Reviewing E_{peak} relations with Swift and Suzaku data

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Abstract. In recent years several authors have derived correlations between gamma-ray burst (GRB) spectral peak energy (Epeak) and either isotropic-equivalent radiated energy (Eiso) or peak luminosity (Liso). Since these relationships are controversial, but could provide redshift estimators, it is important to determine whether bursts detected by Swift exhibit the same correlations. Swift has greatly added to the number of GRBs for which redshifts are known and hence Eiso and Liso could be calculated. However, for most bursts it is not possible to adequately constrain Epeak with Swift data alone since most GRBs have Epeak above the energy range (15-50 keV) of the Swift Burst Alert Telescope (BAT). Therefore we have analyzed the spectra of 78 bursts (31 with redshift) which were detected by both Swift/BAT and the Suzaku Wide-band All-sky Monitor (WAM), which covers the energy range 50-5000 keV. For most bursts in this sample we can precisely determine Epeak and for bursts with known redshift we can compare how the Epeak relations for the Swift/Suzaku sample compare to earlier published results.

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INTRODUCTION

Since the launch of the *Swift* gamma-ray burst explorer [1] mission we have seen a greatly increased number of gamma-ray bursts (GRBs) for which X-ray and optical counterparts have been detected, leading to a known or inferred red shift for a much larger sample of bursts. For the first 384 bursts that triggered *Swift*, 130 have a published red shift. As burst red shifts became known, a number of authors derived relationships between various measured quantities of the prompt emission, usually relating the time-averaged $\nu F \nu$ spectral peak energy (E_{peak}) of the prompt emission to bolometric properties of the explosion. It is difficult to test this relationship using *Swift* data alone is difficult because the narrow bandpass of the Burst Alert Telescope (BAT) [2] (15-150 keV for a strong modulated response) falls below E_{peak} for the majority of GRBs. However, by combining the *Swift* data with results from another instrument with a higher energy response, it is possible to accurately determine E_{peak} for all bursts which are bright enough for reasonable spectral fits.

Due to their large fields of view, it is not uncommon that GRBs will be observed by both the BAT and the Wide-band All-Sky Monitor (WAM) on *Suzaku* [3, 4]. Between August 2005 and September 2008, 44 bursts triggered both instruments. Of these bursts 21 have redshifts. There are an additional 41 bursts untriggered in WAM (and 1 untriggered in BAT), 11 of which have redshifts. After rejecting 8 bursts which could not be fit, we were able to fit the spectra of 77 bursts jointly detected by BAT and WAM. Of this set, 18 bursts were best fit by a simple power law model, thus we have 59 bursts (28 with redshifts) for which E_{peak} can be determined – about two per month and 20% of all Swift triggers (27% of triggers with redshifts) during the period of overlap between *Suzaku* and *Swift*. This compares to 8 Swift bursts in the sample reported by Amati [5]. This technique is ready to be applied to all Swift/GLAST simultaneous detections.

METHODOLOGY

All of the bursts used in this study triggered either the Burst Alert Telescope (BAT) on Swift or the Wide-Band All-Sky Monitor (WAM) on Suzaku, and in most cases triggered both instruments. The burst spectra used in this study were fit jointly to the BAT and WAM data and fits include the time-intergrated spectra, the peak second of the BAT light curves, and sets of various time resolved intervals. Either one or two of the four WAM detectors were used in the fits, depending on which dectectors were hit. For the BAT bursts event data was used to derive first a light curve in the 15-200 keV band. From this light curve we used the standard *Swift*/BAT tool *battblocks* to determine the total time interval of the burst in the BAT energy range T_{100} and those subsidiary peaks of the prompt emission which were found by the tool to be statistically significant.

