A DIRECT TEST OF THE COSMOLOGICAL MODEL FOR COSMIC GAMMA-RAY BURSTS BASED ON PEAK ALIGNMENT AVERAGING

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ABSTRACT

The cosmological origin of cosmic gamma-ray bursts is tested by using the method of peak alignment for the averaging of time profiles. The test is applied to the basic cosmological model with standard sources, which postulates that the difference between bright and dim bursts results from the different cosmological redshifts of their sources. The average emissivity curve (ACE_{bright}) of a group of bright BATSE bursts is approximated by a simple analytic function that takes into account the effect of the squeezing of the time pulses with increasing energy of photons. This function is used to build the model light curve for ACE_{dim} of dim BATSE bursts, which takes into account both the cosmological time-stretching of the light curves of bursts and the redshifting of photon energies. Direct comparison between the model light curve and the ACE_{dim} of dim bursts is performed, based on the estimated probabilities of differences between ACEs of randomly selected groups of bursts. The comparison shows no evidence for the predicted cosmological effects. The 3 σ upper limit of the average redshift z_{dim} of emitters of dim bursts is estimated to be as small as ~0.1–0.5, which is not consistent with values of ~1 predicted by current cosmological models of gamma-ray bursts.

Subject headings: cosmology: theory — gamma rays: bursts

1. INTRODUCTION

The cosmological model of cosmic gamma-ray bursts is commonly accepted as one of the most promising concepts concerning the origin of gamma-ray bursts (GRBs). However, it has not yet been conclusively verified by observational data. Two critical tests have been suggested to verify the basic model with standard cosmological sources: dim bursts have to be time-stretched and redshifted in comparison with bright events.

Gamma-ray bursts are known to have very different time histories, and one can hardly check the cosmological effects by direct comparison with particular events. These tests should be based on some averaged time- and spectrum-based signatures that represent the basic properties of GRBs. Several statistical tests have already been implemented to compare different groups of GRBs and to resolve the predicted cosmological effects. In the case of time dilation, two scientific groups have checked the average emissivity curves (ACEs) derived from the peak alignment averaging of bright and dim bursts. These groups reached opposite conclusions: time dilation of dim bursts was observed by one group (Norris 1994; Norris et al. 1994, 1996; Bonnell et al. 1996) but not by the other (Mitrofanov et al. 1992a, 1992b, 1994, 1996). Possible reasons for disagreement have been discussed (Band 1994; Mitrofanov et al. 1996), and the tentative conclusion has been drawn that the claimed dilation of dim bursts possibly resulted from something systematic in the separation of bright and dim groups of events.

On the other hand, in the case of spectral redshift, all groups involved reached a consensus that the averaged spectral hardness of bright GRBs is larger than that of dim events. This has been referred to as the effect of a hardness/intensity correlation (Mitrofanov et al. 1992b, 1992c, 1994, 1996; Paciesas et al. 1993; Norris 1994; Norris et al. 1994). While this effect was originally observed for the average hardness ratio (defined as the ratio of counts at high and low energy channels), it has been recently found also for the average peak energy \( \langle E_p \rangle \) of \( \nu F \), energy spectra (Mallozzi et al. 1995). The average \( E_p \) of the integral spectra of photons was found to correlate with the photons' peak fluxes \( F_{\text{max}} \) at the 256 ms timescale. The effect of the hardness/intensity correlation may be interpreted as a result of cosmological redshifting of dim gamma-ray bursts with respect to bright events. The corresponding cosmological redshift factor, about 1.6–2.2 (Mallozzi et al. 1995), is consistent with original cosmological models based on the interpretations of the log \( N \)--log \( F \) distribution (see, e.g., Emslie & Horack 1994). Therefore, there is a discrepancy between different groups regarding the time dilation of dim GRBs with respect to bright bursts, but on the other hand, there is agreement between them for the hardness/intensity correlation.

