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The distance scale of cosmological γ-ray bursts*

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Abstract. The isotropic but radially non-uniform distribution of γ-ray bursts (GRBs) observed with the Burst and Transient Source Experiment (BATSE) on board the Compton Gamma Ray Observatory (CGRO) suggests that the bursts may be at cosmological distances. At such distances, the expansion of the Universe should have two main effects on the statistics of γ-ray bursts: first, it should stretch the temporal structure, resulting in dimmer bursts to be longer than bright bursts; second, it would decrease the number of γ-ray bursts with distance, resulting in the value of $< V/V_{max} >$ to be smaller than 0.5. Here we have used the observed time dilation (~ 2) to estimate the distance of γ-ray bursts, and then we use another method, calculating the value of $< V/V_{max} >$ to obtain the distance of γ-ray bursts. These two methods are independent and should be self-consistent. Our results show that the redshift of the dimmest bursts determined from these two distinct methods are consistent, $z_{dimmest} \sim 3.2$, corresponding to a burst luminosity of $L \sim 4 \times 10^{50} ergs^{-1}$, which is different from the results reported previously.

Key words: cosmology: theory – γ rays: bursts

1. Introduction

Since the discovery of γ-ray bursts more than 20 years ago, their origin and emission mechanisms remain mysterious, a major reason for this is that the γ-ray burst events are all transient and so far no quiescent counterpart of a γ-ray burst has been observed. These limitations prevent us from measuring the source distance. Before 1991 it was widely believed that the GRBs originate from our Galaxy (Higdon & Lingenfelter 1990). However, the Burst and Transient Source Experiment (BATSE) on board the Compton Gamma Ray Observatory (CGRO) discovered that the distribution of GRBs is isotropic but radially non-uniform (Meegan et al. 1992; Fishman et al. 1994). This suggests that GRBs are either cosmological (e.g. Mao & Paczynski 1992; Piran 1992; Dermer 1992; Fenimore & Bloom 1995) or originated in an extended halo of our Galaxy (e.g. Brainerd 1992; Li & Dermer 1992; Podsiadlowski et al. 1995; Wei & Lu 1996). Although it is now very difficult to determine whether GRBs are within an extended halo of our Galaxy or at cosmological distances, we hope to look for some evidences from analyzing the statistical properties of GRB sources.

If GRB sources are at cosmological distances, then the expansion of the universe would have some effects on the statistics of GRBs. First, the burst temporal structure will be stretched by a factor $(1 + z)$, so on average, the temporal structure of dimmest bursts (presumably distant) should be longer than that of bright bursts (presumably nearer) by a factor $y = (1 + z_{dimmest})/(1 + z_{bright})$. This time dilation phenomenon has been discovered in BATSE GRBs catalog (Norris 1994 ; Norris et al. 1994; Davis et al. 1994). Various tests that measure time dilation between dimmest and bright bursts have been made and a time dilation factor of about 2 has been found. Second, the number of GRBs would be decreased with distance due to redshift, causing the value of $< V/V_{max} >$ to be smaller than 0.5 (the value expected from nearby homogeneous sources), where for a given source, V is the volume of the smallest sphere containing the source, and V_{max} is the maximum volumn accessible to the detector. $V/V_{max} = (C_{max}/C_{min})^{-3/2}$, here C_{max} is the maximum count rate and C_{min} is the minimum count rate required to trigger the instrument. The value of $< V/V_{max} >$ decreases monotonously with redshift z (Mao & Paczynski 1992), so we can determine the redshift z from the observed value of $< V/V_{max} >$. These two methods can estimate the distance scale of GRBs independently, therefore if the distance obtained from these two methods are consistent, it would be strong evidence in favor of the cosmological origin of GRBs.

Fenimore & Bloom(1995) have calculated the redshift z according to the observed time dilation and $\log N - \log P$ distribution (where N is the number of bursts with peak intensity larger

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than P). They found that the redshifts obtained from these two methods are quite different: from the observed time dilation factor of about 2, they obtained a redshift of $z \geq 6$, while $z \sim 0.8$ is needed to be consistent with the observed $\log N - \log P$ distribution. They tend to favor the explanation that a large fraction of the observed time dilation is intrinsic to the bursts rather than the result of the expansion of the universe.

In this paper, we use a method similar to that of Fenimore & Bloom(1995) to calculate the distance scale of bursts according to the observed time dilation and $< V/V_{max} >$ statistics, by assuming a power-law spectrum of bursts. We found that the distance thus calculated is very sensitive to the spectral index α, when $\alpha \sim 1.5$, the distance obtained from these two independent methods are consistent. In the next section, we calculate the maximum redshift of bursts using $< V/V_{max} >$ statistics. In Sect. 3, the redshifts of bursts have been estimated according to the observed time dilation. Finally a short discussion and conclusion are given in Sect. 4.

