Outliers to the Isotropic Energy - Peak Energy Relation in GRBs

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ABSTRACT

The peak energy - isotropic energy (EpEi) relation is among the most intriguing recent discoveries concerning GRBs. It can have numerous implications on our understanding of the emission mechanism of the bursts and on the application of GRBs for cosmological studies. However, this relation was verified only for a small sample of bursts with measured redshifts. We propose here a test whether a burst with an unknown redshift can potentially satisfy the EpEi relation. Applying this test to a large sample of BATSE bursts we find that a significant fraction of those bursts cannot satisfy this relation. Our test is sensitive only to dim and hard bursts and therefore this relation might still hold as an inequality (i.e. there are no intrinsically bright and soft bursts). We conclude that the observed relation seen in the sample of bursts with a known redshift might be influenced by observational biases and from the inability to locate and well localize hard and weak bursts that have only a small number of photons. In particular we point out that the threshold for detection, localization and redshift measurement is essentially higher than the threshold for detection alone. We predict that Swift will detect some hard and weak bursts that would be outliers to the EpEi relation. However, we cannot quantify this prediction. We stress the importance of understanding the detection-localization-redshift threshold for the coming Swift detections.

1 INTRODUCTION

The detection of Gamma-ray Bursts (GRBs) afterglows enabled the determination of the redshift for a few dozens bursts (out of several thousands observed so far). This yielded a small sample of bursts for which the observed properties can be translated into intrinsic ones. This, in turn, initiated the search for relations between various intrinsic properties. Such a relation can have far reaching implications both on the theoretical understanding of GRBs and on the application of GRBs as a tool.

Even before a large sample of bursts with redshift was available, it was suggested that the intrinsic $E_p$ and $E_{iso}$ are correlated (Lloyd et al. 2000, Lloyd-Ronning & Ramirez-Ruiz 2002). Once more than a dozen redshifts were measured, Amati et al. (2002) reported a tight relation between the isotropic equivalent bolometric energy output in $\gamma$-rays, $E_{iso}$, and the intrinsic peak energy of the $\nu f_\nu$ spectrum, $E_p$ (hereafter we denote the $E_p$-$E_{iso}$ relation as EpEi):

$$E_{iso} = A_k E_p^k,$$

where $k \sim 2$ and $A_k$ is a constant. This result was based on a sample of 12 BeppoSAX bursts with known redshifts. Ten additional bursts detected by HETE II (Lamb et al., 2004; Atteia et al., 2004) supported this result and extended it down to $E_{iso} \sim 10^{49}$ ergs (see also Ghirlanda et al. 2004a).

Two bursts, within the current sample of bursts with a known redshift, GRB 980425 and GRB 031203 are clear outliers to the EpEi relation. Both are dim (low $E_{iso}$) and hard (high $E_p$). These two bursts are usually ignored as a peculiar outliers to a confirmed relation. Even though the EpEi relation is based on a small and unique sample (bursts with confirmed redshift and a well observed spectrum), and even though there are two clear outliers, this relation initiated numerous attempts to explain it theoretically and to use it for various applications. Therefore, testing the validity of the EpEi relation with the largest available sample (of several thousands BATSE bursts), is extremely important. This is the goal of this letter.

We present here (Eq. 5) a simple test whether a burst can potentially satisfy the EpEi relation. This test can be carried out for bursts with unknown redshift as long as we have a lower limit on the observed peak energy, $E_{p,obs}$ and an upper limit on the observed bolometric fluence, $F$. A burst that fails this test must be an outlier satisfying: $E_{iso} < A_k E_{p,obs}^k$. On the other hand a burst that passes this test does not necessarily...
satisfy the EpEi relation. One of the known outliers, GRB 980425, fails the test only marginally. However its low measured redshift puts it as a clear outlier.

First, we apply the test to a larger, but yet limited, sample of 63 BATSE bursts with unknown redshifts and a good spectral data (taken from Band et al. 1993 and Jimenez, Band, & Piran, 2001). We find that at least ~ 25% out of these bursts significantly fail the test and therefore are essentially outliers to the EpEi relation. Next, we consider the full current BATSE catalog \(^1\), for which we test all the long bursts \((T_{90} > 2\text{ sec})\) with a complete fluence data in all the four energy channels. The exact spectrum for these bursts is unknown, but we can still use the BATSE four energy channels data to obtain a lower limit on \(E_{p,obs}\) for about half of the bursts. We find that ~ 25% of the bursts in the BATSE sample fail the test, and must be outliers to the EpEi relation. The large numbers of outliers that we find in the different samples of BATSE bursts, suggest that the EpEi relation is not a generic property of GRBs. Our results do not, however, rule out possible correlation between \(E_p\) and \(E_{iso}\). We also do not test here the recently suggested relation between \(E_p\) and the beaming-corrected energy (Ghirlanda et al. 2004a), see however Band and Preece (2005).