Fits were made for each time interval to a simple power law (PL) model, a power law model with an exponential cut-off (CPL), and the two-component (Band) model [6]. The fits for each interval and each model were inspected and a time interval/model was rejected if either (a) the power-law index, α, was not constrained, (b) the reduced chi-squared, $\chi^2_{red} > 2$ or (c) the WAM constant C was not consistent with unity. For the CPL and Band models we added the criteria that (d) E_{peak} be constrained. In addition, for each time interval (time-integrated and time-resolved), the "best" spectral model was determined. The default for each case was a simple power law model. If, however, the difference in χ^2 between the PL fit and the CPL fit or between the CPL fit and the Band fit was $\Delta\chi^2_{(a,b)} > 6.0$, where $\Delta\chi^2_a \equiv \Delta\chi^2_{PL} - \Delta\chi^2_{CPL}$ or $\Delta\chi^2_b \equiv \Delta\chi^2_{CPL} - \Delta\chi^2_{Band}$, then the more complicated model was deemed to be the "best" model. Of course this more complicated model fit also had to meet the acceptability criteria given above. With this selection method, for the full burst intervals, 19 bursts were found to be best fit by the simple PL model, 47 by the CPL model and 11 with the Band model. However, for 43 of the bursts for which the CPL model was the best fit, the Band model was also an acceptable fit. In all of these cases the values of E_{peak} for the two models were identical to within statistics.

In those cases in which either the CPL or the Band model is the best fit and when a red shift is known, we transformed E_{peak} to the source frame by multiplying E_{peak} (observer) by a factor (1+z). After this we determined, for each burst, the isotropic energy (E_{iso}) integrated over the total burst interval and over each time-resolved burst interval. So that we were sure to compare equivalent quantities for each burst, we used only the Band model to calculate the integrated flux, including those cases for which the Band model gives an acceptable fit, but is not the "best" fit model. This is justified because we believe that a Band model is the intrinsic fit to each burst spectrum, and only poor statistics at high energies keep the Band model from being the universally best fit. Bursts for which the high energy power-law index β is not constrained are also included in our sample, and the uncertainty in this parameter contributes to the overall error in the flux. To find E_{iso}, we used the method of [7] to derive E_{iso} from the integrated flux: $E_{iso} = 1/(1+z)\int_1^{10000}[EN(E)dE \times 4\pi * dL^2]$. We also used the methods of [8] to derive for each peak second, L_{iso} over the energy range 30-10,000 keV. To allow direct comparison we used the same cosmological parameters as the earlier authors: H_0 = 65 (72) km/s, Ω_m = 0.3 (0.32) and Ω_Λ = 0.7 (068) for [5] ([8]).

RESULTS

Comparison to Previously Published Relations

For 28 of the Swift/Suzaku bursts in the study set, we have a measurement of both E_{peak} and a spectroscopic redshift. For these bursts we can compare the parameters derived in this work to the results published by Amati [5] and Yonetoku et al. [8].

In Fig. 1 we plot E_{peak} versus E_{iso} and the symbols are explained in the figure caption.[1] and the dashed line is our fit to all Swift long bursts shown in the plot.

We find that our sample shows a clear correlation between E_{peak} and E_{iso} for long GRBs. The points (weighted for statistical variance) as best fit by the line $E_{peak} = 2.11(E_{iso})^{0.49}$, where E_{peak} is in units of keV, and E_{iso} units of 10^{52} erg. The slope of the relationship, 0.49, is consistent with the slope of 0.49 found by Amati [5], but the fit line is shifted toward larger values of E_{peak}. Part of this is due to an abundance of high E_{peak} bursts relative to the Amati [5] sample, but taking only the main body of bursts with 100 keV $< E_{peak} <$ 1000 keV, we achieve a similar result:

[1] The fit and the discussion in the next two paragraphs excludes the subluminous outlier GRB 060505

