Collimated high-energy photons and other possible observational effects of the photon angular and spectral distribution in gamma-ray burst sources

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Abstract. Typical observational gamma-ray burst (GRB) spectra are discussed and, in this connection, what is the origin of the compactness problem and how it was solved at first. If the threshold for $e^-e^+$ pair production depends on an angle between photon momenta, then another solution of the compactness problem is possible. We discuss a possibility of the $\gamma$-rays collimation and the dependence of photon beaming on photon energies. The list of basic assumptions of the scenario describing the GRB source with energy $<10^{49}$ ergs is adduced: the matter is about an alternative to the ultrarelativistic fireball if all long-duration GRBs are related or physically connected with normal/unpeculiar core-collapse supernovae (SNe). Namely, we consider the questions about radiation pressure and how the jet arises on account of even small asymmetry of the radiation field in a compact GRB source. The possibility of a new approach to explanation of the GRB phenomenon is shown. Possible mechanisms of their generation in regions of size $<10^8$ cm are discussed (a compact model of GRBs). Observational consequences of the compact GRB energy release are considered.

Key words: gamma rays: bursts – gamma rays: theory

1. Introduction

There are direct and indirect observational arguments in favor of physical connection between massive or core-collapse supernovae (SNe) and long duration gamma-ray bursts (GRBs), and the list of publications on the topic is ever-increasing. At first this connection was justified by the fact that all GRB host galaxies turned out to be star-forming or starbursting galaxies with high massive star-forming rates (e.g., Djorgovski et al. 2001; Frail et al. 2002; Sokolov et al. 2001). There are more and more occurrences of SN signs in the GRB afterglow light curves and spectra for GRB 970228 (Galama et al. 1999), GRB 970508 (Sokolov et al. 1998), GRB 980326 (Bloom et al. 1999), GRB 990712 (Bjornsson et al. 2001), GRB 991208 (Castro-Tirado et al. 2001), GRB 000911 (Lazzati et al. 2001), GRB 011121 (Bloom et al. 2002), GRB 021211 (Della Valle et al. 2003), GRB 030329 (Hjorth et al. 2003; Stanek et al. 2003), GRB 031203 (Thomson et al. 2004). A comprehensive analysis of SN light in GRB afterglows has been recently done by Zeh, Klose, and Hartmann (2004), and see references therein. If there were more cases of clear and indisputable spectral and photometric signs of association between normal core-collapse SNe (Ib/c type and others) and GRBs, it would be a direct proof of the connection between GRBs and massive stars. The increasing statistics of the GRB-SN associations can impose direct and strong observational constraints on GRB beaming and, hence, we could have an observational estimation of a real total energy reservoir of GRB sources.

The purpose of this paper is to describe the basic assumptions of a scenario of a GRB source with energy $<10^{49}$ ergs; the matter is about an alternative to the ultrarelativistic fireball if all long-duration GRBs are physically connected with normal/unpeculiar core-collapse supernovae (SNe). In Section 2 it should be discussed the typical GRB spec-
2. On the typical GRB spectra and typical photon energies

The rapid temporal variability, $\delta T \sim 10$ msec, observed in GRBs implies compact sources with a size smaller than $c\delta T \approx 3000$ km. But here a problem immediately arises for distant GRB sources (e.g., Carri-gan and Katz 1992): too large energy ($> 10^{51}$ ergs) is already released in only soft $\gamma$-rays ($< 511$ keV and up to 1 MeV) in such a small volume for the sources at cosmological distances ($> 1$ Gpc). For a photon number density $n_\gamma \sim (10^{51}$ ergs$/m_\gamma c^2)/(c\delta T)^3 \sim 10^{57}/(3000$ km)$^3 \sim 10^{32}$ cm$^{-3}$ two $\gamma$-ray photons with a sum energy larger than $2m_\gamma c^2$ could interact with each other and produce electron positron pairs. The optical depth for pair creation is given approximately by $\tau_{e^+e^-} \sim n_\gamma \tau_e^2 (c\delta T) \sim 10^{46}$, where $\tau_e$ is the classical electron radius $e^2/(m_\gamma c^2)$ (the cross-section for pair production is $\sim \tau_e^2$ or $\sim 10^{-25}$ cm$^2$ at these semirelativistic energies). It is the essence of a so-called “compactness problem”: the optical depth of the relatively low energy photons ($\sim 511$ keV) would be so large that these photons could not be observed.

1. Usually in this definition a role of the high-energy photons is emphasized: the $\gamma$-ray photons with energies larger than $2m_\gamma c^2$ (and $> 1$ MeV) could interact with lower energy photons and produce electron-positron pair pairs (Piran 1996; 1999; 1999a; 2004). The average optical depth for this process is $\tau_{e^+e^-} \sim 10^{15}(E/10^{51}$ ergs$) (\delta T/10$ msec)$^2$ for a typical total GRB energy release $E \sim 10^{51}$ ergs in a small volume (e.g. Piran 1999). The “heavy”/hard (or high-energy) photons are present in observational GRB spectra as high energy tails which contain a significant amount of energy. So, according to Piran, the compactness problem arises because the observed spectrum contains a fraction of the high energy $\gamma$-ray photons. In other words, since observations are consistent with a possibility that all GRBs have the high energy tails, it must be the first and basic observational justification of the problem (see e.g. Lithwick and Sari 2001): the optical depth of the high-energy photons ($> 1$ MeV) would be so large that these photons could not be observed. However, here we must make right away several specifying remarks on the typical spectra and typical photon energies in GRBs, including allowance for the well known results of recent observational spectra.

Yes, such high-energy photons did were observed in some cases, but far from being so always. Furthermore, photons with energies $> 100$ MeV were strongly delayed after the main GRB burst. For example, the 20 GeV photon observed with BATSE/EGRET delayed as much as 1.5 hours relative to the GRB itself. It is obvious that in this case a physical mechanism was quite different from one creating typical prompt GRB spectra. (The GRB spectra are described in a review by Fishman and Meegan (1995), see also the catalogue of the spectra by Preece et al. (2000).)

Typical observational GRB spectra turned out to be very diverse, but yet these are mainly soft (but not hard) gamma-ray quanta. It has been known since the moment of GRBs discovery, when their spectra were presented in energy units: e.g., see a review by Mazets and Golentsky (1987). At present many authors point to the same again (Lamb et al. 2003; Baring & Braby 2004; Liang et al. 2004; Atkins et al. 2003; Gialis & Pelletier 2004). Almost all GRBs have been detected in the energy range between 20 keV and 1 MeV. A few have been observed above 100 MeV. In a recent review Piran (2004) also has paid attention to a puzzle of the origin of narrow distribution for the typical energy of the observed GRB radiation ($E_p < 511$ keV, Preece 2000). Besides, by 2000 it was clear that there were other two GRB classes: X-Ray Flashes (XRF) and X-Ray Rich Gamma Ray Bursts (XRR GRB) (Heise et al. 2001; Amati et al. 2002). These are GRBs either without (XRFs) or almost without (XRR GRB) gamma-ray quanta. It is also discussed in detail and there are excellent illustra-
tions in recent papers by Lamb et al. (2003a, 2003b, 2003c) and in other papers by this group.

