How Real Detector Thresholds Create False Standard Candles

Michigan Tech
Michigan Technological University

Amir Shahmoradi, Robert Nemiroff

Department of Physics, Michigan Technological University

Michigan Tech
Michigan Technological University

GRB satellites are relatively inefficient detectors of dim hard bursts. For example, given two bursts of identical peak luminosity near the detection threshold, a dim soft burst will be preferentially detected over a dim hard burst. This means that a high Epeak burst will need a higher peak luminosity to be detected than a low Epeak GRB. This purely detector-created attribute will appear as a correlation between Epeak and luminosity, and should not be interpreted as a real standard candle effect. This result derives from Monte Carlo simulations utilizing a wide range of initial GRB spectra, and retriggering to created a final "detected" sample. In sum, Epeak is not a good standard candle, and its appearance as such in seeming correlations such as the Amati and other Liso vs. Epeak relations is likely a ghost of real energy-related detection thresholds.

I. Description of Model

$$h=0.72,\ \Omega_M=0.23,\ \Omega_\Lambda=0.23,\ 0\le z\le 10$$

Concordance Cosmology is assumed to be valid through the entire simulation

$$\Phi(E)=\begin{cases} AE^{\alpha}e^{-(2+\alpha)E/E_{peak}}, & E\le E_{break}\\ BE^{\beta}, & \text{otherwise}\end{cases}$$

$$E_{break}=\left(\frac{\alpha-\beta}{2+\alpha}\right)E_{peak}$$

GRB spectrum is assumed to be best described by Band function (BM), (best fit model for BATSE, INTEGRAL HETE-2 GRBs)

$$\begin{cases}\alpha>\beta,\alpha>-2 & \text{(I)}\\ \alpha<\beta,\alpha<-2 & \text{(II)}\end{cases}$$

Limits of spectral indices for which BM exists. (II) leads to unrealistic GRBs that have never been observed.

$$\begin{cases}-2<\alpha\le 5\\ -20\le\beta<-0.2\end{cases}$$

Limits of spectral indices for which BM exists. (II) leads to unrealistic GRBs that have never been observed.

$$\begin{cases}1keV\le E_{peak}^{int}\le 10^4 keV\\ 10^{46}\, ergs/sec\le L_{iso}\le 10^{54}\, ergs/sec\end{cases}$$

Limits for the one-second isotropic peak luminosity and intrinsic peak energy of GRB

$$F_T=\frac{\int_{E_{min}}^{E_{max}}\Phi(E)dE}{\int_{E_{min}}^{E_{max}}\varepsilon(E)\Phi(E)dE}\,\frac{\sigma_0\sqrt{\int_{E_{min}}^{E_{max}}B(E)dE}}{f_{mask}\sqrt{Af_{det}\Delta t}}$$

This equation gives 1-second peak flux threshold for GRB trigger by a detector. The Detectors Response Matrix (DRM), is approximated by the detectors efficiency. By this, we are assuming that DRM is strictly diagonal. However, including the exact DRM would only make slight changes which are not important to the first approximation. (Lloyd, et al. 2000, Band, 2003).

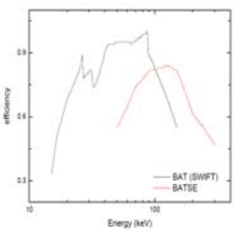
A: The fraction of detector plane that is active
f_{det}: The fraction of detector plane that is active
f_{maskt}: The fraction of the coded mask that is open
Δt: data accumulation time bin (here assumed to be 1024ms)
$\varepsilon(E)$: The efficiency function of detector
$B(E)$: background flux
σ_0: trigger significance

$$P_{bolo}=P\frac{\int_{1/(1+z)}^{10^5/(1+z)}E\Phi(E)dE}{\int_{E_{min}}^{E_{max}}E\Phi(E)dE},\quad P_{bolo}=\frac{L_{iso}}{4\pi D_L^2}$$

$$D_L=cH_0^{-1}(1+z)\int_0^z dz'\left[(1+z')^3\Omega_M+\Omega_\Lambda\right]^{-1/2}$$

Using this equation, 1-second bolometric peak flux can be obtained knowing redshift (z) and 1-second peak luminosity. From that one can obtain 1-second observed peak flux in the detection energy band of the detector.