2. $< V/V_{max} >$ statistics and the maximum redshift

Throughout this paper we adopt the following cosmological scenario: the universe is flat with $\Omega = 1$, the cosmological constant $\lambda = 0$. We assume that all the bursts are standard candles and have the identical power-law spectrum

$$EL(E)dE = cE^{\alpha}dE \tag{1}$$

where the spectral index α is observed to be in the range $0 \sim 1$ for photon energies below a few hundred keV (Band et al. 1993). For a source located at cosmological distance, the observed energy distribution should be redshifted. Therefore, one detector with a fixed energy bandwidth($E_1 \leq E \leq E_2$) is recording different parts of the intrinsic bursts' spectra for different bursts, this calls for the K-correction (Oke & Sandage 1968; Weinberg 1972; Mao & Paczynski 1992). So, for a source with power-law spectrum, located at redshift z, the part of the intrinsic luminosity which is shifted into the detector energy bandwidth is (Mao & Paczynski 1992)

$$L_{obs}(z) = \int_{(1+z)E_1}^{(1+z)E_2} L(E)dE = (1+z)^{\alpha}L_0,$$

$$L_0 = \int_{E_1}^{E_2} L(E)dE \tag{2}$$

The observed peak flux is then

$$F_{obs}(z) = \frac{L_{obs}(z)}{4\pi d_L^2(z)} \tag{3}$$

where $d_L(z)$ is the luminosity distance

$$d_L(z) = 2R_0(1 + z - \sqrt{1+z}) \tag{4}$$

where $R_0 \equiv c/H_0 \simeq 3h_{100}^{-1}Gpc$, h_{100} is the Hubble constant in units of $100kms^{-1}Mpc^{-1}$. For a detector with threshold F_{min}, the source can only be seen at maximum redshift z_{max},

$$F_{min} = \frac{L_{obs}(z_{max})}{4\pi d_L^2(z_{max})} \tag{5}$$

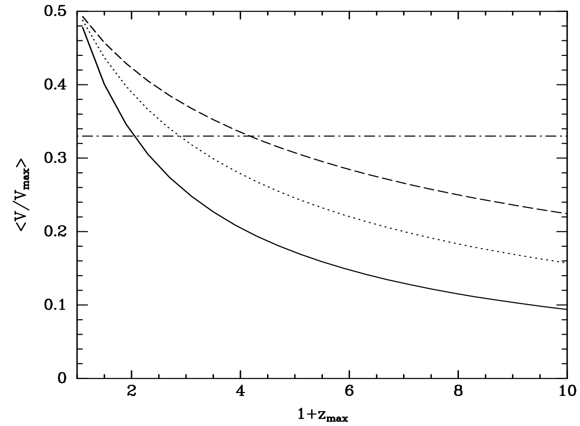

Fig. 1. The variation of $< V/V_{max} >$ with the maximum redshift $(1+z_{max})$. The sources are assumed to be standard candles with identical power-law spectra, $EL(E)dE = cE^{\alpha}dE$. The solid, dot-dashed and dotted lines corresponds to $\alpha = 0, 1, 1.5$ respectively. The horizontal line corresponds to the observed value $< V/V_{max} >= 0.33$.

The statistical value of $< V/V_{max} >$ is

$$< V/V_{max} >=< (\frac{F_{min}}{F_{obs}(z)})^{3/2} >=$$

$$\frac{1}{N(r_{max})}\int_0^{r_{max}} [\frac{F_{min}}{F_{obs}(z)}]^{3/2} \frac{\rho}{1+z} 4\pi r_z^2 dr_z \tag{6}$$

where $N(r_{max})$ is the burst rate detected within the volume for r_{max}

$$N(r_{max}) = \int_0^{r_{max}} \frac{\rho}{1+z} 4\pi r_z^2 dr_z \tag{7}$$

ρ is the rate of bursts per unit comoving volume per unit comoving time, which is assumed to be a constant in this paper. r_z is the comoving distance $r_z = d_L(z)/(1+z)$.

Fig. 1 shows the variation of values of $< V/V_{max} >$ with the maximum redshift z_{max}, which is similar to that of Mao & Paczynski(1992). In Fig. 1, three spectral indices have been adopted, and the horizontal dashed line corresponds to the observed value $< V/V_{max} >= 0.33$,which is obtained from the third BATSE GRB catalog. It follows that the maximum redshift z_{max} is 1.1, 1.9 and 3.3 for the spectral index $\alpha = 0, 1, 1.5$ respectively.