Thus, despite the importance of the problem of the high energy (∼1 MeV) photons release, still there are too many lower energy γ-ray photons in a small volume with $R \sim 3000$ km. The observed fluxes give an estimate of a total GRB energy release to be of $\sim 10^{51}$ ergs in the form of just these low energy photons, or this “standard” estimation ($\sim 10^{51}$ ergs) was obtained from typical observational GRB spectra of just these, most frequently observed low-energy (“target”) photons with the semirelativistic energies, up to 1 MeV, basically. (It is natural that the photon density was estimated using the simple assumption of spherical symmetry. See below the comments to the paper by Carrigan and Katz 1992.)

2. Further it was firmly declared, and other authors have repeated many times that GRB source must be optically thin and the observed spectrum is non-thermal with certainty (Piran 1996; 1999; 1999a; 2004). Now the optically thin source with the non-thermal spectrum is presented as a standard common opinion about all GRBs (Postnov 1999), though unlike time-averaged GRB spectra, time-resolved instantaneous GRB spectra are thermal (black-body radiation with temperature $kT \sim 100$ keV) rather than power-law ones (Crider et al. 1997; Preece et al. 1998, 2002; Ghisellini 2003; Ghirlanda et al. 2003; Ryde 2004). So far different authors have been pointing to these inconsistencies between the standard optically thin synchrotron model and observations (e.g. Preece et al. 2002), and suggesting different alternative scenarios of the solution of this problem (Blinnikov, Kozyreva and Panchenko 1999; Medvedev 2000; Baring & Braby 2004). It turned out that the black-body radiation with $kT \sim 100$ keV is a physical model while the time-averaged non-thermal GRB spectrum is merely an empirical model (Ryde 2004, and other references therein).

Nevertheless, if these theoretical rather than observational statements (Piran 1996) on the possibility that all GRB spectra have high energy tails (1) and the observed GRB spectra are non-thermal (2), are true indeed, the fireball theory (Piran 1999, 1999a) with huge Lorentz factors is the only possible theoretical alternative. It should be admitted though that the standard optically thin synchrotron shock emission theory/model explains everything, except the observational spectra of GRBs themselves (Preece et al. 2002). But for all that, it was left out of account that these “target-photons” ($E_p < 511$ keV) are just the observed typical GRBs. So, it turns out that the main task, according to the standard model, is not the explanation of this observed soft GRB spectrum in terms of photons’ energy/frequency, but the investigation of rare cases of release of hard quanta with energy of more than or $\sim 1$ GeV. In this connection see the paper by Lithwick and Sari (2001) in which, as an alternative to the observed GRB spectrum, an “intrinsic spectrum” that has no cutoff at very high energies is suggested to be explained.

As a result, the origin of the observed and substantially soft GRB spectra with a big number of photons up to $\sim 1$ MeV remains not properly understood. It is especially incomprehensible against the background of conjurations about the huge gamma factor that is supposed to solve the compactness problem. But the question remains: why are mainly soft GRB spectra observed at ultrarelativistic motions of radiating plasma supposed in the fireball model? And what is more, sometimes the GRB spectra do not contain γ-ray quanta at all, as, for example, XRFs known already before 2000 (Heise et al. 2001). Thus, when solving the compactness problem, we somehow imperceptibly incurred another problem of strong contradiction between the ultrarelativistic Lorentz factor $\Gamma \sim 100-1000$ (with 100 MeV and 10 GeV photons) and observed soft ($\sim$ or $< 1$ MeV) γ-ray (GRB, XRR GRB) and X-ray (XRF) radiation of the most classical GRBs. Moreover, it is also important to point out here that the observed black-body prompt GRB radiation with a temperature $kT \sim 100$ keV (Ghirlanda et al. 2003; Ryde 2004) is inconsistent with the Lorentz factor $\approx 10^2 - 10^4$ for the reason that the mean observed temperature can easily exceed MeV in cosmological fireballs (Piran and Shemi 1993).

3. The threshold for $e^-e^+$ pair production depends on the angle between photon momenta

So, is there the compactness problem or not? If yes, then how is it solved? Are there any alternatives of its solutions besides the fireball with its huge Lorentz factor? Particularly, can we do with semi- (not ultra-) relativistic approximation when explaining observed GRB, XRR GRB and XRF spectra? Is the strong gamma-radiation beaming necessary and to what extent can the radiation in GRB, XRR GRB and XRF spectra be collimated? This section concerns another attempt to solve the old compactness problem.

Certainly, in 1998 there already were some discussions of radiation collimation, but mainly in terms of the same standard fireball theory. And it should be kept in mind that in this theory the term collimation refers to jets consisting of plasma, while the term beaming refers to radiation of the same optically thin plasma (Sari 2000). Of course, we could waste not much time for the discussion of Piran’s approach in the previous section, if it were not a circumstance that even before 1992 (i.e. before the BATSE/EGRET mission) the compactness problem was mentioned in connection with the famous burst of 1979 March 5
in the Large Magellanic Cloud. Already then a possibility of collimated γ-ray radiation in explanation of observed soft spectra was not excluded because the cross-section of electron-positron pair production \( \sigma_{\gamma^{-}\gamma^{+}} \) (and annihilation also) depends not only on energy, but on the angle between momenta of colliding particles.

Then there is a comment on the paper by Carrigan and Katz (1992) which has not been so often cited. In fact as early as at the beginning of the 1990th a lot of interesting was said in connection with collimation of γ-rays leaving the source with high photon density in it. It seems that just the collimation solves the problem (see below). The paper by Carrigan and Katz (1992) tells about modeling the observed GRB spectra allowing for the electron-positron pair production effects. These effects could produce effective collimation of the flux because of kinematics of the two-photon pair production: the opacity \( (\tau_{\gamma^{-}\gamma^{+}}) \) is also a sensitive function of the angular and spectral distribution of the radiation field in the GRB source.