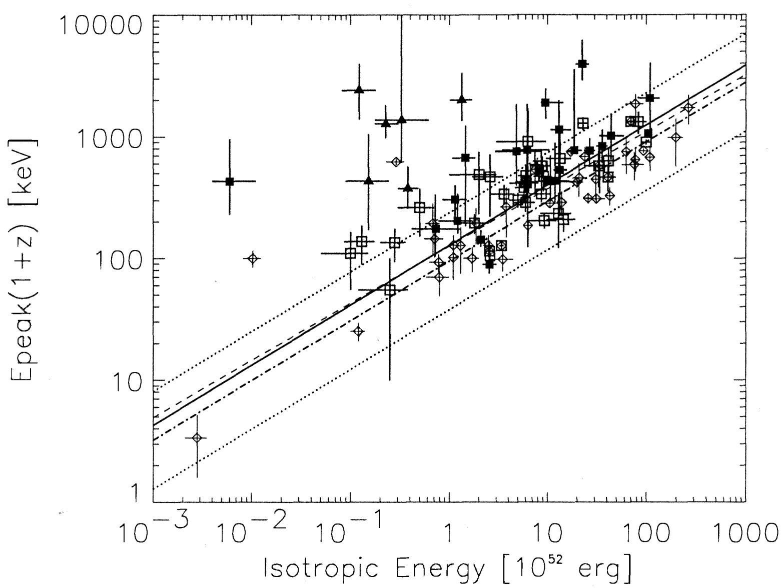

FIGURE 1. Comparison to the results of Amati [5]. Filled points are from this work (long bursts squares; short bursts triangles). Open points are from earlier work: diamonds: [5], and squares: [9, 10]) with *Swift* bursts in the [5] sample marked as open squares surrounding open diamonds. The lines denote: dashed – fit to the long bursts in this sample, solid – fit to all *Swift* bursts, dot-dash – fit from [5], dotted – deviations from [5] fit.

$E_{peak} = 2.14(E_{iso})^{0.50}$.

We see in Figure 1 that short GRBs do not follow the same $E_{peak} - E_{iso}$ relation as long bursts. Short bursts are all outliers to the relation in the direction of lower E_{iso} for a given E_{peak}. If we include GRB 050709 [5], we can make a tentative fit to the short burst distribution, deriving a fit to $E_{peak} = 3.10(E_{iso})^{0.55}$, but this fit is heavily weighted by this single burst, while all other short bursts are in a broad cluster for which no correlation is found. Thus we cannot claim that there is any significant $E_{peak} - E_{iso}$ relation for short GRBs.

Another important relationship was discovered by Yonetoku et al. [8], who found a good correlation between the time-integrated burst E_{peak} and the luminosity in the brightest one second of the burst, L_{iso}. We have compared our results to those of Yonetoku et al. [8] in Figure 2. We see the same general trend as was found in the earlier work, and a very similar slope, but a bias toward higher values of E_{peak} and a much larger scatter in the data. We also do not see a clear distinction between long and short bursts in this plot. Given this very large scatter, we cannot confirm the $E_{peak} - L_{iso}$ relation of Yonetoku et al. [8].

Other correlations from this work

Using our fits to a large number of individual burst pulses we can compare E_{peak} and E_{iso} for individual burst pulses. This result is shown in Figure 3. The best fit to this sample is $E_{peak} = 2.58(E_{iso})^{0.33}$, which is shown by the solid line in Figure 3. On the whole this distribution shows a tighter correlation than does the time-integrated sample, indicating that the $E_{peak} - E_{iso}$ relation is intrinsic to burst pulses. The offset of this distribution from the time-integrated fit can be easily understood. Burst pulses have a distribution of E_{peak} values similar to time integrated E_{peak} values, but since the durations of pulses are shorter there is less integrated flux in a pulse. Because a total burst is made up of a compilation of pulses, each with its own point on the $E_{peak} - E_{iso}$ plot, it is not surprising that the time integrated distribution has a larger intrinsic scatter. This shows that the total burst $E_{peak} - E_{iso}$ relation is a consequence of the relation holding for individual burst pulses. As for the time-integrated sample, short burst pulses are outliers to the overall relationship. There are not enough short burst pulses to be able to say whether or not there is any correlation in this sample.

