\, \delta_{\text{GRB}}}\ \text{erg}.$$

Astrophysical gamma-ray burst models must explain the presence of such energy resource in neutron stars of the galactic halo.

Therefore, the extended halo model with standard sources has the following corollaries:

(a) Fractions δ_0 and δ_{GRB} being about 0.1 each, the total energy necessary to generate GRBs in the halo is about 1% of the total gravitational energy of a neutron star. The origin of this energy and the cause for burst production remain to be elucidated. The said energy may result from internal processes in a star probably associated with phase transitions, or relative diffusion of the spin vortices and magnetic flux tubes in a superfluid superconducting interior of neutron star, etc. (see, for instance, Ref. [57, 58]). For models of neutron star activities based on the assumption of sporadic accretion of small bodies from the surrounding planetary cloud [59], the necessary total small body mass is approximately 1% of the Sun's mass [59]. Finally, this energy corresponds to the total energy of neutron star magnetosphere with the magnetic field strength of more than 10^{15} Gs.

Neutron stars with such superstrong magnetic fields ('magnetars') were proposed as gamma-ray burst sources. Their emission is thought to be directed opposite to the velocity vector of a neutron star that moves away from the disk [60]. Evidently, the notion of directed emission by magnetars diminishes the estimated total energy release (7), (14) by approximately 10 times; the characteristic time during which the sources remain observable must decrease accordingly. The estimated total energy yield for the model of halo source accumulation throughout the Galaxy's life remains unaltered.

(b) Even the strongest gamma-ray bursts have not till now been shown to concentrate towards the galactic disk. This means that high-velocity neutron stars which remained in the disk because of the unfavourable direction of their motion are not able to generate GRBs due to some reasons. This implies that gamma-ray bursts can hardly originate from the internal activity of neutron stars. Other objects or conditions should be sought for which are absent in the disk but do occur in the halo and whose interactions with neutron stars make gamma-ray burst generation possible.

(c) There is no apparent GRBs anisotropy on the celestial sphere. According to computation [51], statistics of events to be accumulated in the foreseeable future will be enough to verify any model of the extended halo with standard sources. However, it has recently been shown [61] that the calculation of angular source distribution must take into consideration deviation of the gravitational galactic potential from isotropy, e.g. due to the contribution by the Andromeda potential. Even small anisotropy of this potential results in substantial isotropisation of halo source directions. Hence, the model of extended halo might remain valid even if isotropy is preserved at a significantly increased number of sources.

(d) The ratio of GRBs detections to the total number of neutron stars in the halo indicates that burst generation must be a recurrent process. The nature of recurrence needs to be clarified. Assuming that burst generation is a Poisson process or occurs at a rate of $1/t_{\rm rec}$, simultaneous observation of all sources for three years must reveal the following number of repeated bursts from a single source

$$n_{\rm rep} = \frac{1}{\delta_0\,\delta_{\rm GRB}} \times \begin{cases} 1 & \text{(for single recession),} \\ 10^{-2} & \text{(for accumulation in the halo)} \end{cases} \qquad (15)$$

Therefore, the presence or absence of a few recurrent sources of classical GRBs allows one to make a choice between the single pass model and the model of source accumulation in the halo.

Until now, the BATSE system does not appear to have recorded recurrent GRBs [62]. This makes preferable the halo model which postulates neutron stars accumulated in the halo throughout the life of the Galaxy to be gamma-ray burst sources [56].

The collection of single pass models include 'magnetar' models [60] and models of accretion from a planetary cloud [59]. Models of the former type meet the geometrical condition that a source emits in the opposite direction to that of its velocity. This condition is satisfied for a single pass model and violated for sources accumulated in the halo within the lifespan of the Galaxy. In the latter case, the applicability of a single pass model depends on the evaluation of the evolution time for a protoplanetary cloud during which small bodies incidentally fall down on a neutron star [59]. This time amounts to 300 Myr and approximately corresponds to the first pass of neutron star in the halo.

(e) Recently found correlation between hardness and intensity of GRBs [97, 98, 102, 103] indicates that sources are not standard candles in terms of energy spectra (see Section 5.4). Nearby objects have harder spectra than distant ones. Hence, the results of statistical tests for uniformity of the spatial distribution (curve $\log N/\log F$, test $\langle V/V_{\rm max}\rangle$) must show a strong dependence on the energy range in which burst fluxes are measured. Such a property of gamma-ray burst counting statistics is actually observed [63] and should be taken into account in constructing source models. The model of halo sources with the standard distribution function for intrinsic luminosities allows, in principle, for the explanation of the observed effect of correlation between hardness and intensity of GRBs. This requires an assumption [64] that both the mean radiation hardness of a source (hardness ratio (HR)) and its maximum spectral energy $E_{\rm p}$ are proportional to the intrinsic luminosity

$$\text{HR or } E_{\rm p} \propto \left(\frac{L}{L_{\rm max}}\right)^{\alpha}. \qquad (16)$$

It turned out that power α must be $0.9-1.8$ at $L_{\rm max}/L_{\rm min} = 30-10$ if the observed effect of correlation between gamma-ray burst brightness and mean hardness $\langle$HR$\rangle$ is to be accounted for [64]. The decrease in mean spectral hardness upon transition from bright to dim bursts may be related to changing relative amount of the observed halo sources of different luminosity with increasing distance. A major contribution to the total amount of bright bursts is made by nearby sources with maximal intrinsic luminosity $L_{\rm max}$. Conversely, the dimmest bursts are generated by the most distant sources with minimal luminosities $L_{\rm min}$.

To sum up, models with standard source distribution in the halo by intrinsic luminosities, provide natural explanation for the correlation between spectral hardness and intensity of gamma-ray burts.

4.3 Feasible physical models of GRBs generation by neutron stars in an extended halo

Gamma-ray burst energy may result from thermonuclear flares of matter on the neutron star surface, the matter being accreted from an old companion (as is the case with X-ray bursters) or from the interstellar medium. Thermonuclear burning is known to release about 10^{18} erg g^{-1}. Therefore, for a complete energy output of around 10^{43} erg, approximately 10^{25} g of hydrogen needs to be burnt. If the mean recurrence time is about $3\times10^{3}-10^{5}$ years (see (11), (12)), such a mass will be accumulated at the accretion rate of 3×10^{12}–10^{14} g s^{-1}. This value is significantly higher than 10^9 g s^{-1} obtained by Bondy and Hoil for the possible gas accretion rate in the interstellar medium. On the other hand, it seems unlikely that practically all high-velocity neutron stars in the halo would be components of close binary systems capable of accreting second component matter.

Another way to account for gamma-ray bursts in an extended halo is to take advantage of collisions between neutron stars and interstellar comets or asteroids. In order to ensure the necessary burst rate for these objects, collisions must occur with the characteristic recurrence time not less than 10^5 years. This implies the comet concentration around 10^{17} pc^{-3}. The total number of comets in an extended halo with the volume of 10^{15}–10^{18} pc^3 is 10^{32}–10^{35}. The upper limit on the total halo mass corresponds to the galactic dark matter about $10^{12}M_{\odot}=10^{45}$ g. If this mass is entirely concentrated in small bodies, then average mass of each body can not exceed 10^{10}–10^{13} g. On accretion of 1 g of matter, about 10^{20} erg is released. Therefore, accretion of bodies with mass 10^{10}–10^{13} g on a neutron star corresponds to the total energy yield of 9 – 10 orders of magnitude less than is necessary to emit one gamma-ray burst.