In \(\S 2\) we present the basic ideas of our analysis. We apply the test to the sample of BATSE bursts with a known peak energy in \(\S 3\) and to the whole BATSE catalog in \(\S 4\). We discuss the implications of this result as well as possible reasons why so few outliers were found in the samples of bursts with known redshifts in \(\S 5\).

2 TRAJECTORIES ON THE \(E_{iso}-E_p\) PLANE

Consider a burst with known bolometric fluence, \(F\), and observed peak energy, \(E_{p,obs}\), but an unknown redshift, \(z\). Assuming a \(z\) value we can evaluate the intrinsics \(E_{iso}\) and \(E_p\). The trajectory of the burst on the \((E_{iso}, E_p)\) plane as we vary \(z\) is given by:

\[
E_{iso} = 4\pi D^2 \tilde{r}_c(z)(1+z) F
\]

\[
E_p = (1+z)E_{p,obs}
\]

where \(D \equiv c/H_0\) and \(\tilde{r}_c(z)\) is the dimensionless comoving distance to redshift \(z\). This trajectory represent all the possible values of the intrinsic \(E_p\) and \(E_{iso}\) for given \(E_{p,obs}\) and \(F\). On these trajectories \(E_p \propto E_{iso}^A\) for small \(E_{iso}\) values while \(E_p \propto E_{iso}\) for asymptotically large values of \(E_{iso}\). Several such trajectories are plotted in Fig. 1.

The EpEi relation (Eq. 1) is represented by a curve on the \((E_{iso}, E_p)\) plane. For \(k \geq 1\) (which is satisfied by any reasonable fit to the observed data) there are values of \((F, E_{p,obs})\) for which the trajectories (on the \((E_{iso}, E_p)\) plane) do not intersect the EpEi curve for any value of \(z\). These trajectories correspond to outliers to the EpEi relations (which is not satisfied for any value of \(z\)). Put differently, one can imagine using the EpEi relation to determine the redshift of observed bursts. For the bursts that the trajectories do not intersect there will be no value of \(z\) for which the EpEi relation is satisfied (Ghirlanda et al. 2004b). A second group of \(F, E_{p,obs}\) values are these for which the trajectories intersect the EpEi line. These bursts can potentially satisfy the EpEi relation as there is a possible \(z\) value for which this relation can be satisfied. Fig. 1 illustrates the two types of trajectories.

Substituting Eqs. 2 & 3 in Eq. 1 we obtain a general condition for an intersection between a trajectory of an observed burst and the EpEi line:

\[
\frac{A_k}{4\pi D^2} \frac{E_{p,obs}^k}{F} = \frac{\tilde{r}_c(z)}{(1+z)^{k-1}}.
\]

The dimensionless function on the r.h.s. depends only on \(z\). It vanishes as \(z\) vanish and at large values of \(z\) (for \(k > 1\)) and hence it has some maximal value denoted \(C_k\). All the bursts for which the observables on the l.h.s. are larger than this maximal value are outliers to the EpEi relation. We define a ratio

\[
d_k \equiv \frac{A_k}{4\pi D^2 C_k} \frac{E_{p,obs}^k}{F}.
\]

- Bursts with \(d_k < 1\) can potentially satisfy the EpEi relation.
- Bursts with \(d_k > 1\) cannot satisfy the EpEi relation. For these bursts \(d_k\) is a measure of the minimal “distance” of the burst from the EpEi relation. Namely, the observed combination \(E_{p,obs}^k / F\) should decrease by this factor in order that the EpEi relation would be potentially satisfied.

