Choosing a measure of GRB brightness that approaches a standard candle

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Abstract. Studies using the GRB brightness as a distance indicator require a measure of brightness with a small intrinsic dispersion (close to a standard candle). There is unfortunately no general agreement on the definition of such a quantity.

We show here that the comparison of the size-frequency curves obtained with various measures of brightness can be used to select the quantity which is closer to a standard candle. Our method relies on a few general assumptions on the burster spatial distribution, namely that nearby bursters are homogeneously distributed in an Euclidean space with no density or luminosity evolution. We apply it to 5 measures of GRB brightness in the Current BATSE Catalog and we find that the GRB size-frequency distribution depends significantly on the energy window used to measure the GRB brightness. The influence of the time window being, in comparison, negligible. Our method suggests that the best distance indicator in this Catalog is the fluence measured below 100 keV, indicating that GRB luminosities have a smaller intrinsic dispersion below 100 keV than above.

PRINCIPLE OF THE METHOD

We start from the basic observation that GRB size-frequency curves (log(N)-log(flux)) represent a convolution of the burster distributions in distance and luminosity. These two distributions, however, cannot be easily disentangled and if we want to learn something about the GRB luminosity function, we have to make assumptions on the burster radial distribution.

Practically we assume that:

- The slope -3/2 observed at the bright end of the size-frequency distribution reflects an actual spatial homogeneity of nearby bursters (in an Euclidean space).

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

At this point we should stress that the assumptions stated above define the validity of our method. In particular our method is not relevant if the intensity
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).

Distribution of bright bursts is significantly affected by source evolution [1]. Under these assumptions, the GRB size-frequency curve follows the law expected for spatially homogeneous sources (with a slope = -3/2) at its bright end, and progressively deviates from this law for fainter bursts. We demonstrate below that the number of bursts seen in the homogeneous part of the size-frequency curve depends on the intrinsic width of the burster’s luminosity distribution, and we explain how this number can be used to compare the intrinsic dispersion of various measures of the GRB luminosity. Let \( N_h \) be the total number of sources in the homogeneous region that have emitted a burst and \( n_{3/2} \) the number of sources that we measure in the homogeneous part of the size-frequency curve.

- For \textit{standard candles}, the size-frequency curve deviates from homogeneity only when all the sources in the homogeneous region have been sampled, and we have \( n_{3/2} = N_h \).

- For sources with a \textit{broad luminosity dispersion}, the size-frequency curve deviates from homogeneity when the (intrinsically) bright sources become detectable beyond the homogeneous region. If the luminosity dispersion is broad, this occurs while only part of the sources in the homogeneous region are detectable, and we expect \( n_{3/2} < N_h \).

This situation is illustrated on Fig. 1, which displays \( f_{3/2} = n_{3/2} / N_h \) as a
function of the luminosity dispersion of the sources. This figure shows that the ratio $f_{3/2}$ decreases as the luminosity dispersion increases.

In the real world we do not know $N_h$, so we cannot decide how close to a standard candle is a given measure of the GRB luminosity. We can, however, compare the values of $n_{3/2}$ obtained for different definitions of the GRB luminosity, in order to decide which one has the smallest intrinsic dispersion.

APPLICATION TO THE CURRENT BATSE CATALOG\(^1\)

Figure 2 illustrates the application of this method to the bursts in the Current BATSE GRB Catalog [2]. We have chosen 5 measures of the GRB luminosity given in this Catalog:
- P64, the peak flux in the 50-300 keV energy range accumulated over 64 ms.
- P1, the peak flux in the 50-300 keV energy range accumulated over 1 s.
- F12, the fluence in the energy range 25-100 keV.
- F23, the fluence in the energy range 50-300 keV.
- F34, the fluence above 100 keV.

Figure 2 displays the size-frequency distribution of 1103 GRBs with $T_{90} > 2$ s, the extrapolation of the homogeneous part of the curve, and an estimate of $n_{3/2}$.

Influence of the time window. In the three panels of the first row (P64, P1 and F23), the luminosity is measured in the same energy domain (50-300 keV) but with different integration times (64 ms, 1 s and the entire burst duration). The deviation from homogeneity occurs at $P64 = 6.9 \text{ ph cm}^{-2} \text{ s}^{-1}$, $P1 = 6.6 \text{ ph cm}^{-2} \text{ s}^{-1}$ and $F23 = 10^{-5} \text{ erg cm}^{-2}$. This justifies a-posteriori our second assumption, since the catalog of BATSE is over 99% complete at and above these intensities. The values of $N_h$ and their 90% error bars are respectively 129 [78-151], 95 [74-130] and 139 [100-210], for P64, P1 and F23 (the error bars are computed from a bootstrap resampling of the size-frequency curve). These three measures of intensity show little difference from the point of view of our analysis, suggesting that the choice of the time window is not crucial in the search for a standard candle luminosity.

Influence of the energy window. In the three panels of the second row (F12, F23 and F34), the luminosity is integrated over the entire burst but in different energy ranges (25-100, 50-300 and >100 keV). The departure from homogeneity occurs at $F12 = 2.6 \times 10^{-6} \text{ erg cm}^{-2}$, $F23 = 10^{-5} \text{ erg cm}^{-2}$ and $F34 = 3.9 \times 10^{-5} \text{ erg cm}^{-2}$. We 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 $N_h$ 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)

\(^{1}\) As available on 1997, june 30th
is significantly closer to a standard candle than the fluence measured at higher energies.\textsuperscript{2}

Contrary to the time window, the energy window appears as a crucial parameter in the search for a luminosity with a small intrinsic dispersion.

\textbf{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. In the rest of the discussion we assume that source evolution does not dominate the size-frequency distribution of bright GRBs.

The fact that the width of the $\gamma$-ray burst luminosity function changes with the energy calls for a careful definition of the GRB luminosity when the intensity is taken to reflect the distance to the sources (e.g. to compare the properties of nearby and distant bursters). Measures at low energies (below 100 keV) are clearly preferred.

We also note that the combination of \textit{i)} a broad luminosity function and \textit{ii)} a spatial density which varies with the distance has interesting consequences for the comparison of faint and bright GRBs. Intrinsically bright bursters 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 \textit{observed} brightness do not contain the same proportion of \textit{intrinsically} bright bursters. This changing proportion may produce brightness-dependent burst properties (spectral and/or temporal) which could strengthen or counteract cosmological effects. If, as suggested by this study, the GRB luminosity function is broader at high energies, we predict that average burst properties will appear more \textit{brightness-dependent} when brightness is measured at higher energies.

Finally, 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 flux 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, in accordance with what we observe.

\textsuperscript{2) Our method provides almost identical values of $n_{3/2}$ (237 and 224) for the fluence distribution in 25-50 keV and 50-100 keV.}
FIGURE 2. Value of $n_{3/2}$ for various measures of the GRB brightness (see text).

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