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GRB Physics And Cosmology With Peak Energy-Intensity Correlations

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Abstract. Gamma Ray Bursts (GRBs) are immensely energetic explosions radiating up to 10^{54} erg of energy isotropically (E_{iso}) and they are observed within a wide range of redshift (from ~ 0.01 up to ~ 9). Such enormous power and high redshift point at these phenomena being highly favorable to investigate the history and evolution of our universe. The major obstacle in their application as cosmological study-tools is to find a way to standardize the GRBs, for instance similar to SNe Ia. With respect to this goal, the correlation between spectral peak energy ($E_{p,i}$) and the "intensity" is a positively useful and investigated criterion. Moreover, it has been demonstrated that, through the $E_{p,i} - E_{iso}$ correlation, the current data set of GRBs can already contribute to the independent evidence of the matter density Ω_M being ~ 0.3 for a flat universe scenario. We try to inspect and compare the correlations of $E_{p,i}$ with different intensity indicators (e.g., radiated energy, average and peak luminosity, bolometric vs. monochromatic quantities, etc.) both in terms of intrinsic dispersion and precise estimation of Ω_M. The outcome of such studies are further analyzed in verifying the reliability of the correlations for both GRB physics and their standardization for cosmology.

INTRODUCTION

The typical spectra of GRBs prompt emission can be explained in terms of the Band function (Band et al. 1993)[1] which can be considered as a smoothly broken power law with the spectral fit parameters namely the low energy index α, the high energy index β, the break energy E_0 and the overall normalization. In this function, if $\beta < -2$ then the νF_ν (spectra in terms of Energy) spectral peak energy is given by $E_p = E_0 \cdot (2+\alpha)$. Here, E_p is the photon energy at which the energy spectrum attains a peak. For those GRBs with fairly reliable observations of the redshift and a good spectral profile, it is then possible to compute the cosmological rest–frame peak energy ($E_{p,i}$). The correlation of $E_{p,i}$ with the total radiated isotropic–equivalent energy (E_{iso}) or peak luminosity ($L_{p,iso}$) is one of the highly exploited correlations for standardizing long GRBs. The correlation is derived from combination of huge luminosities of GRBs (usually more than 10^{52} erg/s) and redshift distribution extending up to 9 (i.e. much beyond that of SNe Ia). Hence, it seems to be very interesting device for considering measurements of the cosmological parameters and, in perspective, the properties of dark energy.

The prime issue regarding this standardization is the observed scatter in distribution of GRBs. Apart from that, in the past years there have been debates about the validity and authenticity of this correlation. Under these considerations, an important task is the consideration of correlating $E_{p,i}$ with all the possible intensity indicators associated to GRBs. This comparison between purely observed quantities can help us to clarify the possible causes of the dispersion and hence can point out the best correlation candidate for standardizing GRBs with most constrained spread. This comparison is vital also for the better understanding of the selection and instrumentation biases affecting the standardization of GRBs.

In this short paper, we present some partial and preliminary results of a fairly organized data collection and analysis aimed at comparing the different $E_{p,i}$ – "Intensity" correlations not only from the point of view of their dispersion but also their accuracy in the estimate of cosmological parameters and their applicability for understanding GRB physics and GRB classification.

Data Sample

We assemble the spectral information of GRBs with measured redshift beginning from February 1997 till September 2013. Our database comprises of redshift (z), both energy indices (α and β), the peak energy $E_{p,i}$ computed from the break energy E_0, t_{90}, exposure time, the fluence and the value of peak flux.

The redshift distribution covers a wide range ($0.033 \leq z < 9.0$) thus extending far beyond that of Type Ia SNe ($z \leq 1.7$). For the oldest GRBs (BeppoSAX, BATSE, HETE-2) and other GRBs up to mid 2008, the data was adapted from Amati et al 2008.[2]

The essential criteria behind selecting the measurements from a particular GRB mission are based on following aspects:

1. The observations were preferred for which the exposure time was at least 2/3rd of the whole event duration.
2. Considering the broad energy band and good calibration, Konus- WIND and Fermi/GBM were selected whenever available. For Konus- WIND, the measurements were taken from the official catalog (Ulanov et al. 2005[3]) and from GCN archives `(http://gcn.gsfc.nasa.gov/gcn3_circulars.html)`. In case of Fermi/GBM, the observations were taken from Gruber at al. 2011[4] as the official literature and from several other papers (e.g., Ghirlanda et al. 2004[5] , Ghirlanda et al. 2005[6] , Friedman- Bloom 2005[7] , etc.). The observations from SUZAKU were not included given that the uncertainties in the calibration are higher and also due to the fact that it operates in a narrow energy band.
3. The SWIFT BAT observations were considered when no other preferred missions (Konus- WIND , Fermi/GBM) were able to provide information. Also, it was considered only for those GRBs for which the value of $E_{p,obs}$ were within the energy band of the instrument. For Swift GRBs, the $E_{p,i}$ values derived from BAT spectral analysis alone were chosen from the results reported by the BAT team (Sakamoto et al. 2008 a,[8] b[9]). Other BAT $E_{p,i}$ values reported in the literature were not considered, because either they were not confirmed by Sakamoto et al. refined analysis (e.g., Cabrera et al. 2007[10]) or they are based on some speculative methods (Butler et al. 2007[11]). The GCN circulars were also considered when needed.