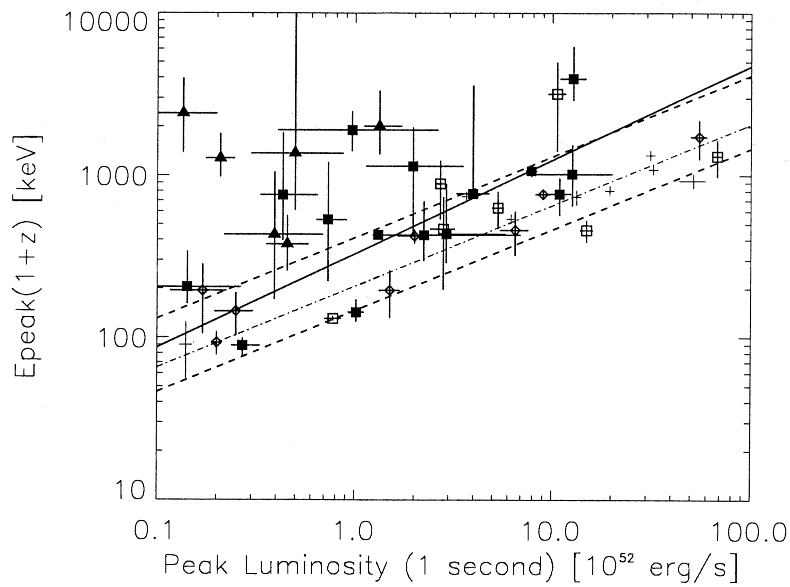

FIGURE 2. Comparison of this sample (filled squares: long bursts; filled triangles: short bursts) to that of Yonetoku et al. [8] (crosses and diamonds) and Krimm et al. [11] (open squares). The solid line is the best fit to this data set. The best fit lines (dash-dot line) and deviations (dashed lines) are from Yonetoku et al. [8]. This plot uses the time-integrated E_{peak} and the peak second flux.

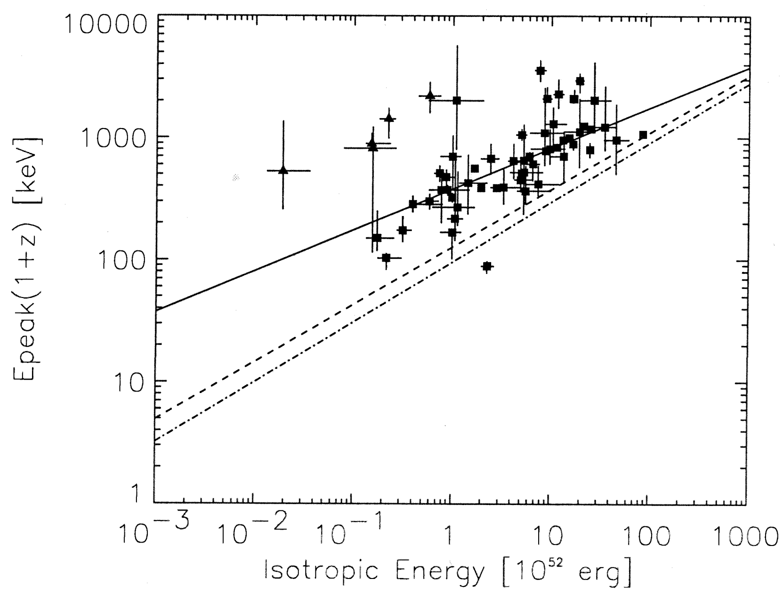

FIGURE 3. Plot of the individual sequences for the burst sample. Long bursts are shown as squares and short bursts as triangles. The solid line is the best fit to this distribution (see text), the dashed line is the best fit the time-integrated bursts (Figure 1), and the dash-dot line is the fit from Amati [5]