Separate pulses of GRBs are known to squeeze with increasing energy of photons (Norris et al. 1986; Fenimore et al. 1995), and therefore, the average curve of emissivity becomes narrower at higher energies (Mitrofanov et al. 1996). According to the cosmological model, when bright and dim bursts are detected at the same energy band in the observer's frame of reference, their time profiles were actually emitted at less hard and at harder energy ranges in comoving frames of reference, respectively. Therefore, in making a comparison between bright and dim bursts from sources with small and large redshifts, one should suppose that the intrinsic squeezing of the light curves of dim bursts due to the increase of energy of the emitted photons could partially compensate for their stretching due to the cosmological time dilation.

This paper provides a test of the basic cosmological models of GRBs and assumes them to be standard sources. It uses the average emissivity curves for groups of bright and dim bursts and takes into account the effects of cosmological time-stretching in the observer frame together with the internal energy-dependent squeezing of bursts' light curves in the comoving frames.
2. ANALYTIC APPROXIMATION OF THE AVERAGE CURVE OF EMISSIVITY FOR A GROUP OF BRIGHT GRBs

The average curve of emissivity of GRBs was introduced (Mitrofanov et al. 1994, 1996) as a general signature of the time variability of bursts. To build an ACE, all time histories of averaging bursts should be normalized by peak numbers of counts $C_{\text{max}}$, aligned at their peak bins $t_{\text{max}}$, and then averaged at all bins along the time scale. Comparison between the first, second, and third BATSE catalogs (Fishman et al. 1994; Meegan et al. 1994, 1996) has shown that the ACE has a rather stable shape: it has one peak profile with a steep rise front and gentle back slope, and its width decreases with increasing energy of photons used for averaging (Mitrofanov et al. 1994, 1996).

For the present analysis, DISCLA data were used from the large-area BATSE detectors (LADs) with 1024 ms time resolution on three discriminator channels, numbers 1 (25–50 keV), 2 (50–100 keV), and 3 (100–300 keV). Two basic intensity groups of BATSE GRBs were selected from the third BATSE catalog (3B; Meegan et al. 1996): 296 bright bursts with $F_{\text{int}} \geq 1$ photon cm$^{-2}$ s$^{-1}$ and 332 dim events with $F_{\text{int}} < 1$ photon cm$^{-2}$ s$^{-1}$. Only bursts with $t_{90} > 1.0$ s were taken for consideration.
The group of bright bursts is used as the reference sample to find the analytic approximation of ACE_{bright} at three discriminator channels (Fig. 1). The function

$$f_{\text{bright}}(t) = \left( \frac{t_i^{(0)}}{t_i^{(0)} + |t - t_{\text{max}}|} \right)^{a_{\text{RF}}(j)} a_{\text{RF}}^{(0)} w_{\text{RF}}^{(0)}$$

approximates ACE_{bright} profiles at each discriminator channel, $i = 1, 2, 3$, with a power index of $a_{\text{RF}}(j)$ at the rise front (RF), $t < t_{\text{max}}$, and $a_{\text{BS}}(j)$ at the back slope (BS), $t > t_{\text{max}}$, respectively. Instead of three different functions (eq. [1]) for each of three channels, a single function $f_{\text{bright}}(t, E)$ could be implemented that approximates the shape of ACE_{bright} at different energies $E$ and that corresponds to these channels:

$$f_{\text{bright}}(t, E) = \left[ \frac{t_{\text{bright}}(E)}{t_{\text{bright}}(E) + |t - t_{\text{max}}|} \right]^{a_{\text{RF}}(j) a_{\text{BS}}^{(0)} w_{\text{BS}}^{(0)}}$$

where the functions

$$t_{\text{bright}}(E) = a_{\text{RF}}(j) t_{\text{bright}}(E/|t|) + a_{\text{BS}}(j) t_{\text{bright}}(E/|t|) + a_{\text{BS}}^{(0)} t_{\text{bright}}(E/|t|)$$

represent the change of ACE_{bright}'s shape with energy. A difference between three observed ACE_{bright} profiles (Fig. 1) and the model approximation (eq. [2]) could be evaluated by using the function

$$S_{\text{bright}} = \sum_i \sum_j \frac{[\text{ACE}_{\text{bright}}(i, j) - f_{\text{bright}}(t_i, E_j)]^2}{\sigma^2(\text{ACE}_{\text{bright}})}$$