3 BURSTS WITH A KNOWN OBSERVED PEAK ENERGY

Following the observations (Amati et al., 2002; Lamb et al., 2004; Atteia et al., 2004) we present here (and in \(\S 4\) the results for \(k = 2\) with \(A_k = 1^{+1}_{-0.5}, 10^{39}\text{ergs/keV}^2\). The error introduced here is our estimate of the spread in the data. All the bursts in the sample of Atteia et al. (2004) are consistent within 1\(\sigma\) with these values. Our results do not change qualitatively for other values of \(k\) and \(A_k\) that yield a reasonable

\(^1\) http://www.batse.msfc.nasa.gov/batse/grb/catalog/current/
we obtain:

with fit to the data. The cosmological parameters that we consider are $\Omega_m = 0.3$, $\Omega_\Lambda = 0.7$ and $h = 0.7$, for which $C_2 = 0.56$. For these values we obtain:

$$d_2 = 8 \cdot 10^{-10} \left( \frac{E_{p,\text{obs}}/1\text{keV}}{(F/(1\text{erg cm}^{-2}))} \right)$$

We consider a sample of BATSE bursts (from Band et al., 1993, and Jimenez et al., 2001) with unknown redshifts for which the observed peak energy has been determined. We consider only bursts with a high spectral index smaller than $-2$ in order to ensure that the break energy in the observed spectrum is indeed the peak of $\nu F_\nu$. Our sample includes 63 (40 bursts from Band et al. 1993, and 23 bursts from Jimenez et al. 2001). Using the spectral fits for these bursts we derive their bolometric fluence (0.1-10000 keV).

Fig. 2 depicts a color map of $d_2$ for each burst on the $F, E_{p,\text{obs}}$ plane. The observed values of our sample (including error bars where available) are marked on this map. From Fig. 2 it is evident that a significant fraction of the bursts cannot satisfy the EpEi relation. Fig. 3 depicts a histogram of the fraction of bursts with $d_2$ larger than a given value. We account for uncertainties in the measurement of $E_{p,\text{obs}}$, when possible, by using an $E_{p,\text{obs}}$ value that is smaller by $1\sigma$ than the measured value (unfortunately we can do it only for the Band et al. 1993 sample since the uncertainties in the measurement of $E_{p,\text{obs}}$ are not reported in Jimenez et al., 2001). Fig. 4 shows that $\approx 40\%$ of the bursts have $d_2 > 2$ while $25\%$ of the bursts have $d_2 > 4$ (9/40 from Band et al., 1993 and 6/23 from Jimenez et al., 2001). Since the scatter in the EpEi relation is a factor of 2 we consider, conservatively, a burst with $d_2 > 4$ as an outlier. Finally, $13\%$ of the bursts are very far from the relation having $d_2 > 10$. We stress that these are only lower limits. While bursts for which $d_2 < 1$ can satisfy the EpEi relation, they do not necessarily do so.

4 BATSE BURSTS

Only a small fraction of BATSE bursts have a published $E_{p,\text{obs}}$ values. Still we can obtain a lower limit of $E_{p,\text{obs}} > 250\text{keV}$ for all BATSE bursts for which:

$$F_{E_1,E_2} > 1.25,$$

where $F_{E_1,E_2}$ is the fluence between $E_1$ and $E_2$ reported in the four BATSE windows. This lower limit holds for a Band spectra (Band et al. 1993) over a wide range of low and high spectral indices ($\alpha$ and $\beta$ respectively). As a test of the validity and robustness of this criterion we apply it to the BATSE bursts with known $E_p$ (Band et al. 1993 and Jimenez et al. 2001, including those with $\beta > -2$ and those with known

![Figure 1](image-url)
Figure 2. A color map of $d_2$. The region marked in white, where $d_2 < 1$ corresponds to allowed solutions of the $E_{\text{p}}$-$E_{\text{iso}}$ relation. Larger values are marked with darker colors and they correspond to the minimal ratio between $E_{\text{iso}}$ given by the $E_{\text{p}}$-$E_{\text{iso}}$ relation and $E_{\text{iso}}$ given by the $(E_{\text{p}}, E_{\text{iso}})$ trajectory, for the same value of $E_{\text{p}}$. Also marked on this figure are values of $F$ and $E_{\text{p,obs}}$ for 39 BATSE bursts from Band et al. (1993) (diamonds), and 22 BATSE bursts from Jimenez et al. (2001) (squares). For 29 [15] out of these 61 bursts $d_2 > 2$ [4]. GRB 980425 (full star) has a marginal $d_2 \approx 3$.

We find that indeed all the bursts in the sample, apart for one, that satisfy Eq. 7 have $E_{\text{p,obs}} > 250$ keV (23 bursts all together).

Using this lower limit on $E_{\text{p,obs}}$ we can obtain a lower limit on $d_2$ for a large sample of BATSE bursts, where we take $F$ in $20 - 2000$ keV energy range (the sum of all 4 channels) as the bolometric fluence.