Finally, the third way in which the accretion model can be realised is the accretion of small bodies from a near-stellar, planetary and/or cometary cloud on a neutron star [59]. It is supposed that during a flare of a supernova in a binary system with a massive component, the resulting neutron star may leave this system carrying away a substantial part of the second component's mass (ca 3×10^{28} g). This portion gives rise to a protoplanetary cloud in which planets and small bodies are formed. It is also supposed that during the first 10^3 years of cloud evolution, incidental accretion of matter on the neutron star is apparent as flares of a source of soft gamma-ray repeaters. After the completion of the planetary system formation, excitations of cometary trajectories by planets might lead to occasional falls of comets on the neutron star with production of classical gamma-ray bursts.

The main difficulty encountered in this model is related to the evaluation of the total mass of the comets destined to fall down onto the star and to provide the total resource of gamma-ray bursts energy. According to the above estimate of the total released energy, this mass amounts to 10^{31} g. Obviously, conditions necessary for the formation of a sufficiently massive protoplanetary cloud with such total mass of colliding comets are unlikely to occur. In this case, the full probability of the formation of a gamma-ray burst source $\delta_0\,\delta_{\rm GRB}$ in an extended halo is described by the product of the probability of a supernova flare in a close binary system and the probability of realisation of favourable conditions for the neutron star to escape and be incorporated into a protoplanetary cloud with a sufficiently large mass of the second component.

On the other hand, it follows from the estimation of the possible number of recurrent bursts that the probability $\delta_0\,\delta_{\rm GRB}$ can not be smaller than 10^{-2}–10^{-3}. Otherwise, the number of recurrent bursts would be large enough and they would be easy to observe (see (15)). Therefore, in order to provide the astrophysical basis for the model of accretion from a cometary cloud, it is necessary to demonstrate that 1 – 0.1% of all neutron stars are formed in close binary systems which they leave after having taken with them a protoplanetary cloud with the total mass of not less than 1% of the solar mass.

Internal energy of a neutron star can serve as a source of gamma-ray burst energy during incidental starquakes [57]. Starquakes may be due to the nonequilibrium star composition or the energy preserved in rotation vortices and/or flux tubes of the internal magnetic field. The probability of phase transition to result from the pion condensate formation [65] does not explain the generation of multiple gamma-ray bursts by a single star because such a transition in course of intrinsic star evolution occurs but once.

Starquakes caused by rotation vortices in the superfluid nucleus of a neutron star may be associated with differential angular rotational velocity of superfluid and normal matter that becomes apparent as the crust rotation slows down [58]. This velocity can not grow infinitely because the Magnus force that arises between the shell and the superconducting nucleus tends to counteract the rotation. These processes are responsible for the nonequilibrium state in which the moment of rotation of superfluid vortices is transferred onto the shell. This is believed to result in the release of about 10^{38} erg of energy, i.e. much less than it is necessary to generate one burst in the corona.

However, such a mechanism of vortical diffusion can yield much more energy if a neutron star has the internal magnetic field of 10^{15} Gs or so [58]. In this case, the total energy of the field is $\sim10^{48}$ (10^{-15} Gs) erg which is approximately equivalent to the total energy resource which is necessary for a star to generate a complete series of consecutive gamma-ray bursts.

In the inner superfluid and superconducting domain of a neutron star such a field has the form of magnetic flow tubes, each having field energy of about 10^{44} erg. These tubes and rotation vortices are usually nonparallel and form an intricate interpenetrating structure in the interior of the star.

Collectively, the slowdown of rotation and the decay of the magnetic field result in relative movements of vortices and tubes and their emergence at the surface, while intersection between them inside the star creates strains which are relieved through starquakes. Concurrently, about 10^{41}–10^{42} erg of energy is released [58], in agreement with the estimated energy of GRBs. Therefore, in the presence of the superstrong magnetic field inside a neutron star, interdiffusion of flux tubes and vortices may cause sporadic starquakes the total number and energy of which are in perfect agreement with the respective estimates obtained for gamma-ray burst sources.

4.4 Prospects of observational verification of the galactic gamma-ray burst model

At present, there are no direct observational tests facilitating the choice between the extended halo model and the cosmological model of gamma-ray bursts. The lack of apparent stretching of averaged profiles of dim gamma-ray bursts versus averaged profiles of bright gamma-ray bursts is in conflict with those variants of the cosmological model which predict the extension factor of more than 1.5 although variants predicting smaller extension remain acceptable (see Section 5). On the other hand, the galactic model of extended halo admits the possibility of stretching averaged dim gamma-ray burst profiles relative to those of strong events. At the same time, both models readily explain the effect of correlation between hardness and intensity of gamma-ray bursts. For the cosmological model, this effect is considered to be a natural sequel of cosmological redshift. In the extended halo model, a simple assumption of correlation between spectral hardness and internal luminosity is equally useful for explaining this effect.

Unbiased isotropy of local source distribution over the celestial sphere can not be considered as a direct argument in favour of the cosmological model or against the galactic one. Calculations of real neutron star motions in a halo [61] showed that their trajectories are sufficiently chaotic to 'wash out' all possible effects of anisotropy.

Direct observation of the halo of the nearest spiral galaxy M31 (the Andromeda nebula) seems to be probably the sole observational test available for the final choice between the cosmological and galactic models, using an instrument which is sensitive enough for the purpose. A special cosmic project EREBUS has been developed to make such observations [66]. If currently observable gamma-ray bursts are actually produced by galactic sources, EREBUS experiments must demonstrate a significant number of gamma-ray bursts from M31. Conversely, if gamma-ray bursts are of cosmological origin, the sensors will not record excess sources in the direction of M31. Hopefully, the project will be accomplished within a future years and will provide direct observational evidence of the nature of gamma-ray bursts.

5. Cosmological gamma-ray burst models

5.1 Observational evidence of cosmological origin of gamma-ray bursts

It is known that the BATSE experiment provided information about celestial coordinates of more than 1,000 gamma-ray burst sources [4]. These sources show highly homogeneous localisation on the sky (Fig. 1). Evaluation of dipole and quadrupole moments of such distribution suggests a very high degree of isotropy [67]. All attempts to obtain evidence of anisotropy for any individual subset of gamma-ray bursts selected in terms of a specific trait have failed. At the initial stage of the BATSE experiment, gamma-ray bursts of moderate intensity (neither too bright, nor very dim) were reported to be concentrated close to the disk (effect about 2.9σ) and the centre (effect about 3.2σ) of the Galaxy [68]. However, further studies provided additional data that did not confirm the presence of large-scale anisotropy. Effects of gamma-ray burst concentration towards the disk and the centre of the Galaxy proved to be lower (0.3σ and 1.7σ respectively) [4, 67]. For the arbitrary axes of the dipole and quadrupole constituents of anisotropy, the deviation of the dipole moment from 0 and the quadrupole moment from 1/3 is 0.9σ and 0.3σ, respectively. Therefore, it is safe to argue that there is no large angular-scale anisotropy on the celestial sphere. This inference holds for both all gamma-ray bursts taken jointly and for their individual subsets selected by different parameters or traits.