where $E_j$ corresponds to the mean energies at three discriminator channels $i = 1, 2, 3$ and $t_i$ corresponds to the time bins of ACE curves for $j = -19$ to $j = 19$. Errors concerning observed ACE profiles were estimated from the sample variance. The parameters of approximation $a_{\text{RF}}^{(0)} = 1.80^{+0.33}_{-0.28}$ s, $a_{\text{RF}}^{(0)} = 1.31^{+0.13}_{-0.12}$, $a_{\text{BS}}^{(0)} = 1.10^{+0.10}_{-0.09}$, $x_1 = -0.10 \pm 0.16$, and $x_3 = 0.06 \pm 0.09$, and $x_3 = 0.11 \pm 0.08$ were estimated from the best-fitting of all three ACE_{bright} profiles at channels $i = 1, 2, 3$. This fitting leads to the minimum $S_{\text{bright}}$ in equation (6), which corresponds to a rather small value of the Pearson criterion: a reduced $\chi^2$ of 0.66 for 108 degrees of freedom. Therefore, one might conclude that equation (2) offers a rather good approximation of the observed ACE_{bright} profiles for the basic group of bright bursts in a broad energy range, from 25 to 300 keV. On the other hand, rather small values of the reduced $\chi^2$ points out that the errors of ACE_{bright} were probably overestimated by the sample variance algorithm, or that there was some correlation between them.

However, the Pearson criterion allows us to determine the confidence region for the estimated parameters of the fitting function (eq. [2]). According to Lampton, Margon, & Bowyer (1976), the confidence region for the significance level $\lambda$ could be determined by the five-dimensional contour $S_{\text{contour}}$ in the six-dimensional parameter space, which is given by the equation

$$S_{\text{contour}} = S_{\text{bright}}^{(\text{min})} + \chi^2(\lambda)$$

where $\chi^2(\lambda)$ represents the value of the $\chi^2$ distribution for significance $\lambda$ for 6 degrees of freedom. The $\pm 1$ $\sigma$ errors for each of the six parameters, presented above, were estimated from the condition that equation (6) for $S_{\text{bright}}$ equals $S_{\text{contour}}$ when the parameter goes up and down from the best-fitting value, while another five parameters are used as free parameters for minimization. Therefore, each of these 12 points could be interpreted as $\pm 1 \sigma$ deviations from the minimum point along the axes of corresponding parameters inside a five-dimensional contour $S_{\text{contour}}$.

Actually, these 12 points in the six-dimensional parameter space correspond to 12 fitting models (eq. [2]) of the ACE_{bright} curves. Were they taken all together, they would present the $\pm 1$ $\sigma$ corridor of analytic approximations around the best-fitting model that leads to $S_{\text{bright}} = S_{\text{contour}}$. The boundary curves of this corridor are presented in Figure 1. One can see that all these models provide a rather good approximation of all three ACE_{bright} profiles measured at the three energy discriminators.

3. COMPARISON BETWEEN THE AVERAGE EMISSIVITY CURVES FOR DIFFERENT GROUPS OF BURSTS

Particular gamma-ray bursts are known to have very different time histories and energy spectra. Therefore, ACE curves could vary for particular groups of bursts randomly selected from the total database. Groups with $N_{\text{rep}}$, bursts could be defined as representative samples, provided the differences between their ACEs were comparable to the errors from the sample variance for each group. For smaller groups with $N < N_{\text{rep}}$ a difference between ACE curves could be significantly larger than would be expected from the sample variance. Therefore, the comparison of ACEs of different groups has to take into account the actual distribution of differences between ACE profiles due to a random choice of contributing bursts.