Because of the importance of the photon angular and spectral distribution to the opacity, below an analysis of formula (1) for the threshold of the pair production processes from the paper by Carrigan and Katz (1992) is given. The argument proceeds as follows: two photons with energies \( E_1 \) and \( E_2 \), which are above the threshold energy \( (E_1 + E_2 > 2 \cdot E_{th}) \) for electron-positron pair production

\[
E_1 \cdot E_2 \geq 2(m_e c^2)^2 / (1 - \cos \theta_{12})
\]  

may produce a pair, where \( 2(m_e c^2)^2 = 2(511 \text{ keV})^2 \), \( \theta_{12} \) is the angle between the directions of the two γ-rays, and \( E_{th} = \sqrt{E_1 E_2} \). The cross section for pair production reaches the maximum at a finite center-of-momentum photon energy: e.g. \( E_1 + E_2 > 2 \cdot E_{th} = 2 \cdot 511 \text{ keV} \) for \( \theta_{12} = 180^\circ \), or \( E_1 + E_2 > 2 \cdot E_{th} \approx 2 \cdot 700 \text{ keV} \) for \( \theta_{12} \approx 90^\circ \), or \( E_1 + E_2 > 2 \cdot E_{th} \) tending to infinity \( (\gg 1 \text{ MeV}) \) for \( \theta_{12} \approx 0^\circ \). If the source photon spectrum is not sharply peaked, the relatively high-energy photons \( (E > E_{th}) \) will, therefore, form pairs predominantly with relatively low-energy photons \( (E < E_{th}) \). It means that the observed/released GRB spectra will be soft, since the high-energy photons will be held by the threshold of pair production. Thus, because any reasonable source spectrum will contain much more low- or moderate-energy photons \( (\lesssim 511 \text{ keV}) \) than high-energy photons, the emergent spectrum will differ most markedly from the source spectrum at high photon energies \( (E \gtrsim 1 \text{ MeV}) \) at which it (the emergent spectrum) will be heavily depleted. In other words, the observed (emergent) spectrum becomes softer. Then, the \( \gamma^{-}\gamma^{+} \) pairs eventually annihilate to produce two (infrequently 3) photons, but usually not one high- and one low-energy photon.

The result is that high-energy photons are preferentially removed from the observed spectrum. The observation of a measurable amount of flux with \( E > E_{th} = \sqrt{E_1 E_2} \) is not expected unless the optical depth \( \tau_{\gamma^{-}\gamma^{+}} \) to pair production is equal to 1 or less, because the threshold for electron-positron pair production (1) is also a sensitive function of the angular distribution of the radiation field (in the very source).

Thus, the observation of a considerable number of quanta with \( E > 1 \text{ MeV} \) due to the filter effect (1) is not expected, if only the optical depth for the \( e^{-}\gamma^{+} \) pair production is not proved \( \lesssim 1 \) indeed. As is seen from the paper by Carrigan and Katz (1992), in 1992 it was generally accepted that typical energies of most photons in observed GRB spectra are still rather small. Further in the paper, Carrigan and Katz adduce the estimates of distances to burst sources of such photons with the semirelativistic energies. The matter is that the problem of a compact source (in relation to the 1979 March 5 event in LMC) and a surprisingly big distance arises indeed. But not because of a problem with the release of “heavy” (100 MeV, 1 GeV, or more) ultrarelativistic photons which interfere with “light” \( (\lesssim 1 \text{ MeV}) \) target-photons observed in the GRB spectra. The powerful 1979 March 5 event in LMC was observed without any super heavy photons in its spectrum. To make sure of it one should just look at the spectra of this burst published by Mazets and Golenetskii in their review (1987).

To explain why the effect of the photon \( \gamma^{-}\gamma^{+} \) confinement does not function in this GRB source (1979 March 5 event in LMC), Carrigan and Katz discuss different possibilities. In particular, they immediately point out to the angle dependence (1) of the threshold of the \( e^{-}\gamma^{+} \) production. A possible “loophole” exists if the source produces a strongly collimated beam of photons. (Thus, the question is about an asymmetry of the radiation field in the source.) In this case, even high-energy photons are below the threshold for the pair production if \( \theta_{12} \) is small enough. The presence of such a “window” in the opacity for collimated photons suggests that in a region opaque to pair production much of the radiation may emerge through this window, in analogy to the great contribution of windows in the material opacity to radiation flow in the usual (Rosseland mean) approximation.

The use of the words “strongly collimated” in this (“old”) paper could be somewhat confusing. What means strongly indeed? At that time there were no observations of GRB spectra in the region of high energy \( E \). Heavier photons with \( E \sim 10 \text{ MeV} \) (beyond the peak of \( \sim 1 \text{ MeV} \)) have been reliably observed only with EGRET/BATSE. In particular, from formula (1) for such photons an estimation of the collimation angle can be obtained (without any “target-photons”): 

\[
1 - \cos \theta_{12} = 0.522245 \text{ MeV}^2 / (10 \text{ MeV} \cdot \text{MeV})
\]
10\,MeV) \approx 0.005. It corresponds to \theta_{12} less than 6 degree only. It means that the quanta with energy \sim 10\,MeV leaving the source within a cone of \sim 6^\circ opening angle do not give rise to pairs, and all softer radiation can be uncollimated at all. So the collision of 10 \,MeV quanta with quanta of lower energy occurs at angles greater than (0.522245 \,MeV^2/(10 \,MeV \cdot 100\,KeV) \approx 0.5) \times 60^\circ, and softer quanta leaving the source within the cone of such opening angle do not prevent neither heavy nor (especially) light quanta to go freely to infinity.

Thus, formula (1) demands more or less strong collimation only for a small part of the highest quanta radiated by the source. If one looks at energetic spectra of typical GRBs (the same reference to Mazets and Golentsevskii 1987) presented in the old way of \( F(cm^{-2}s^{-1}KeV^{-1}) \) vs. \( E(KeV) \) — the number of photons per a time unit in an energy range unit per an area unit versus the photons energy, — then everything becomes clear. Only a small part or a small amount of quanta/photons observed beyond a threshold of \approx 700\,KeV can be collimated, but within a cone of < 90^\circ opening angle :). At present, 6 degrees for 10 \,MeV quanta would not be considered as a strongly collimated beam. Now such opening angles (of jets) are considered to be quite suitable in the “standard” or the most popular theory of fireballs. If one proceeds right away from an idea that it is necessary to release quanta with the energy up to 10 \,MeV, then we would obtain at once a version of a collimated theory with the \Gamma of \sim 10. But such a way in the standard fireball theory is a dead end also. The allowing for an initial collimation of GRB radiation can drastically change this model (see below) for the collimation arising directly in the source but not because of a huge \Gamma of \sim 1000 what would be needed to solve the compactness problem.