Some authors reported studies on small angular-scale anisotropy of gamma-ray bursts which was expected to be apparent as a small-scale inhomogeneity of the source distribution over the sky [69]. Given cosmologic origin of gamma-ray bursts, celestial localisation of their sources may possibly correlate with that of galaxies, their clusters, and quasars. However, the analysis of inhomogeneous localisation of gamma-ray bursts at a small angular scale did not reveal any deviation from isotropy [70, 71]. Nor did attempts to directly identify gamma-ray bursts with known extragalactic sources yielded any meaningful result.

To conclude, there are at present no data showing a deviation of gamma-ray bursts from an isotropic celestial distribution. On the other hand, statistical analysis of GRBs with different intensities provides unambiguous evidence that their sources cannot be standard candles that uniformly fill up the Euclidean space.

Statistics of BATSE gamma-ray bursts indicates that the dependence $N(>F)$ does not closely follow the -3/2 power law (see Fig. 4) [4]. Dim bursts appear to be deficient if compared with their number estimated following this law. Therefore, statistical analysis of gamma-ray burst localisations on the celestial sphere and the number of bursts of different intensity shows that their sources are isotropically distributed along all spatial directions, but they cannot be standard candles showing the homogeneous distribution in the Euclidean space.

Based on this inference, it was suggested to associate gamma-ray bursts with sources at cosmological distances.

Generally speaking, the cosmological hypothesis was first suggested in the very beginning of gamma-ray burst studies as a logical alternative to galactic and heliospherical models [72–75]. However, all basic ideas concerning gamma-ray bursts that were formulated before the initiation of the BATSE experiment in 1991 totally ruled out their cosmological origin. In the first place, spectra of many gamma-ray bursts were found to exhibit certain features that were interpreted as electron cyclotron resonances and lines produced by electron–positron annihilation at the surface of neutron stars. Second, there were observational reports on the weak burst concentration towards the galactic disk. Third, some gamma-ray bursts were shown to repeat which suggested their origin from recurrent sources. However, large statistical material obtained in the BATSE experiment did not confirm the presence of spectral lines in classical gamma-ray bursts; on the other hand, it allowed one to single out recurrent gamma-ray bursts into a separate class of events. Therefore, as soon as a high degree of isotropy in conjunction with spatial inhomogeneity was unambiguously established, cosmological models became very popular again. Since 1991 – 1994, they have dominated theoretical concepts concerning classical gamma-ray bursts (see, for instance, Ref. [76]).

In accordance with the majority of these models, burst sources have standard properties in the relevant reference frames. The observed $\langle V/V_{\max}\rangle$ ratio is supposed to be due to non-Euclidean nature of spacetime at cosmological scales. In selected models, the value of $\langle V/V_{\max}\rangle$ is directly related to the redshift of weak burst sources localised at the maximum distance from an observer (on the threshold of detectability). The relationship between burst counting statistics and cosmological models was investigated by many authors; the all studies yielded concerted results (Table 1) [77].

Table 1. Characteristic parameters of cosmological gamma-ray burst sources [77].

Redshift of weak burst sources	Luminosity (erg s^{-1})	Number of events	References
$Z = 1$	10^{50}	3×10^{-7} year^{-1} hal.$^{-1}$	[78]
$Z = 1.5$	2×10^{51}	2×10^{-6} year^{-1} hal.$^{-1}$	[79]
$Z = 1.2$	4×10^{51}	10^{-7} year^{-1} Mpc^{-1}	[80]
$Z = 0.8$	5×10^{50}	2×10^{-8} year^{-1} Mpc^{-1}	[81]

5.2. Nature of cosmological gamma-ray burst sources

Gamma-ray burst detection rate and estimated value of maximal redshift agree with a birth rate of roughly $\dot{R}_{\rm GRB} = 10^{-6}$ events per year in a standard galaxy. The rapidly variable flux of gamma-ray bursts corresponds to the spatial scale of energy release which is smaller than the size of any star excepting neutron stars and black holes. Their cosmological origin can be explained in the context of models that simulate sources able to generate isotropic gamma-radiation with energy $E_{\rm GRB} = 10^{50}$–10^{51} erg within a few seconds (or tens of seconds). Such energy constitutes a large portion (0.1 – 1%) of the total gravitational energy of a neutron star with a mass comparable to that of the Sun.

Hence, a suggestion has to be done that gamma-ray bursts may originate from catastrophes in evolution of relativistic compact stars (neutron stars and black holes) during which a substantial portion of their total energy is emitted. Today, a most popular model postulates mergers of constituent components in compact binary systems (neutron star + neutron star or neutron star + black hole) (see, for instance, Refs [82, 76, 79]). Short characteristic time of a gamma-ray burst and the concomitant energy release might also be explained by another model according to which a burst results from the collapse of a degenerate magnetised dwarf to a neutron star with the millisecond rotation period and a superstrong magnetic field [83, 84].

It is known that evolution of binary systems of relativistic compact stars inevitably results in their cataclysmic merger, with energy of $E_{\rm NS/NS} > 10^{53}$ erg being concurrently released in a burst of gravitational radiation, a pulse of emitted neutrinos, and a gamma-ray burst. Observations of three double pulsars allowed the number of such mergers in our Galaxy to be calculated as amounting to $\dot{R}_{\rm NS/NS} = 10^{-5.5\pm0.5}$ events a year [85].

A merger of relativistic stars in a compact binary system gives rise to the central object of about (2–3) $M_\odot$ with relativistic temperature. Thereafter, a thick accretion disk is formed round this object, by virtue of orbital momentum. During the merger, energy is released from both the central object and the accretion disk. According to numerical calculations, a coalescing system shows maximum transparency along the rotation axis which causes major gamma-rays to arise in the form of two narrow beams parallel to the axis [86]. If the beams have characteristic angle of divergence δ, the number of mergers apparent as gamma-ray bursts is a fraction $\approx \delta^{-2}$ of the total. It follows from the above estimates of the number of mergers NS/NS in a galaxy and the frequency of these events, based on the observed number of gamma-ray bursts , that the angle of divergence for the two beams must be sufficiently large ($\delta > (\dot{R}_{\rm NS/NS}/\dot{R}_{\rm GRB})^{1/2} = 1$–$0.3$ rad). Hence, the observed number of gamma-ray bursts is rather close to the threshold value permitted by the model of cataclysmic mergers of close binary relativistic stars.

Certain authors reported much higher cataclysmic merger rates for relativistic stars in the Galaxy. According to Ref. [87], they amount to $\dot{R}_{\rm NS/NS} = 10^{-3.5}$ events a year in the case of double neutron stars. Simulation of stellar evolution by Monte-Carlo modelling yielded comparable results [88]. In the latter case, the acceptable angle between a beam of gamma-photons and the rotation axis of the system may be much smaller (about $\delta = 0.06$ rad = 3 degrees).

To conclude, data on evolution of close binary systems suggest high frequency of catastrophic mergers of their compact relativistic components in the surrounding region with Z near 1.0. Energy released during such events is sufficient to account for the observed gamma-ray bursts. At present, this scenario is most widely accepted for the explanation of gamma-ray burst production at cosmological distances.

Other cosmological models make use of the analogy of gamma-ray burst spectra with hard radiation spectra of active galactic nuclei [89, 90]. It is supposed that gamma-ray bursts are caused by accretion of a relativistic star on a large black hole, with the mass equivalent to 10^3–10^6 solar masses. The accretion perturbs the dominant beam of particles from the massive black hole which leads to the generation of a burst of gamma-rays with complicated profiles in a wide solid angle. However, none of the observed gamma-ray bursts has so far been identified with such bright extragalactic sources as active galactic nuclei. Nor has it been estimated in astronomical terms how often active galactic nuclei can serve as sources of gamma-ray bursts and whether there is a correlation between their activity and burst rates. That is why this model is not very popular.