3. The time dilation and distance scale

There have been a variety of tests that measure the time dilation between bright and dimmest bursts, and a factor of about 2 has been found (Norris 1994; Norris et al. 1994). In these analyses, the BATSE bursts were assigned to a brightness class depending on their peak count rates. In this paper we will use a similar definition, and from the BATSE 3B catalog, we obtain 64 bursts in the bright class, 101 bursts in the dim class, and 103 bursts in the dimmest class.

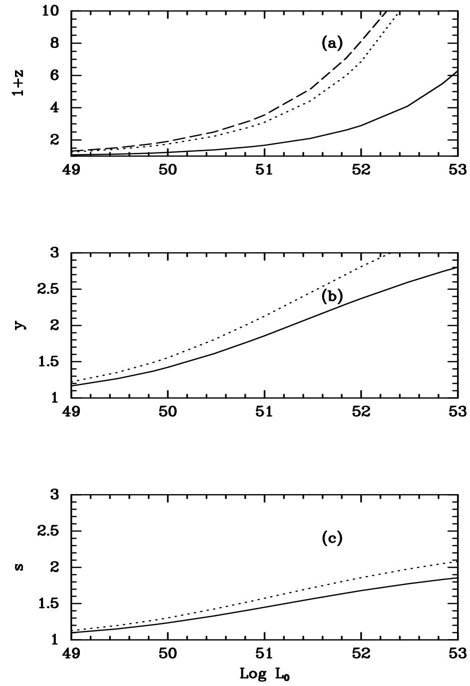

Fig. 2. a Averaged redshift $(1+z)$ vs. standard candle luminosity L_0 for three brightness classes: solid, dot-dashed and dashed lines are for the bright ,dim and dimmest classes of bursts. Here α = 0. **b** The variation of y(the ratio of 1 + z factors) with the luminosity L_0, which does not include the W-correction. **c** The relationship between the observed time dilation, which include the W-correction, and the luminosity L_0.

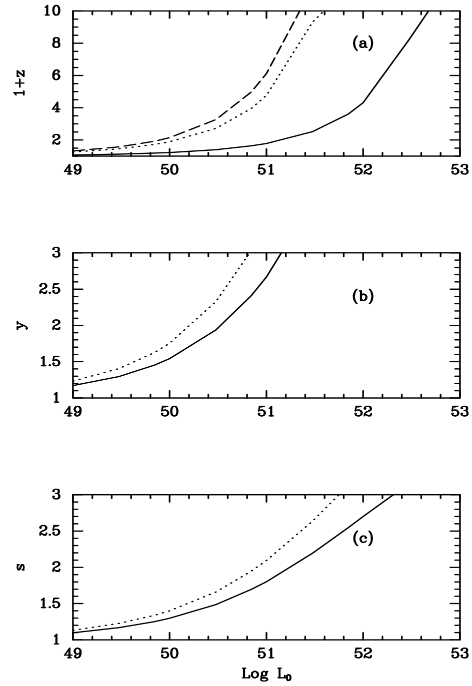

Fig. 3a–c. The same as Fig. 2, but for α = 1.

According to Eqs. (2)-(3), for a given burst, the peak flux F_{obs} is a function of L_0 and α. So if we fixed L_0 and α, then the redshift z of a burst can be determined. In order to convert the photon flux P into the peak energy flux F, one needs to know the spectrum of bursts. Here we adopt the power-law spectrum with spectral index α. For one brightness class, when the redshift z of each burst has been determined, we calculate their averaged value, which is taken to be the redshift of this brightness class. Fig. 2a, Fig. 3a and Fig. 4a show the variation of averaged redshift (1 + z) with luminosity L_0 for different spectral index: $\alpha = 0, 1, 1.5$ respectively, the solid, dot-dashed and dotted curves are for the bright, dim and dimmest class of bursts.