The size of the representative sample of time histories of GRBs is unknown, but from the comparison by Mitrofanov et al. (1997) of ACE curves from the 1B, 2B, and 3B databases, it appears that $N_{\text{rep}}$ could be about the presently available number of bursts, $\sim 10^3$. As was found there, the Pearson criterion provides a rather sensitive test to measure differences between ACEs for any two groups of bursts, namely, groups I and II, at any discriminator channel $j$:

$$S_{\text{contour}}^{(j)} = \sum_j \frac{[\text{ACE}_{\text{bright}}(i, j) - \text{ACE}_{\text{bright}}(j)]^2}{\sigma^2(\text{ACE}_{\text{bright}}(i, j))}$$

The magnitude $S_{\text{contour}}^{(j)}$ was used to compare ACE profiles for randomly selected groups of events. It was found that
groups with \( N \) increasing from \( \sim 30 \) up to \( \sim 300 \) became more and more representative with respect to the full set. In particular, the probability distribution \( P_{300}^{(2)}(S_{\text{dim}}) \) at discriminator \( i = 2 \) was obtained from \( 10^5 \) random choices of two groups with \( N = 303 \) among the total 3B set of 638 BATSE bursts (Fig. 2). This distribution does not depend significantly on the intensity of selected bursts, because the main contribution to \( S_{\text{dim}} \) is the actual difference of their time histories.

Thus, equation (8) could be used for direct comparison between ACE profiles of groups of bright and dim bursts, and the significance of a physical difference \( S \) between them could be estimated as the probability of obtaining \( S \) greater than \( S_{\text{dim}} \) according to the distribution \( P_{300}(S_{\text{dim}}) \) provided by the Monte Carlo random choice test (Fig. 2). This probability distribution will be used below to compare the analytic model, based on the ACE_{bright} of bright bursts, and the actual ACE_{dim} measured for the group of dim events.

4. DIRECT COSMOLOGICAL TEST BASED ON THE ANALYTIC APPROXIMATION OF THE AVERAGE CURVE OF EMISSIVITY

The simplest test of cosmological model of GRBs could be based on the standard candle assumption, which means that at all cosmological distances all sources have the same properties in their comoving frame. This basic version of the cosmological model assumes that all groups of bursts should have the same ACE provided that they were averaged in comoving frames. Therefore, any difference between the ACEs of bright and dim bursts measured in the observer frame should indicates the cosmological effects.

Let us assume that the emitters of bright and dim bursts have average redshifts \( z_{\text{bright}} \) and \( z_{\text{dim}} \), respectively. If two standard sources at \( z_{\text{bright}} \) and \( z_{\text{dim}} \) emit bright and dim bursts with photon energy \( E_{\text{bright}} \) and variability timescale \( \tau_{o} \), they would be detected in the observer frame at energies \( E_{\text{bright}} = E_{o}/(1+z_{\text{bright}}) \) and \( E_{\text{dim}} = E_{o}/(1+z_{\text{dim}}) \) and with variability at timescales \( \tau_{\text{bright}} = \tau_{o}(1+z_{\text{bright}}) \) and \( \tau_{\text{dim}} = \tau_{o}(1+z_{\text{dim}}) \), respectively. The so-called stretching factor can be introduced:

\[
Y(z_{\text{bright}}, z_{\text{dim}}) = (1 + z_{\text{dim}})/(1 + z_{\text{bright}}),
\]

which equals the ratio of energies of photons \( E_{\text{bright}}/E_{\text{dim}} \) and/or the ratio of variability timescales \( \tau_{\text{dim}}/\tau_{\text{bright}} \) at the observer frame of reference, provided they are the same in comoving frames.

To test the basic cosmological model, the analytic approximation \( f_{\text{bright}}(t, E) \) (eq. [2]) should be transformed into the model function \( f_{\text{dim}}(t, E) \) according to cosmological redshifting and time-stretching transformations, which has to represent the measured ACE_{dim} profiles for the group of dim bursts. According to the assumption of standard candles, one can postulate

\[
f_{\text{dim}}(t, E) = f_{\text{bright}}(t/Y, EY),
\]

Using equation (2), one can restate equation (10) as

\[
f_{\text{dim}}(t, E; Y) = \left[ \frac{Y t_{\text{bright}}(YE)}{Y t_{\text{bright}}(YE) + |t - t_{\text{max}}|} \right]_{\text{max}}(YE, \text{max}(YE)),
\]

which can be used either as a function of one stretching parameter \( Y \), or as a function of the two redshifts \( z_{\text{bright}} \) and \( z_{\text{dim}} \).