One way or another, the light flux is to lead to corresponding effects of radiation pressure upon the matter surrounding the source. And if in addition the radiation is collimated, then the arising of jets (at so enormous light flux) becomes an inevitable consequence of even a small asymmetry of the radiation field in the source. But the question is if

4. Is the jet a GRB source or not?

Indeed, perhaps one should take into account right away this angular dependence of the threshold of the pair \( e^-e^+ \) production (1) before the ultra relativistic limit, allowing for a possibility of a preferential (most probably by a magnetic field) direction in the burst source on the surface of a compact object — the GRB source. Does a preferential direction in the source sound wrong? But one way or another, in the model of fireball with jets the radiating plasma is to be accelerated up to enormous velocities. What is the mechanism? In the fireball theory this question is not solved yet, and the origin of GRB spectra also remains incomprehensible. In the end, does the jet radiate by itself and is it the GRB source? That is the question. Can we do without the radiating and accelerated (nobody knows by what) jet up to a huge value of the Lorentz factor, by supposing that the source of GRB radiation is already collimated by the burst source itself? At least, the rather strong collimation of GRB \gamma-rays, reaching near-earth detectors, can be observably justified. The GRBs could be the beginning of the explosions of usual massive or core-collapse SNe (Sokolov 2001a, 2001b).

All results of photometrical and spectral observations of host galaxies confirm the relation between GRB and evolution of a massive star, i.e., the close connection between GRB and relativistic collapse with SN explosion in the end of the star evolution. (Here it is already possible to aduce a lot of references: Djorgovskii et al. 2001; Frail et al. 2002; Sokolov et al. 2001; etc.) The main conclusion resulting from the investigation of these galaxies is that the GRB host galaxies do not differ in anything from other galaxies with close value of redshifts \( z \): neither in colors, nor in spectra, star-forming rates, luminosities, and surface brightness. It means that these are the galaxies (“ordinary” for their redshifts) constituting the base of all deep surveys.

In point of fact, this is the main result of optical identification of GRBs with (ordinary) objects of already known nature: GRBs are identified with galaxies up to \approx 26 \,st. \,magn. With allowing for the results of direct optical identifications this makes it possible to estimate directly from observations an average yearly rate of GRB events in every such galaxy by accounts of these galaxies for the number of galaxies brighter than 26th \,st. \,magn. It turns out to be equal to \( N_{GRB} \sim 10^{-8}\,yr^{-1}\,galaxy^{-1} \). (But most probably this is only an upper estimate, see in Sokolov 2001b). Allowing for the yearly rate of (massive) SN explosions \( N_{SN} \sim 10^{-3} - 10^{-2}\,yr^{-1}\,galaxy^{-1} \), the ratio of the number of GRBs, related with the collapse of massive stars (core-collapse SNe), to the number of such SNe is close to \( N_{GRB}/N_{SN} \sim 10^{-5} - 10^{-6} \). Most likely, this is also only the upper estimate for Ib/c type SNe (Sokolov 2001a). Porciani & Madau (2001) obtained an analogous estimate: (1 – 2) \cdot 10^{-6} for II type SNe.

Here we proceed from the simplest assumption, which has been confirmed from 1998 by increasing number of observational facts, that all long-duration GRBs are related to explosions of massive SNe. Then the ratio \( N_{GRB}/N_{SN} \) should be interpreted as a very strict \( \gamma \)-ray beaming of quanta reaching an observer, when gamma-ray radiation (a part of it) of the GRB source propagates to very long distances
within a very small solid angle
\[ \Omega_{\text{beam}} = \frac{N_{\text{GRB}}}{N_{\text{SN}}} \sim (10^{-5} - 10^{-6}) \cdot 4\pi. \] (2)

Another possible interpretation of the small value of \( \frac{N_{\text{GRB}}}{N_{\text{SN}}} \) — a relation to a rare class of some peculiar SNe — seems to be less possible (or hardly probable), since then GRBs would be related only to the \( 10^{-5} - 10^{-6} \)th part of all observed SNe in distant galaxies (up to 28th mag). These are already not simple peculiar SNe, with which the Paczynski’s hypernova is sometimes identified (Paczynski 1999; Fields et al. 2002). Peculiar supernovae/“hypernovae”, such as 1997ef, 1998bw, 2002ap, turn out to be too numerous (Richardson et al. 2002; Podsiadlowski et al. 2004).

Now there are already other papers (Lamb et al. 2003a, 2003b, 2003c), pointing out to a possibility of collimated radiation from the GRB source (2). And the more numerous are GRB/SN coincidences of type of GRB 030329/SN 2003dh or GRB/“red shoulder” in light curves, the more confident will be the idea that GRB radiation is collimated, but not related to a special class of SNe/“hypernovae”. Many consider this term ("hypernovae") poorly defined and no longer use it. The more so, that explosion geometry (SN explosion can be axially symmetrical) makes the attempts to select a class of “hypernovae” more complex (Willingale et al. 2004, see the end of their text). Today there are more facts for the collimation (2), and we think that soon it will be accepted not only by Lamb et al.

Let us suppose that only the most collimated part of gamma radiation get to an observer, say, along a rotation axis of the collapsing core of a star with magnetic field. And if GRBs are so highly collimated, radiating only into a small fraction of the sky, then the energy of each event \( E_{\text{beam}} \) must be much reduced, by several orders of magnitude in comparison at least with a (so called) “isotropic equivalent” \( E_{\text{iso}} \), of a total GRB energy release (\( E_{\text{iso}} \sim 10^{51} - 10^{52}\text{ergs} \) and up to \( 10^{53}\text{ergs} \)):

\[ E_{\text{beam}} = \frac{E_{\text{iso}}}{4\pi} \sim 10^{45} - 10^{47}\text{ergs}. \] (3)

If it is just this case which is realized, and if the energy of \( \gamma \)-rays propagating in the form of a narrow beam reaching an observer on Earth is only a part of the total radiated energy of the GRB source (from \( \sim 10^{51}\text{ergs} \) to \( \sim 10^{49}\text{ergs} \)), then the other part of its energy can be radiated in isotropic (or almost isotropic) way indeed. But at the spherical luminosity corresponding to a total GRB energy of, e.g., \( \sim 10^{45} - 10^{47}\text{ergs} \), no BATSE gamma-ray monitor detector, even the most sensitive one, would detect flux, corresponding to so low luminosity for objects at cosmological distances of \( z \gtrsim 1 \), and if the observer is outside the cone of the collimated component of radiation (2). I.e. (3) can be close to the lower estimate of the total radiated energy of GRB sources, corresponding to the flux measured within the solid angle (2), in which the most collimated component of the source radiation is propagating. (We always suppose that all long-duration GRBs are related to SNe.)