5.3 Feasible physical models of gamma-ray burst generation at cosmological distances

It is suggested in the framework of the cosmological scenario that the energy of two relativistic stars or a degenerate dwarf collapsing to a neutron star ($E_{\rm GRB} \sim 10^{50}$–10^{51} erg) is released into a very small space volume with a scale of $R_0 \sim 10^7$–10^8 cm, within a very short time of $\sim R_0/c$. The density of electromagnetic energy in this volume is so large that it tends to be opaque for hard photons with respect to photon–photon generation of electron–positron pairs [91]

$$\tau_{\rm ph/ph} = \frac{fE_{\rm GRB}\sigma_{\rm T}}{R_0^2 m_{\rm e} c^2} \sim \frac{10^{19} f E_{\rm GRB\,(51)}}{R^2_{0(7)}}\,, \qquad (17)$$

where f is the fraction of primary photons with the energy above the pair production threshold. Due to the large optical thickness in the energy-releasing volume, photons, electrons, and positrons must be in equilibrium at a temperature about

$$T_0 \sim 6E^{1/4}_{\rm GRB\,(51)} R^{3/4}_{0(7)}\ \text{MeV}. \qquad (18)$$

A clot of electromagnetic energy thus formed is an agglomeration of photons and electron–positron pairs referred to as a fireball (see for instance, Refs [91 – 94]). This agglomeration has huge internal radiation pressure which is not equilibrated by any external force; hence, fireball expands with relativistic velocity [92].

Apart from the electromagnetic constituent, a fraction of fireball energy is associated with baryons. The main baryon components are protons. On the whole, the fireball must be neutral; therefore, the total number of protons is equivalent to the excess of electrons over positrons. Accordingly, the optical fireball thickness with respect to the baryon component is determined by the Thompson section of photon scattering on these excessive electrons:

$$\tau_{\rm bar} = n_{\rm bar}\sigma_{\rm T} R_0 \sim \tau_{\rm ph/ph}\,\frac{m_{\rm e}}{m_{\rm p}} \sim 3\times 10^{15}\,\frac{fE_{\rm GRB(51)}}{\varepsilon R^2_{0(7)}}\,. \qquad (19)$$

An important characteristic of a fireball which markedly affects its evolution is the ratio ε of the radiation energy $E_{\rm rad}$ to the total baryon rest energy $M_{\rm bar}\,c^2$. At the early stage of fireball formation and expansion, the radiation energy is higher than the energy of electron–positron pairs ($\varepsilon \gg 1$); hence, fireball extension is radiation-dominated.

In this phase (see, for instance Ref. [91]), the Lorentz factor for the expansion Γ grows in proportion to the fireball radius R while radiation energy density w decreases as R^{-4}. Due to this, characteristic radiation temperature of the fireball in the observer's rest system does not change ($T_{\rm obs} \sim \Gamma w^{1/4} \sim T_0$). In the co-moving reference frame, the fireball uniformly expands in each point, but in the system of the observer, its size $R_{\rm obs} \sim R/\Gamma$ remains constant around the initial value R_0. Extension in the radiation-dominated phase proceeds until the Lorentz factor attains $\Gamma \sim \varepsilon$ and the fireball radius becomes

$$R_\varepsilon \sim R_0 \varepsilon \sim 10^{11} R_{0(7)} \varepsilon_{(4)} \text{ cm.} \quad (20)$$

Simultaneously, baryon kinetic energy becomes comparable to electromagnetic energy.

In the next phase of baryon-dominated fireball expansion, the Lorentz factor remains unaltered, nor does the shell thickness of the extending fireball ($\sim R_0$) change. The electron concentration in the shell decreases in proportion to R^{-2}, and the fireball becomes transparent as soon as its radius is

$$R_{\rm c} \sim 10^{15} R_{0(7)}^{3/8} E_{\rm GRB(51)}^{3/8} \text{ cm} \quad (21)$$

At this moment, the radiation to be emitted by the fireball separates from matter.

The final phase of the fireball evolution is essentially related to its interaction with the surrounding interstellar medium [30]. By analogy with models of supernova shell extension, it is assumed that this phase starts at the moment when the loss of fireball momentum due to braking in the interstellar medium becomes comparable to the momentum itself. At this final stage, similar to the situation with supernovae, a part of fireball energy which was 'absorbed' by the baryonic component during the radiation-dominated phase undergoes conversion to the energy of internal/convergent and external/divergent blast waves and eventually transforms back to electromagnetic energy. The radius of transition to the baryon retardation phase is

$$R_{\rm br} \sim 10^{15} E_{\rm GRB(51)}^{1/3} \varepsilon_{(4)}^{-2/3} n^{-1/3} \text{ cm.} \quad (22)$$

It follows from the comparison of relations (21) and (22) that these scales are of the same order at $\varepsilon \sim 10^4$. At $\varepsilon > 10^4$, the scale relation $R_{\rm br} < R_{\rm c}$ indicates that the baryon-dominated phase of fireball free expansion is virtually absent, and braking in the interstellar medium occurs in the radiation-dominated phase. At $\varepsilon < 10^4$, the baryonic component of the fireball undergoes free expansion with the Lorentz factor $\Gamma \sim \varepsilon$, prior to braking caused by the interaction with the interstellar medium.

Therefore, the fireball, as a physical object, is a relatively simple physical system whose evolution can be described by simple physical relations. In the case of free expansion of a fireball in radiation-dominated and baryon-dominated phases, its physics in many respects resembles conditions at early stages of the expansion of the Universe. The effect of relativistic Lorentzian contraction in the observer's system makes up for the geometrical shell extension. Therefore, the characteristic length of a pulse emitted by a fireball in these phases depends on its initial size ($\sim 10^{-3} R_{0(7)}$ s).

In the retardation phase, characteristic physical features are similar to those associated with the supernova shell expansion in the interstellar medium. The length of a pulse emitted in this phase depends on characteristic times of transformation of baryon kinetic energy to the energy of external and internal blast waves and its further dissipation to radiation [95, 96].

The cosmological model implies that the conspicuous profile diversity of classical gamma-ray bursts is due to fireball retardation in the interstellar medium. This phase lasts for a few seconds, in agreement with characteristic lengths of gamma-ray bursts. Hard short-period gamma-ray bursts can be associated with the emission of an internal blast wave that propagates towards the fireball centre. The interstellar medium is inhomogeneous which accounts for the complicated blast wave geometrical front patterns. Gamma-rays from different blast wave fragments might have different properties and might come to an observer at different time. Blast wave non-uniformity during the fireball retardation phase could be responsible for gamma-ray bursts with complicated multi-peak profiles in which emitted pulses are separated by 'void' intervals characterised by the background photon counting rate.

5.4 Prospects of observational verification of the cosmological gamma-ray burst model

The development of cosmological gamma-ray burst models proceeded side by side with the elaboration of methods for their observational verification. These tests can be arbitrarily categorised into two groups. One of them includes tests designed to identify spacetime singularities associated with non-Euclidean geometry of the expanding Universe. The other group encompasses tests based on the evaluation of the effects of physical conditions on gamma-ray bursts generated by extending fireballs. The two groups are discussed below.