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**Table 1**

| Energy Range (keV) | Best Fit | Reduced \( \chi^2 \) | \( P(>\chi^2) \) | dof |
|-------------------|----------|----------------------|-----------------|-----|
| 25–50 ............ | 0.81 ± 0.02 | 2.3 | 9.2 x 10^-6 | 37 |
| 50–100 ........... | 0.86 ± 0.01 | 1.28 | 0.12 | 37 |
| 100–300 .......... | 0.82 ± 0.02 | 2.0 | 3.0 x 10^-4 | 37 |
| 25–300 ........... | 0.84 ± 0.02 | 2.0 | <10^-6 | 113 |

![Figure 3](image-url) — ACE_{dim} profiles for 332 dim bursts with \( E_{\text{max}}^{(2)} < 1 \) photon cm\(^{-2}\) s\(^{-1}\). The best-fitting models (eq. [11]) of ACEs at each discriminator channel are indicated (solid lines).
of all three curves together. The errors on $Y^*$ correspond to the range of the best-fitting values of $Y$ for the 12 different models (eq. [11]) based on the initial model (eq. [2]) with $\pm 1\sigma$ deviations of its six parameters (see § 2).

The values of the minima $S_{\text{dim}}$ for the best-fitting parameters $Y^*$ are rather large, and according to the Pearson criterion, the model in equation (11) does not agree with the observed ACE$_{\text{dim}}$ profiles for discriminators $i = 1, 3, 1 + 2 + 3$. Only in the case of discriminator $i = 2$ does the model (eq. [11]) with $Y^* = 0.85 - 0.87$ formally agree with the ACE$_{\text{dim}}$ profile. Moreover, instead of the expected stretching, all the best-fitting factors $Y^*$ (Table 1) correspond to squeezing of ACE$_{\text{dim}}$ profiles with respect to the analytic approximation of ACE$_{\text{bright}}$ for bright bursts (eq. [2]).

However, the classic Pearson criterion based on the $\chi^2$ distribution could not be applied in this case because it does not take into account the actual distribution of differences $S_{\text{bright}}$ between ACE profiles due to a random selection of contributing events. A more accurate test of the basic cosmological model, performed below, takes into account the probability distribution of $S_{\text{bright}}$ resulting from the random sampling of BATSE bursts (see § 3). This test provides the upper limits of $z_{\text{dim}}$ for the basic cosmological model with standard sources that can be deduced from the observed profiles of ACE$_{\text{bright}}$ and ACE$_{\text{dim}}$.

According to this model, a group of bursts with fluxes $\sim F$ corresponds to a definite redshift $\sim z$. While in Euclidean space there is a flux dilution law $\sim R^{-2}$ that establishes the well-known flux/distance relation for standard sources, the non-Euclidean dilution of fluxes from cosmological emitters is influenced by the effects of photon-energy redshifting and light-curve time-stretching.

While each burst has a particular energy spectrum, the average spectral distribution that can be obtained for any selected group of bursts as well as ACEs were obtained for their time histories. According to Band et al. (1993), the energy spectra of BATSE bursts $\phi(E)$ is described by the law

$$\phi(E) = \begin{cases} A \left( \frac{E}{100 \text{ keV}} \right)^{\alpha - \beta} \times e^{-E/(2 + \alpha)/E_{\text{peak}}}, & \text{if } E < (\alpha - \beta) E_{\text{peak}}/2 + \alpha, \\ A \left( \frac{E_{\text{peak}}}{100 \text{ keV}} \right)^{\alpha - \beta} \times e^{-E/(2 + \alpha)/E_{\text{peak}}}, & \text{if } E \geq (\alpha - \beta) E_{\text{peak}}/2 + \alpha, \end{cases}$$

where all energies are normalized by 100 keV. The BATSE database includes the spectral data at a 2048 ms timescale, which could be used to find the average spectral parameters at peak time intervals. For the group of bright BATSE bursts, the average spectral parameters at the peaks are $\langle \alpha \rangle = -0.618$, $\langle E_{\text{peak}} \rangle = 329$ keV, and $\langle \beta \rangle = -3.18$ (Mitrofanov et al. 1997).