So, in terms of observational results known today, there is a possibility at least to considerably reduce at once the total (bolometric) energy of GRB explosions even in the model with radiating plasma, i.e. with ultra relativistic jets in the standard fireball model. (Though we are sure that it is not plasma that radiates the GRB, and the jet is a consequence, but not the cause of GRBs. More will be said below.) Then it is possible to estimate the Lorentz factor \( \Gamma \) in the same standard theory with the radiating jet (the formula and relation with the \( \Gamma \) are taken from the paper by Piran (1999)). Even in the theory with the jet radiating GRB, but at the total energy of \( 10^{45}, 10^{47}, 10^{48}, 10^{49} \) ergs, the Lorentz factor \( \Gamma \) turns out to be equal to: \( 18, 32, 42, 56 \) correspondingly. But we do not think the authors of the standard solution of the compactness problem will ever agree to that, though here it is possible to speculate using the closeness of this estimate to what was mentioned above for the angle of collimation and the factor \( \Gamma \) of photons with energy of \( \sim 10\text{MeV} \) (see the end of the previous section). Maybe, Lamb and his co-authors (2003a, 2003b, 2003c) will do so, since they try to adjust the very small angle of the GRB collimation with the standard theory of the radiating jet. But in our opinion, there is only one alternative for the approach (Lamb et al. 2003c): the model (“A Unified Jet Model of X-Ray Flashes, X-Ray-Rich GRBs, and GRBs”) does explain observations, but with \( \Gamma \) of \( \sim 1 - 10 \). Then both the opening of jet and the angle of the GRB collimation are to be simply equal to each other for sure, and the GRB source is to be located in the very beginning, or in the “point” where the jet and radiation arise (see Fig. 5. b. in the paper by Lamb et al. 2003c). But this will be quite a non-standard theory.

Apparently, this question – what does radiate: a “point” or an extent jet? – is crucial for any GRB mechanism. If the GRB source radiation (mainly the hard component of the GRB spectrum) is collimated indeed, then we will have to return to the old idea: the radiation (GRB) arises on a surface (centimeters, meters?) of a compact object. (Perhaps, the radiation in an annihilation line will be also found again.) Further we will try to do without an (a priori) assumption that it is only the jet’s “end” which radiates. The jet is rather a consequence, than a cause. It arises for sure, but because of the strong pressure of the collimated radiation on the matter surrounding a compact (down to \( 10^{-7} \) cm and less) GRB source. Certainly, this jet accelerated by photons up to relativistic velocities will radiate also, but it would be
already an afterglow, but not GRB itself.

5. The radiation pressure and origin of the jet in the compact model of GRB

If the scenario: massive star $\rightarrow$ WR star $\rightarrow$ pre-SN $\rightarrow$ pre-GRB $\rightarrow$ the collapse of a massive star core with formation of a shell around WR is true, then it could be supposed that the reason for arising of a relativistic jet is the powerful light pressure of the collimated or non-isotropic prompt radiation of the GRB source onto the matter of the WR star envelope located immediately around the source itself — a collapsing core of this star.

We can digress for a while from the problem of the mechanism of arising of the GRB source itself and not discuss a question of how these collimated gamma-quanta arouse. For example, the radiation field arising around the source can be non-isotropic — axially symmetric due to magnetic field and effects of angular dependence (1) of the threshold of the $e^+e^-$ pair production. After all, for a while it is sufficient for us that only a part (\(\sim 10\%\) or even 1%) of the total GRB energy (\(\sim 10^{47} - 10^{49}\) erg) may be the collimated radiation, which breaks through the dense envelope surrounding the collapsing core of the WR star. (Then the prompt radiation reaches the Earth and is detected as the GRB.) The main thing now is the collimated flux of radiation from the source and a possibility of existence of dense gas (windy) environment pressed up by radiation from the GRB source embedded in it, and this environment can be the most dense just near the source, if the density is close to \(n = Ar^{-2}\) (the WR law for stellar wind). Here the distance \(r\) is measured from the WR star itself, and \(A \sim 10^{34}\) cm\(^{-1}\) (Ramirez-Ruiz et al. 2001).

For the force of light pressure that can act on gas environment (plasma) around the GRB source (the WR star) we have

\[
L_{GRB} \cdot (4\pi r^2)^{-1} \cdot (\sigma_T/c),
\]

where \(L_{GRB}\) is a so called isotropic luminosity equivalent of the source (\(\sim 10^{40-51}\) erg s\(^{-1}\) and more), \(r\) is a distance from the center (or from the source), \(\sigma_T = 0.66 \cdot 10^{-24}\) cm\(^2\) is the Thomson cross-section, \(c\) is the velocity of light. It is clear even without detailed calculation that near the WR core (\(r \sim 10^8\) cm) such a force can over and over exceed (by 12-13 orders!) the light pressure force corresponding to the Eddington limit of luminosity (\(\sim 10^{38}\) erg s\(^{-1}\) for 1 \(M_\odot\)).

In principle, the isotropic radiation with so huge luminosity \(L_{GRB} \sim 10^{40-51}\) erg s\(^{-1}\) (or the light pressure) can also lead to fast acceleration (similar to an explosion) of environment adjacent to the source. But if we assume that the radiation of the GRB source is non-isotropic and a part of it is collimated or we have very strong beaming with the solid angle \(\Omega_{beam} \sim (10^{-5} - 10^{-6}) \cdot 4\pi\), then the forming of directed motion of relativistic/ultra-relativistic jets becomes inevitable, only because of so huge/enormous light pressure affecting the dense gas environment in the immediate vicinity of the source — collapsing stellar nucleus. Naturally, the formation of jets depends also on degree of ionization, density and temperature of a medium in the immediate vicinity of the GRB source — an asymmetric collapsing nucleus of a massive star (Gorbatsky 2004, private communication). But we can estimate the size of the region within which such a jet can be accelerated by the radiation pressure up to relativistic velocities:

1. If the photon flux producing the radiation pressure accelerating the matter at a distance \(r\) from the center (near the GRB site) is equal to \(L_{GRB} \cdot (4\pi r^2)^{-1}\), then in the immediate vicinity from the GRB source (the collapsing nucleus of WR star) such a flux can be enormous. It is inside this region where the jet originates and undergoes acceleration up to ultra relativistic velocities.

2. To accelerate the matter up to velocity of at least \(\sim 0.3c\), at the outer boundary of this region the photon flux must be at least not less than the Eddington flux \(L_{Edd} \cdot (4\pi R_e^2)^{-1}\). Here \(L_{Edd}\) is the Eddington limit \(\sim 10^{38}\) erg s\(^{-1}\) for 1 \(M_\odot\) and \(R_e\) is the size of a compact object of \(\sim 10^6\) cm. (By definition: \(L_{Edd} \cdot (4\pi R_e^2)^{-1}\) is a flux stopping the accretion onto a compact source — the falling of matter on the source at a parabolic velocity. For a neutron star it is equal to \(\sim 0.3c\).)