It is clear that the most important tests of the first group must be concerned with estimating redshifts of photon frequency and cosmological time dilation for processes at cosmological distances. They may be called geometrical tests. In the case of the simplest cosmological model which regards all sources as standard candles in the corresponding reference frames, all the events must be divided into a group of bright gamma-ray bursts from nearby sources with a small redshift $Z_{\rm bright}$ and a group of dim gamma-ray bursts from distant sources with the redshift $Z_{\rm dim}$. The factor

$$Y(Z_{\rm dim}, Z_{\rm bright}) = \frac{1 + Z_{\rm dim}}{1 + Z_{\rm bright}} \quad (23)$$

describes the redshift for the observed spectral signatures of dim gamma-ray bursts versus the spectra of bright events. The same factor determines the ratio of the observed time scale for the group of dim gamma-ray bursts to the one for bright gamma-ray bursts provided that these scales coincide for both groups of sources in the corresponding reference frame. It follows from Table 1 that this cosmological factor for gamma-ray bursts must be equal to $Y_0 = 1.8$.

'Geometrical' tests recently employed to verify cosmological gamma-ray burst models yielded to conflicting results.

A special procedure of averaging gamma-ray burst profiles by alignment of their principal peaks has been proposed to measure cosmological time dilation [97, 98]. The profile of each burst was normalised on the condition that its principal peak be $f_{\max} = 1.0$. The profiles were aligned

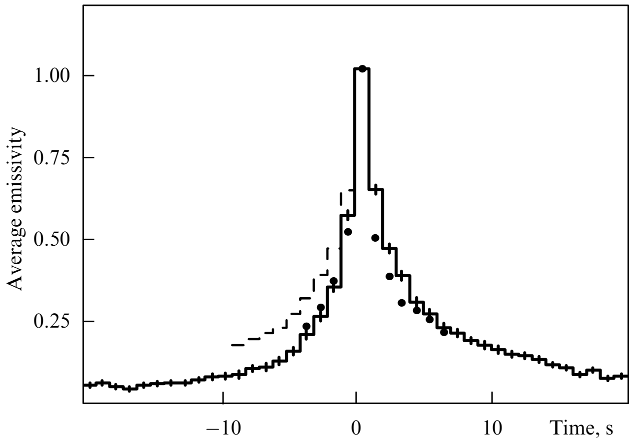

Figure 8. Average curve of emissivity for 338 gamma-ray bursts observed with BATSE [97, 98]. The time-reversed back slope is shown with the dashed curve. Dots represent the APEX gamma-ray burst averaged curve [102].

along the time axis in such a way that maximum peaks coincided at time $t_0 = 0$. After that, the profiles of dimensionless fluxes f_i were averaged for each time interval i. This procedure resulted in the averaged curve of emissivity (ACE) for gamma-ray bursts (Fig. 8). The curve has the single peak structure with the short rising front and longer back slope. Such a shape indicates that the burst production process is asymmetric in time.

Comparison of ACEs in different spectral channels showed that their peaks are narrowing with growing photon energy. On the whole, the shape and the duration of a peak are characterised by the equivalent width

$$t_{\mathrm{ACE}} = \sum 1.024\big(1 + \langle f_i \rangle\big) \ \mathrm{s} \qquad (24)$$

for $f_i > 1.0$. Values t_{ACE} for different spectral changes are presented in Table 2.

Table 2. The widths of rising fronts, back slopes, and full width of ACE at the 0.1 level for spectral discriminators No 1 (25 – 50 keV), No 2 (50 – 100 keV), and No 3 (100 – 300 keV) of BATSE [98].

Parameter	Discriminator No 1	Discriminator No 2	Discriminator No 3
Width t_{ACE} of the rising front,s	3.26±0.05	2.58±0.05	2.11±0.04
Width t_{ACE} of the back slope,s			
Full width t_{ACE}, s	4.98±0.06	4.41±0.05	3.52±0.05
ACE stretching factor relative	8.24±0.05	6.99±0.07	5.63±0.06
to discriminator No 3	1.42±0.15	1.25±0.03	1.0

Interpolation of these values allowed to found the relationship between the equivalent width of the ACE peak and the radiation energy [98]:

$$t_{\mathrm{ACE}}(E) = 5.25\left(\frac{173\ \mathrm{keV}}{E}\right)^{0.23\pm0.06} \mathrm{s}. \qquad (25)$$

Taking into consideration the varying profiles of gamma-ray bursts and the random peak and inter-peak intervals distribution, it may be inferred that ACE is an averaged characteristic of burst variability and should be used in the cosmological time dilation test. Such a test was carried out for a set of BATSE gamma-ray bursts as having the largest counting statistics. Comparison involved ACEs for subsets of bright and dim gamma-ray bursts separated in terms of peak flux measured at a time scale with a resolution of 1024 ms. The simple comparison of these curves in the same energy range of 50 – 300 keV revealed their identity (Fig. 9) [97, 98]. Table 3 shows characteristic times t_{ACE} which do not show also any consistent time scale growth for the variability of dim versus bright bursts.

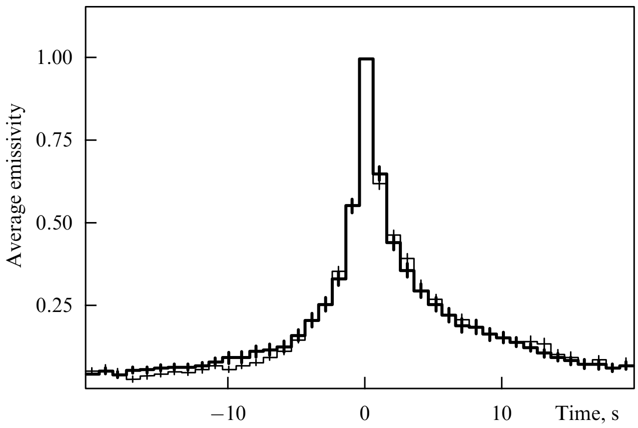

Figure 9. Comparison of average curves for 143 bright gamma-ray bursts observed with BATSE, with the peak flux > 1 phot cm^{-2} (thick line), and 179 dim BATSE gamma-ray bursts with the peak flux < 1 phot cm^{-2} (thin line) [97, 98].

Generally speaking, effect of ACE peak contraction with increasing energy is apt to 'disguise' effects of cosmological time dilation. Indeed, when comparison is performed of bright and dim gamma-ray bursts in the same spectral range, one must take into account that in the co-moving reference frames photon energies of bright and dim events are related as $Y(Z_{\mathrm{dim}}, Z_{\mathrm{bright}})$. In accordance with (25), the initial ACE profile for dim bursts in such reference frames must be narrower than that for bright ones. Therefore, in principle, the cosmological dilation of dim burst profiles can be

Table 3. The widths of rising fronts, back slopes, and full width of ACE at the 0.1 level for spectral discriminators No 2 + No 3 for subsets of bright and dim gamma-ray bursts of the BATSE experiment [98].

Averaged groups	Number of events	Peak flux 1ph cm^{-2} s	t_{ACE}, s at front	t_{ACE}, s at slope	Full t_{ACE}
All	338	—	2.33±0.04	4.21±0.05	6.54±0.06
Bright	143	> 1	2.47±0.06	4.16±0.07	6.64±0.10
Dim	179	< 1	2.25±0.06	4.32±0.07	6.57±0.09
Brightest	73	> 2.5	2.57±0.09	3.65±0.09	6.21±0.13
Dimmest	69	> 0.45	2.14±0.09	4.35±0.12	6.50±0.15

compensated by their internal narrowing in the following reference frame.