Detector efficiencies



Detector sensitivities

SWIFT:
Energy band: 15-150 keV
Sensitivity:

$$F_T\,(\text{for exposure }T)\sim 2\times10^{-10}\,\frac{ergs}{cm^2 s}\left(\frac{T}{20Ks}\right)^{-0.5}$$

$5\sigma_0$ significance

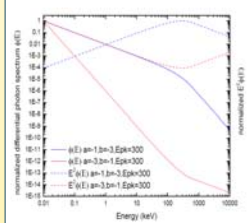
BATSE:
Energy band: 50-300 keV
Sensitivity:

$$F_T\sim 0.3\,\frac{counts}{cm^2 s}$$

5.5σ significance

Band Model for two cases of

$\alpha>\beta,\alpha>-2$, (Blue line)
$\alpha<\beta,\alpha<-2$, (Red line)



Star formation rate

We assume that GRB rate (R(z)) follows star formation history and that the luminosity function LF(L,z) of GRBs can be described by single power law (Guetta, 2007) which is redshift dependent. (Porciani 2001, Lloyd 2002)

$$\frac{dN_{GRB}(L,z)}{dLdzdt}\propto\frac{R_{GRB}(z)}{1+z}\frac{dV(z)}{dz}LF(L,z)$$

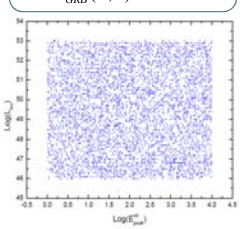
$$R_{GRB}(z)\propto\frac{e^{3.4z}}{e^{3.4z}+22}\quad\text{(Porciani et al, 2001)}$$

$$LF(L,z)\propto L^{-1.6}(1+z)^{1.4\pm0.5}$$

II. Simulation Results

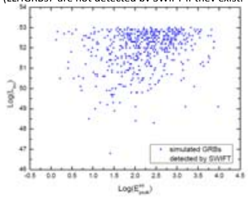
1. Even distribution of GRBs through the whole universe

$$dN_{GRB}(L,z)=Const.$$

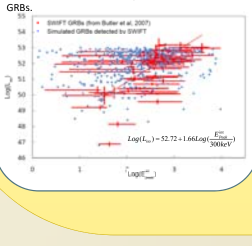


We start by throwing ≈ 5000 GRBs that have quite random peak energy, isotropic luminosity, redshift and spectral indices within the ranges mentioned above. The above graph of Liso-Epeak shows the distribution of fake GRBs created for simulation before being detected by the detector (here SWIFT & BATSE). GRBs having Liso higher than 10^53 ergs/s are not considered for the simulation.

The graph below is the same as above, but only for the bursts that are detected by BAT (onboard SWIFT) after running the simulation. It is clear that there is a cut-off for the region that is detectable by BAT and most of Low Luminosity Hard GRBs (LLHGRBs) are not detected by SWIFT if they exist.

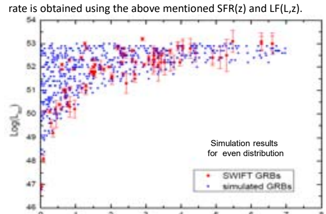


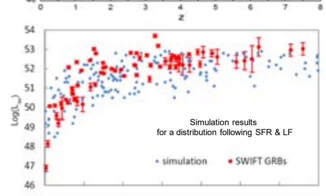
The graph below compares Liso-Epeak plot for simulated GRBs and real GRBs detected by SWIFT so far. (until May, 2007). The correlation line for the real GRB sample fits well with cut-off line for the detected GRBs in the simulation. There is only one burst detectable below 10^47 (ergs/s) out of 530 detected GRBs.

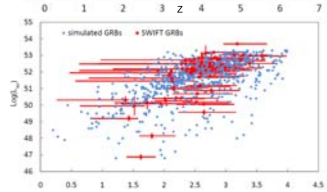


2. simulations following star formation rate (SFR) & luminosity function (LF)

The previous simulation done in (1) was just a very rough analysis of the real universe. However, the general conclusion is still true that there is probably a selection bias in GRB detections by SWIFT, since the real (uneven) distribution of GRBs does not make any changes in the cut-off line. In order to exclude as most unreal GRBs as we can from the graphs in (1), we run the simulation for several SFR & LF models. The best consistency with the real GRB rate is obtained using the above mentioned SFR(z) and LF(L,z).