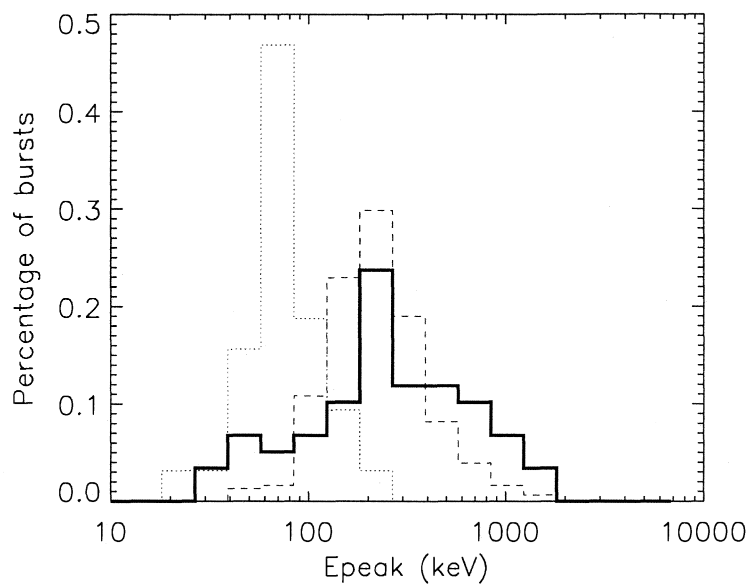

FIGURE 4. Distributions of E_{peak} values for the BAT-WAM joint fits compared to the results from other data sets. The solid black curve is for this sample, the dashed curve is for BATSE bursts (Kaneko et al. [12]), and the dotted curve is for BAT only bursts (Sakamoto et al. [13]).

Comparison to the BATSE Sample

In Figure 4, the best value of E_{peak} for this sample is plotted along with the best values from the BATSE results of [12] and the bursts from [13] for which a CPL or Band model can be fit. Although the BAT/WAM distribution is wider than the BATSE distribution, the median values are quite comparable. For this sample, the median E_{peak} is 282 keV, compared to 251^{+122}_{-68} keV for the BATSE sample. However the BAT/WAM distribution has larger wings at both the high and low energy ends. The high energy wing is consistent with the larger effective area above 300 keV in the WAM as compared to BATSE. This allows us to more effectively fit bursts with $E_{peak} > 300$ keV. The low energy wing is attributed to the lower threshold of BAT compared to BATSE, leading to more triggers on bursts with $E_{peak} < 100$ keV.

The "BAT only" histogram has a very different distribution which results from the narrow energy range of the BAT. Only bursts with 15 keV $< E_{peak} <$ 150 keV can be fit with the BAT data alone. Although the parent distribution is still rising at 150 keV, it becomes more and more difficult to fit a Band or CPL spectrum to the BAT data alone as E_{peak} increases.

SUMMARY AND DISCUSSION

We present here a complete set of time-integrated and time-resolved spectral fits for the prompt emission for a set of 78 bursts, 33 of which have measured red shifts. This provides a very useful addition to the *Swift*/BAT catalog [13], an expansion of previous compilations of bursts for which both E_{peak} and red shift are known [5, 10, 9], and a companion to the *CGRO*/BATSE spectral catalogs [12, 14]. This work shows the power and utility of joint fits with *Swift*/BAT and other instruments with larger energy ranges and we hope that this work will give guidance to future joint fits efforts, such as between *Swift*/BAT and *Fermi*/GBM and LAT.

The main benefit of extending spectral fits beyond the limited BAT energy range is that we are much more likely to cover enough of the spectrum to be able to determine the peak of the $\nu F \nu$ spectrum, E_{peak}. In the majority of BAT/WAM bursts we are able to constrain E_{peak} in either a CPL or Band model fit – those bursts for which only a PL model is an acceptable fit tend to be weak and/or particularly soft bursts, for which the statistics in the WAM were poor.

Another great advantage of studying bursts with *Swift*/BAT and *Suzaku*/WAM is that a far greater percentage of *Swift*-detected bursts have measured red shifts compared to previous missions. This means that we are able to determine not only E_{peak}, but also an estimate of the isotropic radiated energy, allowing us to study $E_{peak} - E_{iso}$ relationships in detail.

We are able to show that an $E_{peak} - E_{iso}$ relationship holds for long GRBs, with the possible exception of sub-energetic bursts such as GRB 980425 and GRB 060505. The slope of the fit to our data matches that derived by other authors such as Amati [5], even though we probe a burst distribution with a higher range of E_{peak} values than have previously been studied. Although we show a clear correlation between E_{peak} and E_{iso}, the large scatter in the distribution makes any use of this relationship to determine a pseudo-redshift problematic. As has been seen before, short GRBs are outliers to the $E_{peak} - E_{iso}$ relationship, having E_{peak} values in a comparable range with long GRBs, but a short burst will typically have $\approx 100\times$ less energy than a long burst of comparable E_{peak}.

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