To check this supposition, we carried out a self-consistent test in which ACE cosmological dilation was evaluated taking into account cosmological redshift and burst profile contraction with increasing photon energy. This test also gave negative results. Cosmological dilation factor was found to be $Y = 0.92 \pm 0.2$ [98].

This finding does not agree with the results of comparison between bright and dim gamma-ray bursts made by Norris and co-workers using the BATSE data set [99, 100]. Their early studies revealed substantial (almost two-fold) stretching of ACE for dim events relative to that for bright ones. In a recent work, these authors estimated the cosmological factor Y to be ~ 1.5. The discrepancy could result from different criteria used to separate gamma-ray bursts to groups of bright and dim events. In the case of Refs [97, 98], the selection was done by the maximum flux for the time scale at which profiles were averaged, whereas Norris and co-workers sorted out gamma-ray bursts using a more sophisticated wavelet-expansion procedure and profile smoothing algorithm. It was shown that ACEs for bright and dim gamma-ray bursts were not significantly different provided the events were selected in terms of the peak flux recorded for the time scale for which averaging was performed.

Another 'geometrical' test of the cosmological model compares averaged spectral signatures for subsets of bright and dim gamma-ray bursts. The spectral parameter used was the ratio of fluxes in the spectral channel of discriminator No 3 (100 – 300 keV) to those in the spectral channel of discriminator No 2 (50 – 100 keV). The comparison revealed their different average hardness. The averaged hardness curve for bright gamma-ray bursts was well above the similar curve for dim gamma-ray bursts for the entire time interval studied (Fig. 10). This effect referred to as the effect of hardness/intensity correlation is in good agreement with the prediction of the cosmological model [76]. It was first reported for a small group of gamma-ray bursts in the APEX experiment in the framework of the FOBOS project [102] and was later confirmed by BATSE data [103, 97, 98].

The hardness/intensity correlation effect has recently been examined in detail by averaging the peaks $\langle E_p \rangle$ of the integral photon spectra for 5 groups of bursts with different intensities [104] (Fig. 11). A cosmological model was used to estimate redshifts of corresponding sources. Cosmological factor Y for gamma-ray bursts of the strongest and the dimmest groups was found to be $1.86^{+0.36}_{-0.24}$ [104].

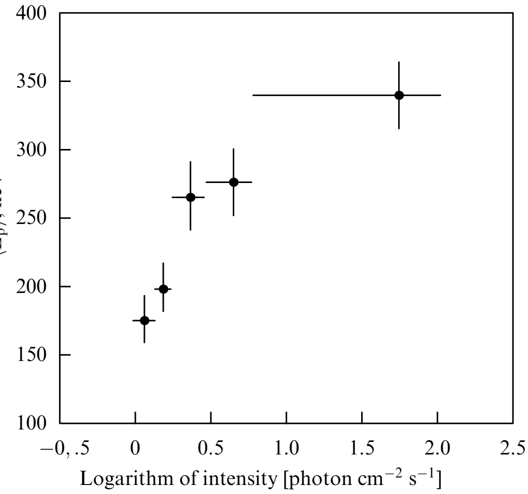

Figure 11. The relationship between the mean peak values of spectral photon distribution and average peak fluxes for 5 groups of gamma-ray bursts with different intensity [104].

However, the possibility of unambiguous cosmological interpretation of the effect of hardness/intensity correlation is questionable. Comparison of ACEs for the above 5 groups selected by burst intensities showed the lack of time dilation effect which has to be associated with cosmological redshift [108]. Figure 12 shows estimated and theoretical values of t_{ACE} calculated using the cosmological model and factor Y as reported in Ref. [104]. There is no agreement between the two quantities.

Direct 'geometrical' tests of the cosmological gamma-ray burst model have so far failed to unambiguously confirm its validity. It turned out that the comparison between averaged time characteristics of bright and dim gamma-ray bursts does

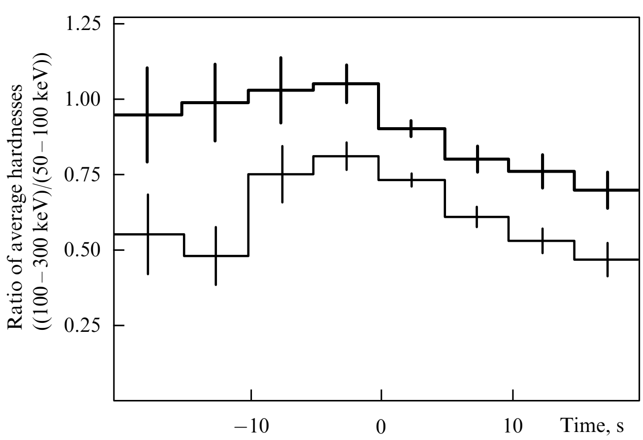

Figure 10. Comparison of averaged radiation hardness curves for 143 bright gamma-ray bursts observed with BATSE, with the peak flux > 1 phot cm^{-2} (thick line), and 179 dim BATSE gamma-ray bursts with the peak flux < 1 phot cm^{-2} (thin line) [97, 98].

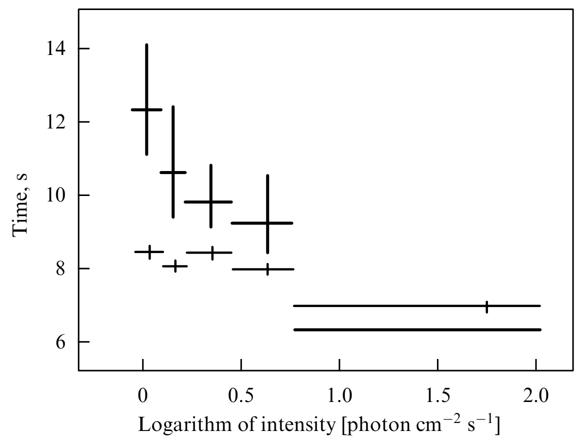

Figure 12. The widths of average emissivity curves for 5 groups of gamma-ray bursts collected by intensities (thin lines). Thick lines show widths of these curves estimated in agreement with dilation factors based on cosmological interpretation of the hardness/intensity correlation effect [108].

not reveal the effect of cosmological dilation. On the contrary, these quantities were found to be in a perfect agreement with each other.

To 'save' the cosmological model, one has to assume that intrinsic properties of gamma-ray burst sources in the co-moving reference frames differ at short and long cosmological distances. Their profiles in corresponding reference frames must 'contract' with increasing redshift in exactly such a way as to ensure complete compensation for the cosmological stretching of profiles which must be apparent in the observer's rest system.

The second group comprises 'physical' tests of the cosmological model. They are, in fact, 'no-tests' designed to search for physical signatures of gamma-ray burst emission which are incompatible with their cosmological origin. In the first place, there is a 'no-test' to reveal anisotropy of gamma-ray bursts on the celestial sphere bearing in mind that the cosmological model has to imply complete isotropy (with a very small dipole effect along the direction of an observer of the cosmological reference frame, which cannot be detected within foreseeable time). Another 'no-test' makes any evidence of the recurrence of classical gamma-ray bursts whereas cosmological gamma-ray bursts are lacking in recurrences. However, this 'no' is not absolute also because, in principle, cosmological scenarios with recurrent bursts are conceivable. The third 'no-test' is intended to identify spectral lines of gamma-ray bursts since the cosmological model makes no provision for their formation. For a cosmological model to be eliminated or made impracticable, suffice it to find out a spectral feature like a cyclotron absorption line in a single burst spectrum.