From the condition that the photon flux \(L_{GRB} \cdot (4\pi r^2)^{-1}\) at distance \(r\) is equal to \(L_{Edd} \cdot (4\pi R_e^2)^{-1}\) (or at least not less than this flux), and taking into account that the luminosity or rather its isotropic equivalent of the GRB radiation is \(L_{GRB} \sim 10^{40-51}\) erg s\(^{-1}\), it is possible to obtain an estimate of the size of \(\sim 10^{12}\) cm \(\approx 14R_\odot\). At least, at this outer boundary the light pressure is still able to accelerate the initially stable matter up to sub-light velocities \(\sim 0.3c\). And deeper, at less distances than \(\sim 10^{12}\) cm from the source, say, at \(r \sim 10^9\) cm (somewhere inside the region of the size less than the characteristic size of collapsing core of the massive star) the light accelerates the matter up to ultra relativistic velocities with the Lorentz factor of \(\sim 10\) at \(L_{GRB} \sim 10^{50}\) erg s\(^{-1}\). It can occur in a rather small volume of the typical size of \(\lesssim R_\odot\), which, in particular, agrees with observations of the variable absorption feature observed simultaneously with GRB 990705 in its BeppoSAX/WFC spectrum (Amati et al. 2000). Thus, inside the region of a size of less (in any case) than \(10 - 15R_\odot\), a relativistic jet arises as a result of the strong light pressure onto the ambient medium.

Certainly, the question about deceleration of such a jet in circumstellar medium of the star progenitor should be considered separately. But perhaps the
strong deceleration due to interaction of the relativistic shock with ambient medium does not arise (as in the fireball model) even at very high densities of this matter around the WR star (up to $n \sim 10^{10} \text{ cm}^{-3}$ for $r \sim 15R_\odot$) because the compact relativistic jet (or “bullet”) is decelerating but not the shock, what is in the model by Panaitescu (2001, Panaitescu & Kumar 2001, 2002). Here there is no such a wide “bulldozer” — a shock wave raking up the matter and, correspondingly, there is no or almost no effective deceleration of “the bullet” as it moves towards less dense matter (with $n = A r^{-2}$) around the massive core of WR star. That is why due to the small deceleration and small radiation losses (but with a large initial momentum), this “bullet” can move at a relativistic speed with the same Lorentz factor $\Gamma$ of $\sim 10$ all the time while the transient (or the GRB afterglow) is observed, i.e. over all its light curve with its peaks or breaks. The shocks, which arise as the jet moves through, only heat this medium and then are radiated in X ray, in optical, in radio where this medium is still dense enough + non-uniformities in distribution of $n(r)$ at distances $\sim 10^{15} - 10^{17}$ cm from the source (Sokolov 2001b).

Below is the list of basic assumptions of the scenario describing the GRB source with energy of order $10^{47} - 10^{48}$ ergs and non-empty space near a massive star progenitor:
1. Around the WR star progenitor of GRB source, from a distance of $\lesssim 10^9$ cm (the typical size of a massive star core) up to $r \gtrsim 10^{15}$ cm (the distance where the interaction between WR wind and ambient/circumstellar medium begins), there is a dense or windy medium — an envelope resulting from the evolution of massive star.
2. The huge light pressure is the cause of the arising of the jet in the region of $\sim 10^9$ cm to $\sim 2 \cdot 10^{11}$ cm, i.e. where the envelope density ($\sim 10^{15} - 10^{10} \text{ cm}^{-3}$) is the highest, but the optical depth for Thompson scattering can be already less than 1 ($\tau \sim \sigma_T \cdot n \cdot r < 1$).
3. The burst itself, probably an almost spherically symmetrical “GRB-explosion”, with a total energy up to $\sim 10^{49}$ ergs arises somewhere in the volume of size $\sim 3 \cdot 10^9$ cm, or at even a smaller depth of $\sim 10^8 - 10^6$ cm, i.e. where the WR law $n = A \cdot r^{-2}$ (for the stellar wind) ceases to be valid. It is possible that the explosion/burst occurs directly on the surface of a compact object, resulting from massive star core collapse.
4) Only the most collimated radiation part of the GRB source propagating within the solid angle of $\Omega_{\text{beam}} \sim (10^{-5} - 10^{-6}) \cdot 4\pi \text{sr}$ goes to infinity, and for all that the total energy of the source is either of the same order as $E_{\text{beam}} = E_{\text{iso}} \Omega_{\text{beam}} / 4\pi \sim 10^{45} - 10^{47}$ ergs or about $10^{49}$ ergs.

Now we can return again to the question about collimation of photons arising on the surface of the compact object. The pairs production will not prevent the photons with wave vectors within a solid angle of the opening of $\theta_{12}$ for $(1 - \cos \theta_{12}) < 2(m_e c^2)^2 / E_1 \cdot E_2$ from free exiting to infinity. The threshold $E_{\text{th}} = \sqrt{E_1 E_2}$ inside this solid angle at small $\theta_{12}$ (for $\sqrt{E_1 E_2 / 2} \gtrsim 511 \text{ keV}$) is very high, and all photons with energies below $E_{\text{th}}$ will freely exit through this “window” in opacity for collimated photons. An initial spectrum of the GRB source is almost what is observed, still the filter (1) affects the most violently the hard range of the observed GRB spectrum — it was mentioned above (Carrigan and Katz 1992). And one should not try “to invent” at once a special mechanism of a very sharp collimation/“channeling” of all photons. It was also mentioned above.

Thus, it is undoubtedly that the GRB radiation is to be collimated, but the collimation (2) concerns mainly only a small part of hard quanta. The pairs production threshold for such quanta naturally and smoothly, according to the law $(1 - \cos \theta)^{1/2}$ rises with the decreasing of the angle between the direction at which the photon is radiated from the surface of the compact object and a selected direction (e.g. the magnetic field) on the surface. As a result, beside a soft component, the more and more hard part of the burst spectrum is passing through, and it is possible to suggest non-isotropic (axially symmetrical) field of radiation around the source. Then, in particular, it is clear why XRF and XRR GRBs are uncollimated completely or rather almost isotropic (Lamb et al. 2003).

