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Letter to the Editor

Gamma-ray bursts: towards a standard candle luminosity

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Abstract. It is usual, in gamma-ray burst (GRB) studies, to compare the average properties of bright and faint GRBs, with the assumption that brightness classes reflect distance classes. When brightness is intented to reflect the distance to the sources, it is nevertheless important to use a quantity with a small intrinsic dispersion. We propose here a method to compare the intrinsic dispersion of various measures of GRB brightness. This method assumes that nearby bursters are homogeneously distributed in an Euclidean space with no density or luminosity evolution. We then use it to compare 5 measures of GRB brightness in the BATSE Catalog. Our analysis reveals that better (i.e. less dispersed) measures of brightness are obtained at low energy and that GRBs are much closer to standard candles below 100 keV than above. We suggest that a beaming of the emission above 100 keV could explain this behaviour.

Key words: Gamma-rays: bursts

1. Introduction

The GRB intensity distribution has been extensively used to improve our understanding of these sources. The $\langle V/V_{max} \rangle$ test for instance has been unvaluable to demonstrate the burster spatial inhomogeneity (Meegan et al. 1992). The LogN-LogP distribution has been shown to be in good agreement with the intensity distribution expected for cosmological sources (e.g. Piran 1992, Wickramasinghe et al. 1993, Fenimore et al. 1993). Finally, it is common to define brightness classes for the purpose of searching cosmological signatures in gamma-ray bursts. In all these studies, the burst brightness appears as a key parameter.

While it is widely acknowledged that C_{max}/C_{min} is the measure of brightness which is appropriate to check the spatial homogeneity of gamma-ray bursters (Schmidt et al. 1988), there is no such agreement on the parameter which should be used for studies where brightness is taken as a distance indicator. These studies require a quantity with small, or no, intrinsic dispersion. We propose below a new way of comparing the intrinsic dispersions of different measures of brightness. When several definitions of brightness are available (e.g. peak flux, fluence...), this method answers the question of which one of these quantities is closer to a standard candle. Sect. 2 describes the method. In Sect. 3, we apply it to a sample of 1471 GRBs detected by BATSE. The implications for gamma-ray bursts are discussed in Sect. 4.

2. The method

We propose a method based on the observation that the sources detected by an instrument have different spatial distributions depending on whether they are standard candles or not. Standard candles are fully sampled out to a distance D_0 and not seen beyond this distance (assuming we have a detector with a sharp intensity threshold). Sources with a broad luminosity function, on the other hand, are fully sampled out to a distance D_1 (the distance at which the intensity of intrinsically faint sources reaches the threshold of the instrument), and only partially detected between D_1 and D_2 (the distance at which the intensity of intrinsically bright sources reaches the sensitivity threshold of the instrument).

Let us consider now the case of a population which is homogeneous for $D < D_h$, and whose spatial density decreases for $D > D_h$. For standard candles, the deviation from homogeneity in the size-frequency distribution cannot be seen until *all the sources in the homogeneous region have been detected*. For sources with a broad luminosity distribution, the deviation from homogeneity is in principle visible when the instrument begins to detect sources in the non-homogeneous region. If the luminosity function is broad enough, this happens while most of the sources in the homogeneous region are still undetected. In this second situation, the number of sources seen in the homogeneous part of the observed size-frequency relation can be significantly smaller than for standard candles.

Fig. 1 illustrates this behaviour for sources having a power law luminosity distribution ($n(L) \propto L^{-\alpha}$ between L_1 and L_2). This figure displays $f_{3/2}$ as a function of the ratio L_2/L_1, where

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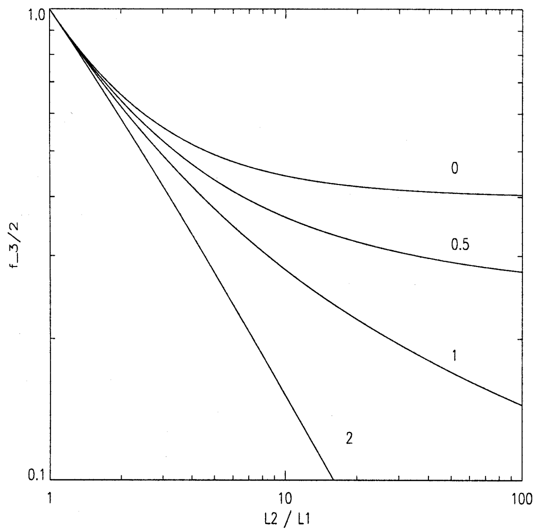