When we came across more than one mission with good observations based on the criteria explained above, we took into account the values and uncertainties of all those observations (hence more than one set for some finely observed GRBs). Also, when the observations were to be included in the data sample, we ensured that the uncertainty on any quantity doesn't go below 10% in order to account for the instrumental capabilities, etc. Hence, even when the error was lower, we assumed it to be 10%.

When available, the Band model (Band et al. 1993[1]) was considered because the Cut-off power law tends to overestimate the value of $E_{p,i}$.

Correlation of $E_{p,i}$ with various "intensity" indicators

In our work, we studied and analyzed the following intensity indicators:

- E_{iso} : The total radiated energy, computed by integrating the spectrum in a standard energy range and assuming isotropic emission.
- $L_{iso_{T90}}$: *The isotropic luminosity averaged over the T90 duration*: The T90 duration, in seconds, is defined as the time computed during which 90% of the burst fluence was accumulated. The start of the T90 interval is defined by the time at which 5% of the total fluence has been detected and the end of the T90 interval is defined by the time at which 95% of the fluence been detected. In our case, the luminosity is integrated over the T90.
- $L_{iso_{Exp}}$: *The isotropic luminosity averaged over the exposure time*: The time interval (in seconds relative to trigger time) used in the spectral fits over the duration of the burst. So the luminosity is computed over the whole duration of the exposure time.
- L_p: The luminosity computed at the peak of the spectrum.

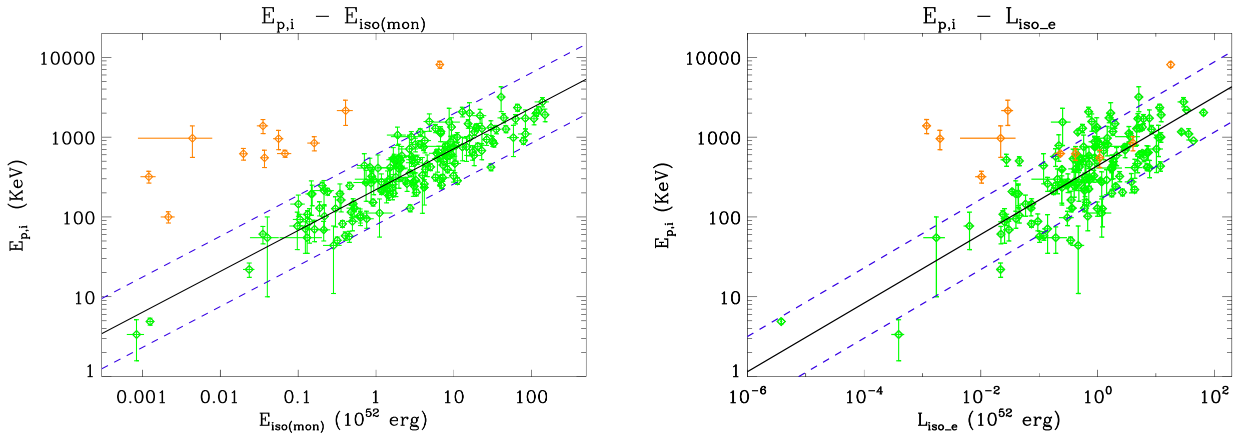

FIGURE 1: The **left panel** shows the monochromatic $E_{p,i}$–E_{iso} correlation where we have only considered the E_{iso} value at the peak of the energy spectrum. The **right panel** shows the $E_{p,i}$–L_{iso} correlation with respect to the exposure time. The green points are long GRBs and orange ones are short. In both the plots, the plain black line depicts the best fit line for that respective correlation and the blue dashed lines are the 2σ scatter limits of $E_{p,i}$–E_{iso} bolometric (Amati) correlation.

All the quantities were calculated over "**Bolometric**" (in the commonly used 1-10000 keV energy band in the cosmological rest frame) and also over "**monochromatic**" range (computed at the peak (E_p) of the νF_ν spectrum).

The fitting parameters (slope, normalization and dispersion) were estimated by following the statistical technique proposed by Reichart et al. (2001)[12] which deals with fitting of the data points affected by extrinsic scatter in addition to the statistical uncertainties. Some of the results are graphically represented in Figure 1 and reported in Table 1. As a reference for comparing the scatter of the different correlations, we utilized the bolometric $E_{p,i} - E_{iso}$ (Amati) correlation.