According to the concept of standard sources, one could use the average spectra of bright bursts $\phi_{\text{bright}}(E)$ as a standard distribution of photons for all emitters. Therefore, one might derive a universal relation between the observed photon fluxes $F$ and redshifts $z$ of corresponding emitters. For two basic groups of 296 bright and 332 dim bursts with average peak fluxes $\langle F_{\text{max}}^{\text{bright}} \rangle = 6.15 \pm 0.35$ photons cm$^{-2}$ s$^{-1}$ and $\langle F_{\text{max}}^{\text{dim}} \rangle = 0.53 \pm 0.03$ photons cm$^{-2}$ s$^{-1}$, respectively, this relation corresponds to the ratio

$$\frac{\langle F_{\text{max}}^{\text{bright}} \rangle}{\langle F_{\text{max}}^{\text{dim}} \rangle} = \frac{\int \frac{1}{E} \phi_{\text{bright}}(E(1 + z)) dE R^2(z_{\text{dim}})}{\int \frac{1}{E} \phi_{\text{dim}}(E(1 + z_{\text{dim}})) dE R^2(z_{\text{dim}})},$$

(13)

where

$$R = \frac{c}{(1 + z)q_0 H_0} [q_0 z + (1 - q_0)(1 - \sqrt{1 + 2q_0})]$$

(14)

is the cosmological distance to a source, $H_0$ is the Hubble constant, and $q_0$ represents the type of cosmological geometry. The geometry of the universe with critical density is tested below with $q_0 = 0.5$. The peak flux (photons cm$^{-2}$ s$^{-1}$) was calculated in the 50–300 keV energy range according to the 3B catalog database.

Using the average values $\langle F_{\text{max}}^{\text{bright}} \rangle$ and $\langle F_{\text{max}}^{\text{dim}} \rangle$ and the average spectral law $\phi_{\text{bright}}(E)$, equation (13) can be transformed into a relationship between two cosmological parameters: an average redshift $z_{\text{dim}}$ of emitters of dim bursts and an average stretching factor $Y$ between dim and bright bursts. Therefore, the $z_{\text{dim}}$ value can be implemented into the model function (eq. [11]) $f_{\text{dim}}(t, E; z_{\text{dim}})$ as a free parameter to check the consistency between the basic cosmological model and the observed ACE$_{\text{dim}}$ curves for dim bursts.

To do this, one must put the $z_{\text{dim}}$ value into the model function $f_{\text{dim}}(t, E; z_{\text{dim}})$ and calculate the difference (eq. [6]) between the model and the ACE$_{\text{dim}}$ profile at the energy discriminator channel $i = 2$. The estimated value $S_{\text{dim}}(z_{\text{dim}})$ corresponds to the probability $P_{300}(S_{\text{dim}}; \text{dim})$ (Fig. 2) of finding the difference $S_{\text{dim}}$ equal to this value. The integrated probability

$$P_{300}(z_{\text{dim}}) = \int_{S_{\text{dim}}(z_{\text{dim}})}^{\infty} P_{300}(S_{\text{dim}}; \text{dim}) dS_{\text{dim}}$$

(15)

can be interpreted as the probability that the cosmological model with $z_{\text{dim}}$ is consistent with observed the ACE$_{\text{dim}}$ profile. Changing $z_{\text{dim}}$, one might create in this way the probability function $P_{300}(z_{\text{dim}})$ (Fig. 4).

To take into account errors in the parameters of the basic analytic model of $f_{\text{bright}}(t, E)$, the main theoretical model (eq. [11]) was used together with 12 additional models with $z_{\text{dim}}$.
The best-fitting values of $Y^{**}$ equal 1.01, 0.80, and 0.88 for $A_{\text{dimmest}}^{(i)}$ at the three energy discriminators $i = 1, 2,$ and 3, respectively. The corresponding values of reduced chi-square are 2.95, 3.20, and 1.90, respectively. Therefore, the best-fitting stretching factors $Y^{**}$ between the samples of the dimmest and the brightest bursts do not manifest any stretching. These values are similar to the best-fitting factors between the basic samples of ~300 bright and dim bursts, and they all display an absence of any cosmological stretching.