Fig. 1. Influence of an intrinsic luminosity distribution on the number of GRBs seen in the homogeneous part of the size-frequency curve. We assume that the luminosity function has the form $n(L) \propto L^{-\alpha}$ between L_1 and L_2. The figure displays $f_{3/2}$ as a function of L_2/L_1, where $f_{3/2}$ is the ratio of the number of GRBs seen in the homogeneous part of the size-frequency curve to the number expected for standard candles. Note that $f_{3/2}$ decreases when L_2/L_1 increases. The curves are for $\alpha = 0, 0.5, 1, 2$ (top to bottom).

$f_{3/2}$ is the ratio of the number of sources *seen* in the homogeneous part of the size-frequency curve normalized to the same number for standard candles. As expected, $f_{3/2}$ continuously decreases when the luminosity dispersion increases.

2.1. Using the GRB size-frequency distribution

As explained above, better measures of brightness are indicated by a larger number of GRBs in the homogeneous part of their size-frequency curve. This is the criterion we propose to use to compare the "quality" of different measures of GRB brightness.

Practically, we measure the point at which the observed size-frequency curve deviates from the extrapolation of the bright end of the distribution. In order to decrease the sensitivity of our test to the behaviour of the curve below the break (which depends on the source luminosity function and on their radial density profile), we have chosen to count the number of GRBs, N_b, when the observed curve is only 20% below the extrapolation of the "homogeneous" part of the curve (i.e. $\log(N_{\rm extrapolated})$ - $\log(N_{\rm observed}) = 0.1$). The confidence region on N_b is computed with the bootstrap method. We construct several simulated samples from the original sample, and we compute a new value of N_b for each of them. The confidence region is defined as the interval which contains a given percentage of the simulated N_b. The error bars on N_b are given below at the 90% confidence level.

As we do not know D_h, nor the number of bursters in the homogeneous region, this method can only tell us that one brightness indicator is better than another, but not whether it is a true standard candle.

2.2. Limits of the method

Our analysis relies on the following assumptions:

1) The slope -3/2 observed at the bright end of the size-frequency distribution is actually due to the spatial homogeneity of nearby bursters.

2) BATSE is sensitive enough to detect all the bursts emitted inside the homogeneous region (we show below that this second assumption is fully justified).

Under these assumptions, the results presented below are valid for both cosmological and galactic models. It should be noted however that this analysis can only be applied to non-evolving sources in an Euclidean space. If gamma-ray bursters appear to be at redshifts of a few as suggested by various authors (e.g. Wijers et al. 1997 and ref. therein), source evolution may dominate the observed size-frequency distribution, and a simple geometrical analysis like this one is not relevant.

3. Application to GRBs

In this section we apply our method to GRBs in the Current Catalog of BATSE as available on 1997, June 30th (Meegan et al. 1997). We have choosen this catalog because it is publicly available, it contains a large number of bursts, it provides several measures of GRB brightness and because BATSE is sensitive enough to fully sample the homogeneous region. We compare various measures of the GRB brightness, like their peak fluxes on different timescales and their fluences in different energy bands. We study separately the influence of the time window and of the energy range.

3.1. Short gamma-ray bursts

Dezalay et al. (1992) and Kouveliotou et al. (1993) have suggested the existence of two classes of GRBs with different durations (below and above 2 seconds). Although both short and long GRBs are isotropic on the sky, it is not clear whether they have the same radial distribution (the sources of short GRBs could be closer or farther than the sources of long GRBs). For this reason we separate the two classes in our analysis. The sample of short bursts is unfortunately too small to allow us to draw conclusions on their luminosity distribution, and the rest of this paper is restricted to the class of long GRBs (1103 bursts).

3.2. Influence of the time window

In this section we compare the peak fluxes on 64 and 1024 ms (hereafter called P64 and P1), and the fluence in the energy range [50-300 keV] (hereafter called F23). These 3 quantities are all defined from 50 to 300 keV but differ by the time window used to integrate the burst brightness.