From the results presented in the panel above, we can estimate the following preliminary considerations:

- The $E_{p,i}$–E_{iso} correlation still claims to be the least scattered among all the correlations considered. This can be explained primely due to the fact that E_{iso} automatically considers that the brightest parts of a GRB play dominant role in determining the E_p value of the time–averaged spectrum. This is not taken into account while using the average luminosity (either over exposure time or T90 duration), which is affected by the assumption that all the time bins of the GRB equally contribute to the average $E_{p,i}$ value. Finally, the computation of the peak luminosity (not shown here) is affected by non homogeneous time scale and energy band on which it is computed, and hence probably produces a slightly more dispersed correlation with $E_{p,i}$, in both cases of time–averaged spectrum and of the spectrum measured at the peak of the light curve (available for a smaller fraction of GRBs).
- The correlation of $E_{p,i}$ with monochromatic quantities is less scattered with respect to what found with the bolometric ones (in table and figures we show the $E_{p,i}$–$E_{iso_{mon}}$, the least scattered amongst all the investigated correlations). This depicts that a part of the scatter is introduced while extrapolating to a bolometric energy band due to the uncertainties on the fitting parameters α and β.
- While studying the average luminosity instead of total radiated energy, the merging of some of the short GRBs into the long GRBs dominant region is observed. This case may be pointing at the necessity of better investigation of the terms and clauses of the classification of GRBs and also of their physical origin.

Implications on the Cosmology

We also investigated the accuracy of each considered correlation for cosmology, by following the maximum likelihood method that takes into account the uncertainties in both the X and Y axes quantities and the extra variance σ_{ext} proposed by Reichart et al. (2001)[12] and the method established by Amati et al. (2008).[2] Indeed, these authors discovered that, remarkably, the −log(likelihood) of the $E_{p,i}$–E_{iso} as a function of Ω_M assumed for the computation of E_{iso} within a flat ΛCDM scenario shows a nice parabolic shape, with a minimum at $\Omega_M \sim 0.30$.

We repeated the same analysis for all examined correlations. We observe that the dispersions of the correlations change uniquely. Also, the minimization of Ω_M varies but still remains considerably near to 0.3.

For all the correlations Ω_M shows a minimum around 0.3, although it is crucial to notice that for $E_{p,i}$–E_{iso} correlations for both bolometric and monochromatic computations, point out the minimization of Ω_M more precisely. The distinctive gain of considering monochromatic frame is that the fit results are independent on α and β and their uncertainties. The graphical representation can be seen from Figure 2 and the parameter computations are presented in Table 1.

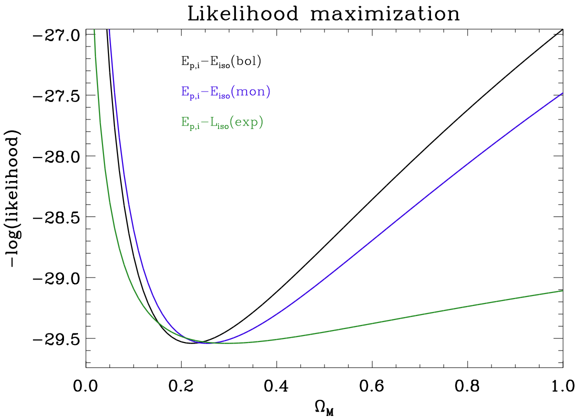

FIGURE 2: Likelihood maximization of some considered correlations as a function of Ω_M for flat CDM cosmology.

TABLE 1: Fit parameters of various GRB correlations

Correlation	**normalization**	**slope**	σ	Ω_M **with 68% C.L.**
$E_{p,i}$–E_{iso} bolometric	$1.95^{+0.04}_{-0.03}$	$0.54^{+0.03}_{-0.02}$	$0.22^{+0.02}_{-0.02}$	$0.22^{+0.25}_{-0.12}$
$E_{p,i}$–L_{iso} for exposure time	$2.64^{+0.02}_{-0.03}$	$0.43^{+0.03}_{-0.02}$	$0.30^{+0.02}_{-0.02}$	$0.29^{+0.44}_{-0.16}$
$E_{p,i}$–E_{iso} monochromatic	$2.34^{+0.02}_{-0.02}$	$0.51^{+0.02}_{-0.02}$	$0.19^{+0.02}_{-0.02}$	$0.25^{+0.18}_{-0.13}$

Conclusions

Our analysis points at the robustness of the $E_{p,i}$–intensity correlation, independent of the choice of luminosity indicator. E_{iso} comes across as the best intensity indicator, especially when considered for monochromatic range (less bias due to extrapolation).

Some of the short GRBs are seen to be lying inside the region which is dominated by long GRBs during the consideration of the luminosity instead of the radiated energy. Hence they may be shedding some light on the ideas behind the physical origin and differentiation of SGRBs- LGRBs.

The $E_{p,i}$–E_{iso} correlations for both bolometric and monochromatic energy scenarios, depict that the minimization of Ω_M is in more accurate order comparatively. The monochromatic $E_{p,i}$–E_{iso} correlation gives us the best accuracy for standardizing the GRBs due to the smaller scatter.

This work gives us some clues about the prospect of utilization of such correlations for cosmological applications.

Also the work positively supports the idea of considering GRBs as probe to study the history and evolution of our universe along with other cosmological objects already established like SNe Ia, galaxy clusters, CMB.

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