Therefore, verification of the cosmological model does not yield an unambiguous conclusion as to its applicability for the explanation of gamma-ray burst origin. Moreover, one may safely maintain that a cosmological model with standard sources contradicts the assumption of similar average temporal characteristics for bright and dim gamma-ray bursts.

Based on the fundamental physical model of the relativistic fireball, one may suppose that changes in the properties of sources at different cosmological distances are unrelated to phases of free relativistic expansion of fireballs. Their dynamics during these phases is governed by fundamental physical relations which must be identical in all co-moving systems. On the contrary, in the retardation phase, a fireball in the interstellar medium depends on the environment which makes it possible to specify physical reasons for sources with different redshifts to have different properties.

It may be supposed that further development of the theory of cosmological models will be focused on studies of possibilities of intrinsic differences of gamma-ray burst sources at different cosmological distances. Simultaneously, results of direct observations will be used for the verification of 'geometrical' and 'physical' tests of cosmological models.

6. Conclusions

The present review unequivocally demonstrates that the problem of gamma-ray burst origin was recently transformed in a global astrophysical problem. There is increasingly growing interest in gamma-ray bursts regardless of whether they reach us from remote galaxies, or from halo of our Galaxy, or from cosmic objects at the periphery of the Solar system, just because this phenomenon has numerous implications for astrophysics. Specialists in almost every branch of modern astrophysics have to deal with gamma-ray bursts one way or another. Attempts at the solution of the problem gave rise to many new ideas and proposals amenable to further fruitful development both in relation to gamma-ray bursts and apart. More and more sophisticated instrumentation is employed to study this mysterious phenomenon of the outer-space. A search for sources of gamma-ray bursts now involves investigation of soft X-rays and high-energy gamma-rays with supporting observations of the UV radiation, optical and radio-waves. In other words, gamma-ray bursts are most extensively studied using different methodologies available in modern physics. The advantage of such multidisciplinary approach is expected to be apparent within the next five years when the problem is likely to be in many respects clarified even if not definitively solved.

Gamma-ray bursts proved to be a hard nut to crack. Nevertheless, the progress is obvious even though it is not very rapid (see, for example, Refs [109, 110]). Many early hypotheses have been discarded as invalid in the light of unquestionable facts, viz., angular isotropy of gamma-ray bursts, their spatial inhomogeneity, the absence of spectral lines, etc. It is tempting to try and foretell the fate of the remaining hypotheses although prognoses in science are almost as insecure as they are in politics and sports.

We suppose that cosmological models are in especially critical conditions now because of the absence of positive output from the specific cosmological tests. Extended galactic halo models are in an equally critical situation, because they are to incorporate two opposite factors. On the one hand, measuring higher degree of burst isotropy leads to the progressively increasing estimation of distances to their sources. On the other hand, there are no anticipated gamma-ray events from the Andromeda halo. The third class of models assuming heliospherical sources of gamma-ray bursts appears to have no good prospects also. Phenomenologically, they may of course correspond to observed gamma-ray bursts but encounter great difficulties (perhaps insuperable) in terms of energetics, processes and conditions of generation of high-energy gamma-rays.

What is left then? There are in fact three options. First, intensive studies under way now may finally lead to the unambiguous choice between the models discussed: cosmological, galactic or geliospheric ones. Second, it may happen, like it was frequently in astrophysics before, that observational picture of the phenomenon will be re-evaluated, and some sources previously excluded will again come out to the foreground. They may be eruptive [105] or neutron [106] stars in the galactic disk or flaring stars in the immediate vicinity of the Sun [107]. And finally, third, in the complete absence of acceptable models (the situation which it seems premature to discuss now), the crisis of basic paradigms might take place, which will certainly touch not only the astrophysics alone. Perhaps, 'new physics' of elementary particles and high energies will be requested, which would not be surprising in the light of striking changes and discoveries in this field during the last 30 years.

References

1. Klebesadel R W, Strong I B, Olson R A *Astrophys. J. Lett.* **182** L85 (1973)
2. Prilutskiĭ O F, Rozental' I L, Usov V V *Usp. Fiz. Nauk* **116** 517 (1975) [*Sov. Phys. Usp.* **18** 548 (1975)]