And what are typical sizes accepted in the standard model? In the paper by Beloborodov (2004) namely the early stages of the GRB explosion are considered. This is just the standard view: GRB afterglow is explained as emission from a decelerating blast wave. The deceleration begins at $R_{\text{dec}} \sim 10^{15} - 10^{17}$ cm. It depends on the ambient density and initial Lorentz factor. So, $R_{\text{dec}}$ is a fireball size before the deceleration begins. And $R_{\text{dec}}$ does not exceed $10^{17}$ cm. In this theory this is actually the size of the region where the GRB prompt emission ($\gamma$-ray burst) with the observed spectrum arises: $\sim 10^{15} - 10^{17}$ cm. Further it is already a zone where the afterglow arises — hours and days after the prompt GRB.

But as was said above, allowing for the influence of the angle between photon momenta in the source on the threshold of $e^- e^+$ pair productions, it is possible to assume that the GRB radiation arises in the region 10 orders smaller. But then there must be quite different physical conditions providing the GRB source energy release.
6. Possible mechanisms of GRB phenomenon in the compact model

Certainly, after all, one should think about the main thing: to assume and investigate a physical mechanism explaining the GRB origin on the surface or close to an object of type of neutron star (NS) or quark/strange star. All possible versions of energy output onto the surface of a compact object or of explosions related somehow to this object should be considered, see the reviews by Bisnovatyi-Kogan (2003, 2004). Below we are examining in outline some of the compact mechanisms of the GRB energy release.

A mechanism of the GRB origin in the vicinity of a collapsing object based on neutrino-antineutrino annihilation was analyzed by Berezinsky and Pritutsky (1987). Earlier GRB production in a SN explosion under the action of neutrino pulse was suggested by Bisnovatyi-Kogan et al. (1975). The starquake, subsequent explosion and outburst from a non-equilibrium layer in the neutron star crust, discovered by Bisnovatyi-Kogan and Chechetkin (1974), is accompanied by gamma radiation due to fission of the ejected super heavy nuclei. This scenario was suggested (Bisnovatyi-Kogan et al. 1975) as an alternative model for GRBs of galactic origin, but now it can be claimed again in the compact GRB model under consideration. As was obtained by Brezinsky and Pritutsky (1987), the efficiency of transformation of the neutrino flux energy \( W_\nu \sim 6 \cdot 10^{53} \) ergs into X-ray and \( \gamma \)-ray energy release of \( W_{\gamma,\gamma} \sim 3 \cdot 10^{48} \) ergs. This is in agreement with the total energy of the GRB source of \( 10^{47} \sim 10^{49} \) ergs in the compact GRB model, with accounts for strong beaming (2).

One of quite well developed mechanisms of compact energy output in the vicinity of the collapsing object (magnetorotational explosion) was suggested for the SN explosion (Bisnovatyi-Kogan 1971). Numerical calculations of the explosion in magnetized rotating gas could give an efficiency of transformation of the rotational energy into kinetic at a level of 10 percent (Ardeljan et al. 2000). Some results of 2-D calculations of the magnetorotational explosion produced by rapidly and differentially rotating, strongly magnetized new-born NS are given by Moiseenko et al. (2003). The energy output is sufficient for the SN explosion, but seems to be low for the total “standard” X-ray and \( \gamma \)-ray energy release of \( \sim 10^{51} \sim 10^{53} \) ergs in the standard fireball GRB model.

Thus, the very idea of existence of strong global magnetic fields in the region of cosmic GRBs generation has already been given many times (see also papers by Usov 1994; Thompson 1994; Meszaros and Rees 1997; Blandford 2002). In this connection another mechanism of compact energy output or of the origin of cosmic GRBs resulting from a decay of magnetized vacuum around NS with such a field can be suggested. Here the energy of order \( 10^{47} \sim 10^{49} \) ergs for the source of GRB in the compact GRB model corresponds well to the value of vacuum energy near NS with a super strong field \( B \sim 10^{15} \sim 10^{16} \) G on condition that the star surface undergoes oscillations (Gnedin 2004). One can suppose that such oscillations (or starquakes) occur at the moment when the NS (or a new-born NS) is being formed as a result of the massive core collapse of a star progenitor. The value of the vacuum energy released in this case depends on both amplitude and frequency of such oscillations. A possibility of decay of the vacuum in a super-strong magnetic field is now discussed rather actively (Calucci 1999; Xue 2003; Rojas and Querts 2004; Metalidis and Bruno 2003). The idea of the decay of the strongly magnetized vacuum in the vicinity of NS with a super-strong magnetic field for explanation of the phenomenon of cosmic GRB was first stated by Gnedin and Kiikov (2001), and the first energy estimates were also obtained there. The energy accumulated in strongly magnetized vacuum is quite sufficient to provide the GRBs energy output in the process of decay of such vacuum. Here the proper oscillations of the NS surface can be a triggering mechanism of such a decay. The result can be a perfect realization of the following chain: the collapse of a massive star core — oscillations of the surface of a new-born NS — the collapse of magnetized vacuum with the energy output. But the main question remains: how the energy of magnetized vacuum is transformed into radiation? One of the possible solutions of this problem based on analogy with the phenomenon of sonoluminescence is suggested in the paper by Gnedin and Kiikov (2001). But the probability of such a process demands a separate special consideration (Gnedin 2004).

Two giant flares were observed on March 5, 1979 and August 27, 1998 from (so-called) soft \( \gamma \)-ray repeaters SGR 0526-66 and SGR 1900+14, respectively. The peak luminosity of these flares was as high as \( \sim 10^{45} \) erg s\(^{-1}\) (Mazets & Golenetskii 1987; Hurley et al. 1999). It will be recalled that the problem of GRB source compactness arose just in the explanation of the 1979 March 5 event (Carrigan & Katz 1992) with the huge luminosity and with the very short observed rise time (to \( 10^{-3} \) s). Such a bursting activity of the SGRs can be explained by the fast heating of the bare surface of a strange star and its subsequent thermal emission (Usov 2001). The heating mechanism may be, for example, the fast decay of super-strong \( \sim 10^{15} \sim 10^{16} \) G magnetic fields. The energy output mechanism in this Usov’s model can be advantageously used to explain the long-duration (cosmological) GRBs in the compact model with the small collimation of the prompt GRB radiation with
strong beaming (2) for γ-rays. In this case, GRBs should be considered as a set of short bursts (like the giant flares of the 1979 March 5 and 1998 August 27 events) with a total GRB duration of \( \sim 10^2 - 10^3 \) s. From the said above in this section it is seen that the attempts to explain GRBs by physics related with a massive compact object have already a rather long history. This experience can be used for detailed development of the compact model of GRB source or GRB scenario with the compact energy output allowing for what was said in the previous sections of our paper about observational and theoretical arguments in favor of such an attempt to solve the problem of the GRB source compactness.