We consider a sample of 751 long ($T_{90} > 2$ sec) bursts from the current BATSE catalogue. Our selection criteria were having fluence in all four BATSE bands, having errors that are smaller than half of the measured values in all the four bands and having a measured $T_{90}$. 361 of these bursts satisfy Eq. 7 yielding a lower limit on their $E_{\text{p}}$. Fig. 3 depicts also the fraction of long bursts out of the sample of 751 bursts, that satisfy Eq. 7 and have $d_2 > n$. We find that approximately 35% of these bursts have $d_2 > 2$, about 30% have $d_2 > 4$ and for 10% this ratio is larger than 15!. While this estimate is less robust than the previous ones (i.e. we cannot quantify the error in the lower limit we obtain for $E_{\text{p,obs}}$) it is clear that a significant fraction of long BATSE bursts cannot satisfy the EpEi relation. This result has been confirmed by Band and Preece (2005) that use a sample of 760 BATSE bursts where $E_{\text{p,obs}}$ is known.

Finally, we have also performed the same test for the 187 short ($T_{90} < 2$ sec) BATSE bursts satisfying the same criteria. These bursts are typically harder than long ones. As they are shorter they also have a lower overall fluence. One could expect that they won’t satisfy the EpEi inequality. We find that more than 75% of BATSE short bursts have $d_2 > 10$. Short bursts cannot satisfy the EpEi relation! This result is similar to the one obtained by Ghirlanda et al. (2004).

5 DISCUSSION

We have presented a simple method for testing whether a burst can potentially satisfy the $E_{\text{p}}$-$E_{\text{iso}}$ relation. This method requires only two observables, the bolometric $\gamma$-rays flux and the peak energy. Both can be determined for every observed burst regardless of its localization and redshift determination. We have carried this test for several samples of BATSE bursts. We find that approximately 25% of the BATSE bursts in these samples fail the test and hence they are outliers to the EpEi relation. We stress that this fraction is only a lower limit as bursts that pass the test may still not satisfy the EpEi relation, once their redshift is known. These results imply that the EpEi relation, in its current form, may not be a generic property of GRBs. It is present only in the small sample of bursts with confirmed redshifts and not in the whole sample of observed bursts.

None of the outliers we find has an isotropic energy larger than the one predicted by the EpEi relation. Truly, our test could not find
such bursts. However, the two known outliers have lower isotropic energy than the one predicted by the EpEi relation. Moreover, already the BATSE data demonstrated the absence of soft and bright bursts. The absence of such bursts is confirmed by BeppoSAX and HETE II which would have easily detected and localized them. Thus, we suggest that the common EpEi relation should be replaced by an EpEi inequality:

$$E_{\text{iso}} \lesssim A_k E_p^k.$$  

(8)

The natural question that arises is why there are so many outliers in the BATSE data while there are only two outliers to the EpEi relation in the current sample of bursts with confirmed redshifts? One possibility is that there are systematic errors. Since \(d_2 \propto E_{p,\text{obs}}^2\), if for some reason \(E_{p,\text{obs}}\) of all the BATSE bursts is overestimated by a factor of \(\gtrsim 2\) or if it is underestimated by the same factor for BeppoSAX and HETE II bursts, then BATSE sample may be consistent with an EpEi relation. The other possibility is that the difference between BATSE data and the current sample of bursts with confirmed redshifts results from an observational selection effect (Lloyd-Ronning & Ramirez-Ruiz 2002). This explanation is supported by the fact that both outliers were not localized in the usual manner by either BeppoSAX or HETE II whose localized bursts compose the localized bursts sample. The first, 980425, was detected and localized by BeppoSAX. However, if it was not for the discovery of SN 1998bw (Galama et al., 1998) the identification of its host galaxy and the measurement of its redshift would have remained questionable. The second outlier, 031203 was localized by INTEGRAL (Sazonov, Lutovinov & Sunyaev 2004). Observational selection affects might play a complicated roll especially since the threshold for redshift measurement might be higher than the threshold for detection. This is intuitively clear as the redshift determination requires not only a detection of the prompt emission but also a fast localization and an afterglow detection.

Our results suggest that Swift, which is expected to reduce the threshold for detection, localization and afterglow detection, will detect dim and hard bursts that do not satisfy the EpEi relation. It is impossible, however, to quantify this prediction without a clear understanding of the threshold for redshift measurement. Moreover, this second threshold would have to be understood in order to use the coming sample of Swift bursts with known redshifts to study the relation between \(E_p\) and \(E_{\text{iso}}\), or other intrinsic properties of the GRB population.

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