However, to find the upper limit of the stretching factors between the two samples of brightest and dimmest events, one has to compare the trial model $f_{\text{dimmest}}(t, E; z_{\text{dimmest}})$ (eq. [11]) with the $A_{\text{dimmest}}$ curve, taking into account the sampling statistics of the two groups. The probability distribution $P_{1.00}(S_{0-\lmt})$ must be used for the two sets of ~100 events (see § 3). According to Mitrofanov et al. (1997), the distribution of $P_{1.00}(S_{0-\lmt})$ will have the same shape as the $P_{3.00}(S_{0-\lmt})$ for sets with ~300 events. Therefore, the value of $S_{0-\lmt}$ for the 3 σ limit will be about the same. However, because of the smaller statistics for samples with ~100 events, the function (eq. [8]) has a denominator ~3 times larger than that for samples with ~300 events, and therefore, the difference between the two ACEs profiles allowed by the 3 σ limit could be ~1.7 times larger.

Similarly to the basic case of two samples of the ~300 bursts, the new samples of the ~100 brightest and dimmest events are compared via the proposed technique, when for selected values of $z_{\text{dimmest}}$, the probability $P_{1.00}(z_{\text{dimmest}})$ is estimated (see eq. [15]) to obtain the found difference between the model profile $f_{\text{dimmest}}(t, E; z_{\text{dimmest}})$ and the observed ACE$^{(i)}$ curve at the third energy-discriminator channel. The corresponding probability function $P_{1.00}(z_{\text{dimmest}})$ is presented in Figure 5. The 3 σ upper limit of the $z_{\text{dimmest}}$ value is 0.46.

Thus, when two samples of the brightest and the dimmest bursts with ~100 events are compared, no significant increase is found for the best-fitting stretching factors when compared with the case of two basic samples of ~300 bright and dim bursts. In both cases, there is no evidence for a stretching effect at all. Using the sampling statistics of bursts, the 3 σ upper limits are estimated as $z_{\text{dimmest}}$ for ~300 dim bursts and of $z_{\text{dimmest}}$ for ~100 dimmest events, which
equal $\sim 0.1$ and $\sim 0.5$, respectively. One might suspect that the larger upper limit in the second case results from the smaller sampling statistics of groups of $\sim 100$ bursts, and it hardly provides further evidence for cosmological stretching in comparison with the basic case of groups of $\sim 300$ events.

However, formally speaking, one has to conclude that the basic cosmological models with standard candles still apply for gamma-ray bursts, provided they correspond to the 3 $\sigma$ upper limit $z_{\text{dim}} < 0.1$ for the group of dim bursts with $E_{p,\text{max}} < 1.0$ photon cm$^{-2}$ s$^{-1}$, or to the upper limit $z_{\text{dim, min}} < 0.5$ for the group of the dimmest bursts with $E_{p,\text{max}} < 0.41$ photons cm$^{-2}$ s$^{-1}$. These limits resulted from the different sampling statistics of these groups, and further observations of bursts will allow us either to decrease these limits or to resolve the time-stretching effect of dim gamma-ray bursts with respect to bright ones.

Two different average photon spectra with power laws $\propto 1$ and $\propto 2$ were used for the test of the basic samples also. In the $P_{300}(z_{\text{dim}})$ versus $z_{\text{dim}}$ plane, these models correspond to upper and lower lines around the main curve that were found for the average energy spectra (Fig. 6). Therefore, the shape of the photon energy spectra does not affect significantly the upper limit of $z_{\text{dim}}$. The upper limits of $z_{\text{dim}}$ can also be estimated also for different parameters of cosmological geometry. Two curves for chance probability $P_{300}(z_{\text{dim}})$ were derived for two different sets of cosmological parameters (Fig. 7): $q_0 = \sigma_0 = 0.1$ (open universe) and $q_0 = \sigma_0 = 1.0$ (closed universe). One may note that these cases of universe geometry lead to 3 $\sigma$ upper limits $z_{\text{dim}} \sim 0.08$, about the same as the case of a flat expanding universe ($q_0 = \sigma_0 = 0.1$).