3. Rozental' I L, Usov V V, Estulin I V *Usp. Fiz. Nauk* **140** 97 (1983) [*Sov. Phys. Usp.* **26** 437 (1983)]
4. Briggs M S *Astrophys. Sp. Sci.* **231** 3 (1995)
5. Kouveliotou C et al. *Astrophys. J. Lett.* **413** L101 (1993)
6. Meegan C A et al. *Nature* (London) **355** 14 (1992)
7. Cline T L et al. *Astrophys. J. Lett.* **237** L1 (1980)
8. Mazets E P et al. *Pis'ma A. Zh.* **6** 609 (1980)
9. Share G et al. *Proc. of Gamma-Ray Bursts* 249 (1994)
10. Murakami T et al. *Nature* (London) **335** 234 (1988)
11. Palmer D M et al. *Astrophys. J. Lett.* **433** L77 (1994)
12. Zel'dovich Ya B, Novikov I D *Stroenie i Evolutsiya Vselennoĭ* (Structure and Evolution of the Universe) (Moscow: Nauka, 1975)
13. Frail D A et al. *Astrophys. J. Lett.* **427** L43 (1994)
14. Rosental' I L, Sviridenko I V *Pis'ma A. Zh.* (in press)
15. Mazets E P, Golenetsky S V *Itogi Nauki i Tekhniki. Ser. Astronomiya* (Recent Progress in Science and Technology Ser. Astron. Vol. 32; Ed. R A Syunyaev) (Moscow: VINITI, 1987) p. 16
16. Teegarden B J *Astrophys. Sp. Sci.* **231** 137 (1995)
17. Palmer D M et al. *Astrophys. Sp. Sci.* **231** 161 (1995)
18. Fishman G J et al. *Science* **264** 1313 (1994)
19. Kuznetsov A V *Kosmicheskie Issledovaniya* **20** 89 (1982)
20. Kuznetsov A V Preprint IKI PR-1913 (Moscow: IKI, 1995)
21. Schaefer B E et al. *Astrophys. J. Suppl.* **92** 285 (1994)
22. Rosental' I L *Astron. Zh.* **71** 542 (1994)
23. Trubnikov B A, Zhdanov S K, Vlasov V P Preprint IAÉ No 5580/6 (Moscow: IAÉ, 1992)
24. Trubnikov B A *Usp. Fiz. Nauk* **160** 167 (1990) [*Sov. Phys. Usp.* **33** 1061 (1990)]
25. Oort O P *BAN* **11** 91 (1950)
26. Bailey M E *Mon. Not. R. Astron. Soc.* **204** 603 (1983)
27. White R S, in *Proc. 23rd Inter. Cosmic Ray Conf., Calgary 1993* Vol. 1, p. 49
28. Maoz E *Astrophys. J.* **414** 877 (1993)
29. Marsden B G, Williams G V *The Catalogue of Cometary Orbits* (Cambridge: Smithonian Astrophys. Observ., 1992)
30. Fishman G J et al. *The First BATSE Gamma-Ray Catalog* (NASA/GSFC, 1992)
31. Clarke T E, Blaes O, Tremaine S *Astron. J.* **107** 1873 (1994)
32. Horack J M et al. *Astrophys. J.* **429** 319 (1994)
33. Duncan M, Quinn T, Tremaine S *Astrophys. J.* **94** 1330 (1987)
34. Hills J G *Astron. J.* **86** 1730 (1981)
35. Marochnik L S, Sholomitsky G V *Astron. Zh.* **63** 1040 (1986)
36. Luchkov B I *Pis'ma A. Zh.* **20** 308 (1994)
37. Luchkov B I, Polyashova O M *Materialy conferentsii COSMION-94* (Proceedings of the COSMION-94 Conference) (in press)
38. Mamedov M F, Radzievskiĭ V V *Statisticheskiĭ Catalog Parametrov Kometnykh Orbit* (Statistical Catalogue of Cometary Orbit Parameters) (Baku: ELM, 1986)
39. Ibadov S *Doklady AN. Tadj. SSR* **19** 11 (1976)
40. Rampino M R, Stothers R B *Nature* (London) **308** 709 (1984)
41. Barthelmy S D et al. *Astrophys. Sp. Sci.* **231** 235 (1995)
42. Hudec R *Astrophys. Sp. Sci.* **231** 239 (1995)
43. Greiner J *Astrophys. Sp. Sci.* **231** 263 (1995)
44. Hartmann D, Epstein R I, Woosley S E *Astrophys. J.* **348** 625 (1990)
45. Lamb D O, in *Neutron Stars: Theory and Observation* (Eds J Ventura, D Pines) (Kluwer Acad. Publ., 1993) p. 545
46. Paczynski B *Astrophys. J.* **348** 485 (1990)
47. Quashnock J M, Lamb D O *Mon. Not. R. Astron. Soc.* **265** L59 (1993)
48. Fishman G J et al. *Astrophys. J. Suppl.* (1995) (in press)
49. Fishman G J et al. *Astrophys. J. Suppl.* (1996) (in press)
50. Smith I A, Lamb D O *Astrophys. J. Lett.* **410** L23 (1993)
51. Hukkila J et al. *Astrophys. J.* **422** 659 (1994)
52. Shklovskiĭ I S, Mitrofanov I G *Mon. Not. R. Astron. Soc.* **212** 545 (1985)
53. Lyne A G, Anderson B, Salter M J *Mon. Not. R. Astron. Soc.* **201** 503 (1982)
54. Gurevich A V et al. *Zh. Exp. Teor. Fiz.* **103** 1873 (1993) [*JETP* **76** 925 (1993)]
55. Lyne A G, Lorimer D R *Nature* (London) **369** 127 (1994)
56. Mitrofanov I G *Astrophys. J.* (in press)
57. Epstein R I, in *Proc. of "High Velocity Neutron Stars as Sources of Gamma-Ray Bursts"* (Eds R Lingenfelter et al.) (1995) (in press)
58. Rudermann M, in *Proc. of "High Velocity Neutron Stars as Sources of Gamma-Ray Bursts"* (1995) (in press)
59. Colgate S, in *Proc. "The 3rd Gamma-Ray Bursts Workshop"* (Eds M Briggs et al.) (1996) (in press)
60. Duncan R C, Thompson C *Astrophys. J. Lett.* **392** L9 (1992)
61. Podsiadlowski P, Rees M J, Ruderman M *Mon. Not. R. Astron. Soc.* **273** 755 (1995)
62. Brainerd J J et al. *Astrophys. J. Lett.* **441** L39 (1995)
63. Belli B M *Astrophys. Sp. Sci.* **231** (1–2) 43 (1995)
64. Mitrofanov I G, Litvak M L, Chernenko A M *Astrophys. J.* (1996) (in press)
65. Migdal A B, Chernoutsan A I, Mishustin I N *Phys. Lett. B* **83** 158 (1979)
66. EREBUS project (NASA report)
67. Briggs M S et al. *Astrophys. J.* **459** 40 (1995)
68. Quashnock J M, Lamb D Q *Mon. Not. R. Astron. Soc.* **265** L45 (1993)
69. Quashnock J M, Lamb D Q *Mon. Not. R. Astron. Soc.* **265** L59 (1993)
70. Meegan C A et al. *Astrophys. J. Lett.* **446** L15 (1995)
71. Brainerd J J et al. *Astrophys. J. Lett.* **441** L39 (1995)
72. Usov V V, Chibisov G V *A. Zh.* **52** 192 (1975)
73. Hulse R A, Taylor J H *Astrophys. J.* **368** 504 (1975)
74. Van den Bergh S *Astron. Astrophys. Suppl.* **97** 385 (1983)
75. Goodman J, Dar A, Nussinov S *Astrophys. J.* **314** L7 (1987)
76. Paczynski B *Acta Astronomica* **41** 257 1991
77. Dermer C D, Weiler T J *Astrophys. Sp. Sci.* **231** 377 (1995)
78. Piran T et al. *Proc. of Gamma-Ray Bursts* (Eds W Paciesas, G J Fishman) (New York: AIP, 1992) Vol. 265, p. 149
79. Mao S, Paczynski B *Astrophys. J.* **388** L45 (1992)
80. Dermer C D *Phys. Rev. Lett.* **68** 1799 (1992)
81. Fenimore E E et al. *Nature* (London) **366** 40 (1993)
82. Blinnikov S I et al. *Pis'ma Astron. Zh.* **10** 177 (1984)
83. Usov V V *Nature* (London) **357** 472 (1992)
84. Usov V V *Mon. Not. R. Astron. Soc.* **267** 1035 (1994)
85. Narayan R et al. *Astrophys. J. Lett.* **379** L17 (1991)
86. Piran T *Proc. of Gamma-Ray Bursts* (Eds G J Fishman et al.) (New York: AIP, 1994) Vol. 307, p. 543
87. Tutukov A V, Yungelson L R *Mon. Not. R. Astron. Soc.* **260** 675 (1993)
88. Jorgenson H et al. *Astrophys. Sp. Sci.* **231** 389 (1995)
89. McBreen C A et al. *Astron. Astrophys. Suppl.* **97** 81 (1993)
90. Roland J, Frossati G, Teyssier R *Astron. Astrophys.* **290** 364 (1994)
91. Piran T *Proc. of Gamma-Ray Bursts* (Eds G J Fishman et al.) (New York: AIP, 1994) Vol. 307, p. 495
92. Cavallo G, Rees M J *Mon. Not. R. Astron. Soc.* **183** 359 (1978)
93. Goodman J *Astrophys. J. Lett. Ed.* **308** L47 (1986)
94. Paczynski B *Astrophys. J. Lett. Ed.* **308** L43 (1986)
95. Meszaros P, Rees M J *Astrophys. J.* **405** 278 (1993)
96. Meszaros P, Rees M J *Proc. of Gamma-Ray Bursts* (Eds G J Fishman et al.) (New York: AIP, 1994) Vol. 307, p. 505
97. Mitrofanov I G *Astrophys. Sp. Sci.* **231** 103 (1995)
98. Mitrofanov I G et al. *Astrophys. J.* **459** 570 (1996)
99. Norris J P et al. *Astrophys. J.* **424** 540 (1994)
100. Norris J P *Astrophys. Sp. Sci.* **231** 95 (1995)
101. Norris J P *Proc. of Gamma-Ray Bursts* (Eds M Briggs et al.) (New York: AIP, 1996) (in press)
102. Mitrofanov I G et al. *A. Zh.* **65** 1052 (1992)