Due to the expansion of the universe, the temporal structure of bursts will be stretched by a factor (1 + z). If the width of bursts' time structure is independent of photon energy, then the time dilation of the dimmest bursts relative to the bright bursts is

$$y = \frac{1 + z_{dimmest}}{1 + z_{bright}} \tag{8}$$

However, Link et al.(1993) and Cheng et al.(1995) have shown that the FWHM of bursts' time structure of high energy bandpass is less than that of low energy bandpass. Therefore, the time dilation factor should include the contribution from the narrowing of time structure at higher energy, this effect was first considered by Fenimore & Bloom(1995). Furthermore, Fenimore et al.(1995) have shown that the narrowing of time structure with energy follows a power-law, the power-law index is $\sim$ 0.4, i.e. it can be written as

$$W(E) \propto E^{-0.4} \tag{9}$$

Thus, the observed time dilation of dimmest bursts relative to bright bursts is

$$s = y \frac{W(yE_L, yE_U)}{W(E_L, E_U)} \tag{10}$$

where the term $W(yE_L, yE_U)/W(E_L, E_U)$ is called as W-correction (Fenimore & Bloom 1995), which accounts for the tendency of narrowing of time history at higher energy. Combining Eqs. (9)-(10), we obtain

$$s = y^{0.6} \tag{11}$$

which is the observed time dilation factor exactly.

Fig. 2b, Fig. 3b and Fig. 4b show the variation of factor y with luminosity L_0 for three different spectral indices, which do not contain the W-correction. Fig. 2c, Fig. 3c and Fig. 4c show the relationship between the observed time dilation and L_0, which include the W-correction factor. Therefore, according to the observed time dilation, we can specify L_0, which can be used in Fig. 2a-4a to obtain the redshift z.

It can be seen from Figs. 2-4 that the relationship between the time dilation and luminosity (also the redshift) is strongly dependent on the power-law index α. For α = 0, Fig. 2 shows that the observed time dilation, as well as the redshift z, varies

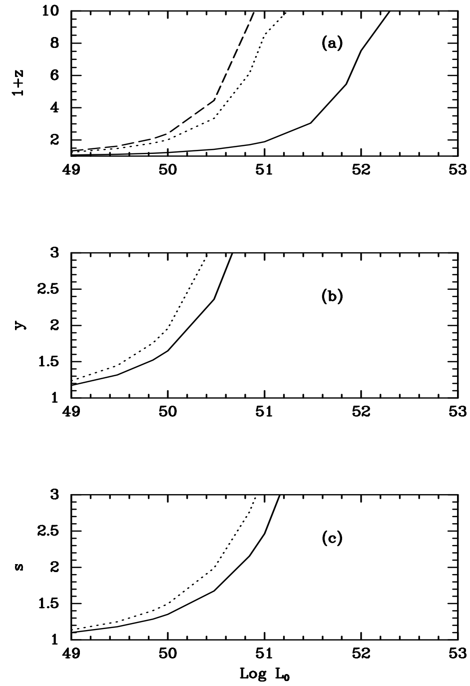

Fig. 4a–c. The same as Fig. 2, but for α = 1.5.

more slowly with luminosity than in the case of α = 1 (or 1.5), i.e. at a given luminosity, the factor y and s are smaller than that of α = 1 (or 1.5). Furthermore, it shows that, for α = 0, no luminosity within the range of our assumption can give a time dilation as large as 2.0 (observed) when including the W-correction. While in the case of α = 1.5, the luminosity corresponding to the observed time dilation (2.0) is only about $4 \times 10^{50} ergs^{-1}$, much smaller than that of α = 1 ($L_0 \sim 10^{51} ergs^{-1}$), the corresponding redshift z of dimmest bursts in the case of α = 1.5 and 1 are about 3.4 and 2.0 respectively.

Comparing with the results of Sect. 2, we found that when α = 0 or 1, the redshift obtained from $< V/V_{max} >$ statistics is much less than that from time dilation tests, while for α = 1.5, the redshifts determined from these two methods are consistent, $z \sim$ 3.4 and $L_0 \sim 4 \times 10^{50} ergs^{-1}$. In the following we use this value to calculate the $\log N - \log F$ distribution.

Given L_0 and the observed peak flux F, we can determine the redshift according to Eqs. (2)-(3). Fig. 5 shows the relation between the redshift z and the peak flux F.

The number of bursts observed in a range of peak flux (F_1 to F_2) is

$$\Delta N(F_1 to F_2) = \int_{r_1}^{r_2} \frac{\rho}{1+z} 4\pi r_z^2 dr_z \qquad (12)$$

Fig. 6 shows our calculated $\log N - \log F$ distribution, which are compared with the BATSE and PVO observations(the observed data are from Fenimore & Bloom 1995). It is obvious that our theoretical values are in agreement with the observations.