7. Concluding remarks

So, XRFs can be not collimated at all or slightly collimated (XRR GRB), but with the low total bolometric energy of \( \sim 10^{47} \) ergs. Since most probably these are actually the explosions of massive SNe at distances of 100 Mpc (Norris 2003; Norris & Bonnel 2003), they can be observed much more frequently than it is predicted by the standard fireball GRB model. One should try to find early spectral and photometrical SN features. Then, in general, the observational problem of XRF/XRR/GRB identification becomes a special section in the study of cosmological SNe. (It will be recalled that the GRB 030329/SN 2003dh was a XRR GRB but not a classical GRB.)

As to normal/classical GRBs and especially those ones with many heavy quanta in spectra, it is possible to obtain directly from formula (1) a (kinematical) estimate of the limit collimation of this gamma radiation, which, in turn, independently agrees with the observational ratio (2) of the yearly rates \( N_{GRB}/N_{SN} \sim 10^{-5} - 10^{-6} \). If the matter concerns quanta with \( E \sim 100 MeV \) of distant and the most distant GRBs, then from \( 1 - \cos \theta_{12} \approx 0.5 MeV^2/(100 MeV \cdot 100 MeV) = 0.5 \cdot 10^{-4} \) it follows that the radiation of such GRBs turns out to be the most collimated. Such photons must be radiated in the cone of an opening of \( \approx 0.5^0 \) and be detected in the spectra of the rather distant GRBs with \( z \approx 1 \) and farther because of geometrical factor only.

Thus, a natural consequence of our compact model of the GRB source is the fact that distant bursts (\( z \gtrsim 1 \)) turn out to be harder ones, while close “GRBs” (\( z \sim 0.1 \)) look like XRF and XRR GRBs with predominance of soft X-ray quanta in their spectra (though the factor 1 + z also works). Naturally, the effects of observational selection due to finite sensitivity of GRB detectors should be also taken into account. For example, the soft spectral component of the distant (classical) GRBs is “cut” out by the detector sensitivity threshold. And the isotropic X-ray burst, simultaneous with the GRB, can be simply not seen in distant (classical) GRBs because of the low total/bolometric luminosity of the source in the compact GRB model (< \( 10^{49} \) ergs). Actually, XRF and XRR GRBs have lower values of \( E_{iso} \) (so called isotropic equivalent), than GRBs (Amati et al. 2002; Lamb et al. 2003a, 2003b, 2003c).

As a result, only radiation within a narrow solid angle near a selected direction (in the GRB source) is observable for GRB detectors: the soft spectral range remainder for the prompt XRR GRBs with \( z \lesssim 1 \) (having climbed over the equipment threshold) and hard (and even heavy) quanta below the threshold of the pair production (1) for classical GRBs with \( z \gtrsim 1 \). (Close XRFs with \( z \lesssim 0.1 \) can not have the γ-ray quanta in their spectra at all for the definite equipment threshold). Though from the review by Postnov (1999) it follows that “typical” GRBs are seen in the range of 30 keV — 100 MeV, but it turns out (and it was known before) that most GRBs are much softer (see Sect. 2). Not without reason Lamb et al. (2003) were just amazed by this important observational result of BeppoSAX and HETE-2 missions. We mean the detection of obvious XRFs and XRR GRBs first by BeppoSAX (Amati et al. 2002) and then by HETE-2. In our compact model of GRB source it (the Amati law) can be a “simple” consequence of formula (1) + collimation (most probably) by magnetic field on the surface of the compact object.

In the scenario of jet formation, which was discussed in this paper and which was also used to interpret the GRB 970508 optical transient (OT) light curves (Sokolov 2001b) an isotropic X-ray, optical and radio emission of the afterglow of the GRB OT is possible. In X-ray lines (Piro et al. 1999; Yoshida et al. 2001; Piro et al. 2000; Antonelli et al. 2000) it was so for sure. At that an initial assumption was just a possibility of the small GRB collimation (2), which follows from the comparison of the rates of GRBs and SN explosions in distant galaxies. It means that the close relation between GRBs and SNe was taken as a basic assumption. All long GRBs are always accompanied by SN explosions, which are sometimes observed, and sometimes not (Sokolov 2001a, 2002). In other words, the long GRB is the beginning of a massive star collapse or the beginning of SN explosion, and GRBs must always be accompanied by SN explosions (of Ib/c type or of other types of massive SNe). Then in any case the total energy release at the burst in γ-rays can be not more than the total energy released by any SN (< or \( \sim 10^{49} \) ergs) in all electromagnetic waves. (It is interesting that the total energy release in X-ray emission lines observed with BeppoSAX, ASCA, Chandra for GRB 970508, GRB 970828, GRB 991216, GRB 000214 is of the same order — see the collected data in the paper by Ghisellini et al. (2002) “Emission lines in GRBs constrain the total energy reservoir.”)
But with so “low” total energy of the GRB explosion ($\lesssim 10^{49}$ ergs) the only possibility to see GRB at cosmological distances ($z \gtrsim 1$) is the detection of at least the most collimated part of this energy ($1 - 10\%$) leaving the source within the solid angle of $\Omega_{\text{beam}} \sim (10^{-5} - 10^{-6}) \cdot 4\pi$. The rest can be inaccessible for GRB detectors with a limit sensitivity of $\sim 10^{-7}$ erg s$^{-1}$ cm$^{-2}$. Certainly, it does not concern the 10 000 times more sensitive X-ray telescopes which were used to make sky surveys with the Ariel V, HEAO-1, Einstein satellites (Heise et al. 2001). For limit sensitivity of $\sim 10^{-11}$ erg s$^{-1}$ cm$^{-2}$ in the band of 0.2–3.5 keV the X-ray observatory (Einstein) recorded Fast X-ray Trasients (unidentified with anything) at a rate of $\sim 10^6$ yr$^{-1}$ all over the sky. It agrees well with an average rate of the massive SNe explosions in distant galaxies, but for the present, GRB-detectors see only $\sim 10^{-7}$ part of this huge number of the distant SN explosions as GRBs.

It is natural that at the total/bolometric energy of “GRB” $\sim 10^{47} - 10^{49}$ ergs and at the GRB energy (3) released in the narrow cone (2), “the fireball” also looks quite a different way. As to the compactness problem solved by the fireball model for GRB energies of $10^{52} - 10^{53}$ ergs, there is no such a problem for “γ-burst” energies $\sim 10^{47} - 10^{49}$ ergs. In any case, allowing for the low γ-ray collimation from the surface of the compact object – GRB/XRR/XRF source, which is necessary for the angular dependence of $e^+e^-$ pair production (1), this problem is solved under quite beam of at least the most collimated part of this energy at cosmological distances ($z \gtrsim 1$).

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