5. DISCUSSION AND CONCLUSIONS

The performed comparison of the ACE profiles for groups of bright and dim bursts does not allow for $z_{\text{dim}}$ larger than $\sim 0.1$–0.5 for the basic cosmological model with standard sources. Moreover, the $ACE$-based limit of redshift of dim bursts agrees with noncosmological models of GRBs in flat Euclidean space.

There are two well-known estimations of the redshifts of emitters of GRBs according to cosmological models. The first is based on the average parameter $\langle V/V_{\text{max}} \rangle = 0.33 \pm 0.01$ for the 3B database (Meegan et al. 1996). One should expect $\langle V/V_{\text{max}} \rangle = 0.50$ for a homogeneous distribution of standard sources in Euclidean space. On the other hand, the observed parameter $\langle V/V_{\text{max}} \rangle$ is consistent with the non-Euclidean geometry of the expanding universe. For distant emitters of dim bursts, the $geometry$-based upper limit of redshift was estimated at about 0.5–2.0 (Wickramasinghe et al. 1993). Taking into account the coupling of the spectral shape and the temporal profiles of bursts, Fenimore & Bloom (1995) have obtained a much larger upper limit, $\sim 2$–6.

Another estimate of a cosmological limit of the redshift was based on the effect of the hardness/intensity correlation of GRBs. The average peak of $V_{\text{max}}$ of the bright burst was found to be much softer than the average peak of bright bursts (Mallozzi et al. 1995). The corresponding ratio between peak energies of dim and bright bursts leads to the $spectra$-based upper limit of redshift, which was estimated at $\sim 1$.

There is agreement, at least qualitatively speaking, between $geometry$-based and $spectra$-based upper limits of redshifts of distant emitters of GRBs. These estimations result in $z_{\text{dim}} \sim 1$ and even much larger. On the other hand, the $ACE$-based upper limit of $z_{\text{dim}} \sim 0.1$–0.5 does not agree with either the geometry-based or the spectra-based limit. Therefore, the basic model of GRBs with standard cosmological sources is not consistent with all possible constraints. This is the main conclusion of the present paper.

In developing a cosmological model of GRBs, one should postulate some kind of $z$-dependent property or properties of outbursting sources that can ensure consistency. Generally speaking, $z$-dependence could be attributed to different properties of burst sources, such as an outburst's rate density, luminosity, average energy spectra, and average light curves. There is a reasonable consistency between $geometry$-based and $spectra$-based limits of redshifts of dim burst emitters. Therefore, one need not suggest any intrinsic $z$-dependence either for the outbursts' rate density, or for the energy spectra of the emitted gamma rays, because they would both lead to consistent limits of $z$ for the model with standard sources. On the other hand, to make agreement between them and the $ACE$-based limit, one should postulate some sort of intrinsic evolution of outbursting sources that leads to intrinsic squeezing of their light curves with increasing redshift. There are physical conditions in local cosmological space that vary with $z$: the local density of...
matter, the local temperature of the microwave background, etc., but how much, if at all, these conditions could actually influence the light curves of bursts is unknown at the present. Obviously, a priori there is no physical reason to propose this kind of evolution, and it could be considered to be pure phenomenological speculation.

In addition to the ACE-based test, the time dilation tests should also be applied in conjunction with other time-based parameters of bright and dim GRBs, such as pulse width and interpulse duration. Comparison of distinct time-based signatures for different intensity groups of bursts would allow to distinguish the basic effect of cosmological time-stretching and energy redshifting, which should be identical for all time-energy signatures from other effects resulting from z-dependent evolution, which should be different for each of the temporal parameters. The cosmological paradigm of GRBs could be finally proved with these tests, and new knowledge would be obtained about intrinsic properties of close and distant GRB sources in the comoving reference frames. These studies will be done elsewhere.

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