The size-frequency distributions for these 3 parameters are displayed in Fig. 2 (a,b,c), along with the extrapolation of the bright end of the distribution. The deviation from homogeneity occurs at P64 = 6.9 ph cm^{-2} s^{-1}, P1 = 6.6 ph cm^{-2} s^{-1} and F23 = 10^{-5} erg cm^{-2}. This justifies a-posteriori our second assumption, since the catalog of BATSE is over 99% complete at

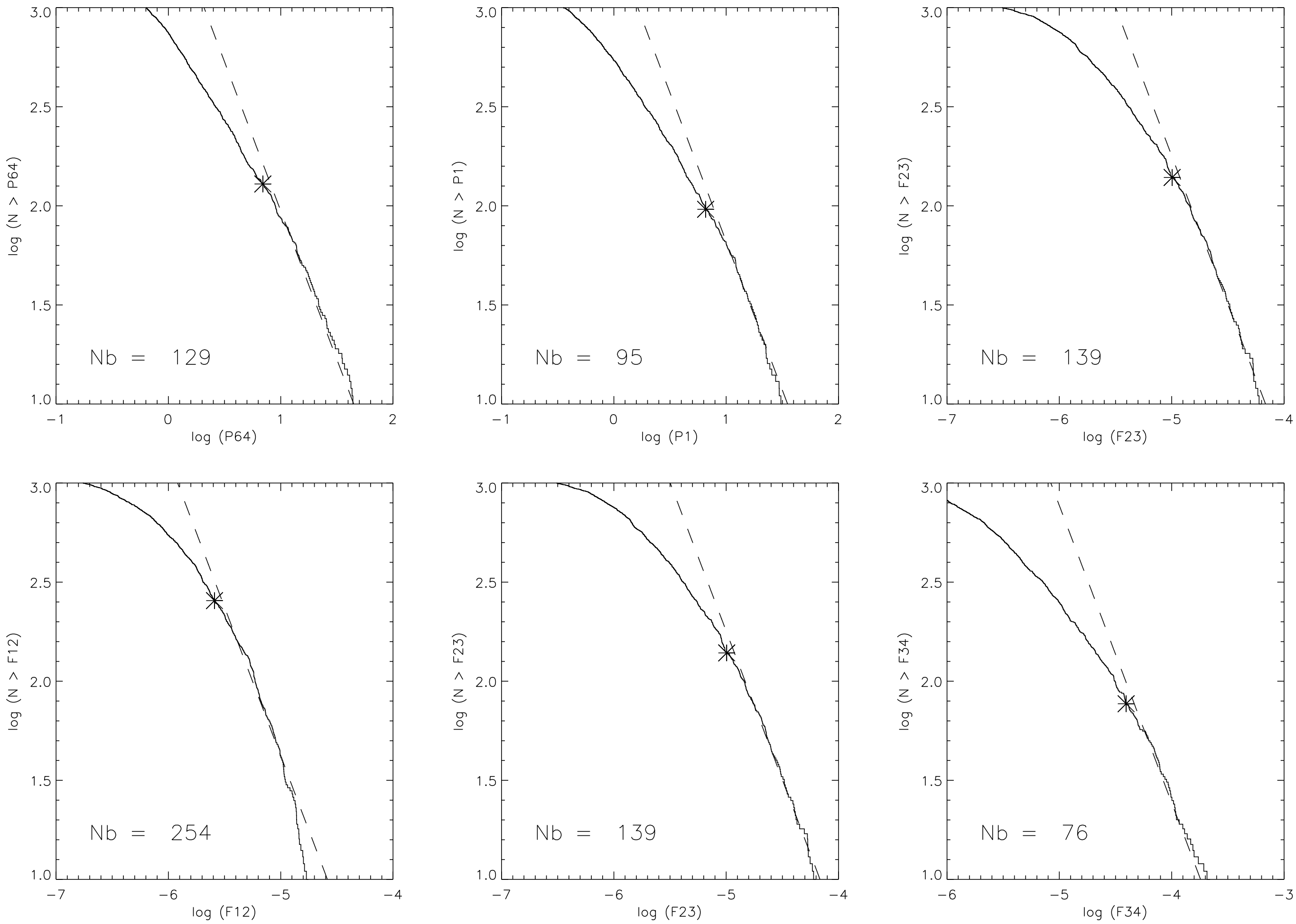

Fig. 2. Number of GRBs in the homogeneous part of the size-frequency curve for various measures of intensity (see Sect. 3.2).

and above these intensities.[1] The values of N_b and their 90% error bars are respectively 129 [78-151], 95 [74-130] and 139 [100-210], for P64, P1 and F23. These three measures of intensity show little difference from the point of view of our analysis, suggesting that the corresponding luminosities have comparable intrinsic dispersions. We conclude that the choice of the time window does not seem to be crucial in the search for a standard candle luminosity.