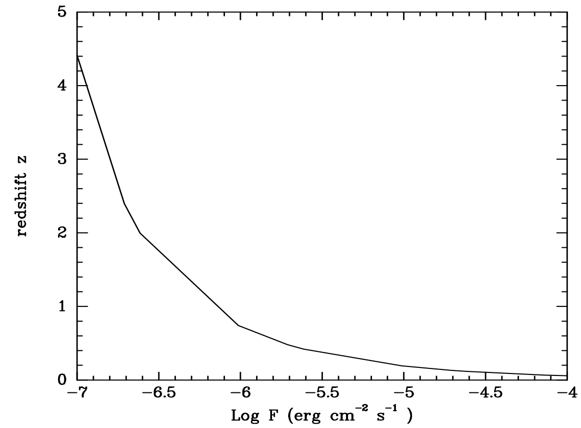

Fig. 5. The relationship between the redshift z and the peak flux F.

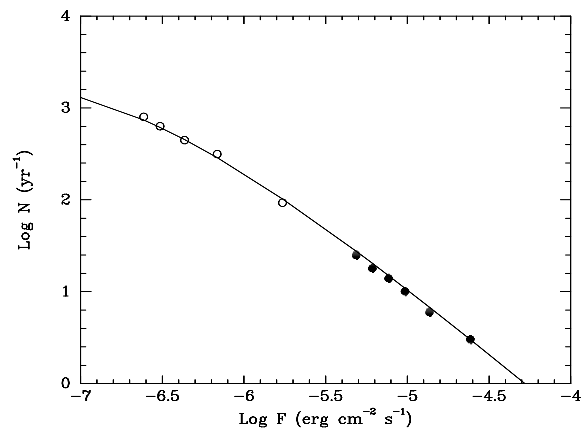

Fig. 6. The calculated $\log N - \log F$ distribution with $L_0 = 4 \times 10^{50} ergs^{-1}$ compared with the observation. The observed data are from Fenimore & Bloom(1995). The open circles and the filled circles denote the data observed by PVO and BATSE respectively.

4. Discussion and conclusions

Up to now, many features of GRBs, such as energy sources, radiation mechanisms et al., still remain mysterious. Among them, the distance scale of GRBs is the most puzzling question. Since the distance is unknown, the theoretical model is difficult to be built to account for the other characteristics of GRBs. Thus, a lot of efforts have been made to estimate the distance scale of GRBs.

Many tests show time dilation of $\sim$ 2 between the BATSE bright bursts and the dimmest bursts (Norris 1994; Norris et al. 1994; Davis et al. 1994), this provides a clue to the distance scale of GRBs. On the other hand, the $< V/V_{max} >$ statistics can also give a distance scale of the dimmest bursts. These two methods are independent, so if the distances determined from these two methods are consistent, it would be a strong evidence in favor of cosmological origin of GRBs. Fenimore & Bloom(1995) calculated the redshift z according to the observed time dilation and the $\log N - \log P$ distribution, and found that the results are quite different, thus they conclude that either a large fraction of the observed time dilation is intrinsic to the bursts rather than be the result of expansion of the universe, or strong density evolution and/or luminosity evolution would be required. Here we performed a calculation similar to that of Fenimore & Bloom(1995), but assuming a power-law spectrum of bursts(which in fact adds a free parameter α). Our calculation shows that the redshift determined from these two independent methods are consistent with each other, the redshift of dimmest bursts is about 3.2, rather than a redshift of 1 or 2 (Mao & Paczynski 1992; Wickramasinghe 1993; Norris et al. 1995), and also very different from that of Fenimore & Bloom(1995).

In this paper, the form of Eq. (2) comes from the fact that the observed energy distribution of a source located at cosmological distance will be redshifted. But this form can also represent the evolution of luminosity. Therefore in the present paper, the parameter α may indeed contain two effects: one is the redshift contribution, and another is the luminosity evolution. Our results imply that there should be evolution of burst luminosity (since the observed value of α mainly lie between 0 and 1, while in our calculation α = 1.5 is required to ensure the distance scale to be consistent in two methods), similar to that of AGN.

From Figs. 1-4 we can find that both the value of $< V/V_{max} >$ and the time dilation factor are very sensitive to the parameter α. It should be noted that these two quantities depend on α in opposite direction, i.e. when α increases, the redshift corresponding to the observed value of $< V/V_{max} >$ also increases, while the redshift corresponding to the observed time dilation decreases, and vice versa. Therefore, there should be one best value of α which can explain the observed time dilation and $< V/V_{max} >$ statistics simultaneously.

In summary, our results show that, when considering the redshift effects and/or the luminosity evolution, the distance scale of γ-ray bursts can be determined uniquely, $z \sim$ 3.4, from the two independent methods, i.e. $< V/V_{max} >$ statistics and the time dilation factor. However, the existence of the latter (time dilation) was suggested by Norris et al. (1994), and questioned by Mitrofanov et al. (1996), its correctness remains to be proved in the future.

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