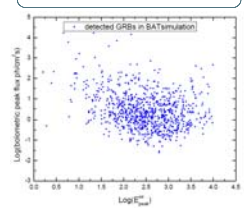




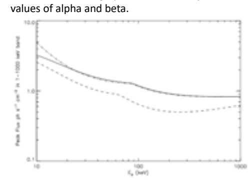


The above graph compares the distribution of the simulated GRBs with SWIFT observations. As it is clear in the graphs of part (1), there was a fake population of bursts in the upper left side of Liso-Epeak graph that we tried to eliminate them in the graph above. Our analysis of the SWIFT GRBs shows that the farther the GRB is from the best linear fit (on the upper left hand side of the graph), the less real it might be and the number of real GRBs in that region drops exponentially with an exponent of ~ -2.96. We used this to remove smoothly the fake GRBs. It has also been noticed before in BATSE sample of GRBs that these bright, soft bursts do not exist. However, there might be real bursts on the other side of the graph (which corresponds generally to intrinsically dim, hard bursts) that are not detectable. The existence of such bursts has already been predicted by several authors (Nakar 2005,Butler 2008,...) and some outliers to Liso-Epeak relation have been detected by different experiments. (GRB 980425, GRB 031203, see also Schaefer 2007)

3. Properties of detected GRBs in the simulation

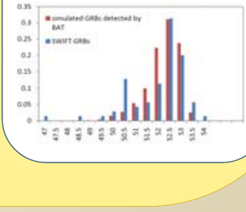


The above graph shows the bolometric count rate for the detected GRBs in the simulation of BAT vs. Epeak. While the peak flux threshold is the same for all GRBs, their bolometric peak flux shows a slight variation with Epeak. This is consistent with the results of Band, 2003 which is plotted below. However, There are some differences between the above graph and Band results. The reason is that we have used very different values of spectral indices (alpha and beta) for the fake sample of GRBs, while the graph below is only for fixed values of alpha and beta.



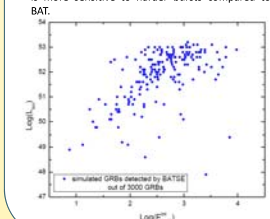
Peak flux (1–1000 keV) threshold of the Swift BAT detector calculated by Band (2003). Solid line: alpha=-1,beta=-2. Dashed line: alpha=-0.5,beta=-2. Dot-dashed line: alpha=-1,beta=-3

The histogram below shows the normalized distribution of the real GRBs detected by SWIFT and the results of the simulation using the star formation rate and the luminosity function mentioned earlier. We should note that our simulation does not follow exactly the star formation rate and the luminosity function distribution, since the range of luminosity is so wide that the simulation can only follow the SFR and LF for GRBs with very low probability of detection (i.e. high luminosity GRBs).



4. Simulation of BATSE onboard CGRO

We also ran the simulations for BATSE in the detection energy range of 50-300 keV. The result is the same as for SWIFT, that is, there is a clear cut-off in the plot of Liso-Epeak. This implies that BATSE sample of GRBs is probably contaminated by the selection effects of the detector and low luminosity hard burst are likely to be missing in BATSE sample of GRBs. This is in addition to the fact that BATSE was less sensitive than BAT onboard SWIFT and was not as good as SWIFT in detecting low luminosity bursts. The simulations show that for a given number of bursts, BATSE generally detects less GRBs than SWIFT does. The histogram of the peak energy of the detected GRBs for both instruments, also shows that BATSE is more sensitive to harder bursts compared to BAT.



III. Conclusion

We ran several Monte Carlo simulations for BAT and BATSE GRB detectors. The simulations show that for an even distribution of GRBs in the universe with quite randomly chosen spectral parameters, the detectors can create fake correlations between these parameters. The simulations for BAT also show that the detection biases might also result in a slight correlation between the duration of GRBs (i.e. T90) and their one-second isotropic peak luminosity, that is, for a given luminosity, longer bursts generally have more chance of detection than shorter bursts. The simulations also indicate the existence of an optical observational bias in detection of GRBs. This can explain why the cut-off line is slightly shifted to right side of best linear fit to the real GRB sample. As we go to the right of the plot (higher Epeak), bursts become fainter, but still detectable in our simulation, while in the real detection process, fainter GRBs have less chance of redshift measurement. We also find the same common features in all other spectral correlations of GRBs like Tlag-Liso, Trt-Liso, and Amati relation which implies that these correlations are likely due detector triggering biases.

References:

1. Shahmoradi, Amir and Nemiroff, Robert J, 2015, MNRAS, 451, 126-143
2. Shahmoradi, Amir, 2013, The Astrophysical Journal (ApJ), 766, 111
3. Shahmoradi, Amir, 2013, Stanford eConf Proc. C1304143, paper 14; arXiv:1308.1097
4. Shahmoradi, Amir and Nemiroff, Robert J, 2010, MNRAS, 407, 2075–2090
5. Shahmoradi, Amir and Nemiroff, Robert J, 2011, MNRAS, 411, 1843–1856
6. Shahmoradi, Amir and Nemiroff, Robert J, 2009, AIP Conf Proc, 1133, 425
7. Shahmoradi, Amir and Nemiroff, Robert J, 2009, AIP Conf Proc, 1133, 323