3.3. Influence of the energy window

We now compare the burst fluences in the energy ranges [25-100 keV], [50-300 keV] and [100-2000 keV], we call these numbers F12, F23 and F34. The BATSE catalog does not provide peak fluxes at energies other than [50-300 keV], so we do not consider peak fluxes in this section.

The size-frequency curves for F12, F23 and F34 are displayed in Fig. 2 (d,e,f), along with the extrapolation of the bright end of the distribution. The departure from homogeneity occurs at F12 = 2.6 10^{-6} erg cm^{-2}, F23 = 10^{-5} erg cm^{-2} and F34 = 3.9 10^{-5} erg cm^{-2}. We again checked that the trigger efficiency of BATSE for GRBs in the homogeneous part of the size-frequency is greater than 98% in the 3 cases. The values of N_b and their 90% errors are respectively 254 [190-318], 139 [100-210] and 76 [60-112]. These numbers show that the GRB size-frequency distribution contains about 3 times more GRBs in its homogeneous part when F12 instead of F34 is used to measure the burst intensity. This suggests that the low energy fluence (below 100 keV) is significantly closer to a standard candle than the fluence measured at higher energies. We used the same method to compare the fluences in the energy bands F1 [25-50 keV] and F2 [50-100 keV] and found very little difference between these two quantities, with N_b being 237 [186-283] and 224 [181-247] for F1 and F2 respectively. We conclude that F12 provides the closest approximation to a standard candle in the Catalog of BATSE and that the energy window appears as a crucial parameter in the search for a luminosity with a small intrinsic dispersion.

[1] The trigger efficiency of BATSE is directly available in the catalog as a function of P64 and P1. For F23 we checked that the burst with the smallest value of P1 in the homogeneous part of the size-frequency curve has P1 = 0.58 ph cm^{-2} s^{-1}, a value above which the Catalog is 99% complete.

4. Discussion

We have proposed a new method to compare the intrinsic dispersion of various measures of GRB brightness. An essential assumption of this method is that the slope -3/2 at the bright end of the size-frequency curve is due to the spatial homogeneity of nearby bursters. If on the other hand, source evolution dominates the GRB size-frequency curve, the slope -3/2 might have a completely different interpretation, invalidating the conclusions of our analysis (for instance density evolution could cancel the effects of a non-Euclidean space, simulating a homogeneous distribution of bursters in an Euclidean space). In the rest of the discussion we assume that source evolution does not dominate the observed GRB size-frequency distribution.

When applied to GRBs in the Current Catalog of BATSE our method shows that the measure of luminosity with the smallest intrinsic dispersion is the time integrated luminosity below 100 keV. This result is however not complete since we restricted our analysis to 5 measures of brightness given in the Catalog.

This study calls for a careful definition of the GRB brightness when this quantity is used as a distance indicator (e.g. to compare the properties of nearby and distance bursters); measures at low energies are then clearly preferred.

We finally note that the combination of (1) a broad luminosity function and (2) a spatial density which varies with the distance has interesting consequences for the comparison of faint and bright GRBs. Intrinsically bright bursts are detected to large distances (typically larger than the size of the homogeneous region) where the burster spatial density decreases rapidly. Intrinsically faint bursts on the other hand are only visible to much smaller distances where the burster density is constant (if we remain in the homogeneous region) or slowly decreasing. As a consequence, going to lower intensities increases the number of bright GRBs much less (in percentage) than the number of intrinsically faint bursts. In other words, burst classes based on the *observed* brightness do not contain the same proportion of *intrinsically* bright bursters. This changing proportion may produce brightness-dependent average burst properties (spectral and/or temporal) which could strengthen or counteract cosmological effects. Because our study suggests that the GRB luminosity function is more extended above 100 keV, we expect GRB properties to be more brightness-dependent when brightness is measured above 100 keV. For instance the well known hardness-intensity correlation (e.g. Dezalay et al. 1997) could be explained in this way if it appears that it is stronger when the intensity is measured at higher energies.

While we do not address here the reasons which make the luminosity at low energies a better standard candle, we note that this behaviour could well be explained by an anisotropy of the emission above $\sim$100 keV. Such an anisotropy would make the brightness at high energies dependent on the aspect of the source. From the point of view of the size-frequency distribution, a beaming of the emission is equivalent to the existence of a luminosity function. Hence a beaming factor which changes with the energy may just appear as an energy dependent luminosity function, which is precisely what we observe.

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