A universal GRB photon energy-peak luminosity relation

R. Willingale¹, P.T. O’Brien¹, M.R. Goad¹, J.P. Osborne¹, K.L. Page¹, N.R. Tanvir¹

ABSTRACT

The energetics and emission mechanism of GRBs are not well understood. Here we demonstrate that the instantaneous peak flux or equivalent isotropic peak luminosity, $L_{iso}$ ergs s$^{-1}$, rather than the integrated fluence or equivalent isotropic energy, $E_{iso}$ ergs, underpins the known high-energy correlations. Using new spectral/temporal parameters calculated for 99 bursts with redshifts from BATSE, BeppoSAX, HETE-II and Swift we describe a parameter space which characterises the apparently diverse properties of the prompt emission. We show that a source frame characteristic-photon-energy/peak luminosity ratio, $K_z$, can be constructed which is constant within a factor of 2 for all bursts whatever their duration, spectrum, luminosity and the instrumentation used to detect them. The new parameterization embodies the Amati relation but indicates that some correlation between $E_{peak}$ and $E_{iso}$ follows as a direct mathematical inference from the Band function and that a simple transformation of $E_{iso}$ to $L_{iso}$ yields a universal high energy correlation for GRBs. The existence of $K_z$ indicates that the mechanism responsible for the prompt emission from all GRBs is probably predominantly thermal.

Subject headings: Gamma Rays: bursts — radiation mechanisms: non-thermal — ISM: jets and outflows

1. Introduction

The energetics of the central engine which powers the explosion responsible for a GRB are both intriguing and fundamental to our understanding of these cosmic events. The isotropic energy outflow at source, estimated using the integrated gamma-ray fluence, is enormous, up to $E_{iso} \sim 10^{54}$ ergs, and even if the outflow is collimated in jets the total energy involved is still huge, $E_{\gamma} \sim 10^{51}$ ergs. The possibility that the explosion taps a standard energy reservoir has been pursued by many authors following the initial suggestion

¹Department of Physics and Astronomy, University of Leicester, LE1 7RH, UK
from Frail et al. (2001). If this total energy available were, indeed, roughly constant (or predictable through other means) and we could reliably estimate the collimation, then GRBs could be used as a cosmological probe to very high redshifts, Bloom et al. (2003), Ghirlanda et al. (2004).

Early on it was noted that, based on analysis of BATSE data, there was a correlation between $E_p$, the peak of $E \cdot F(E)$ where $F(E)$ ergs cm$^{-2}$ keV$^{-1}$ is the observed spectrum, and the fluence (Mallozzi et al. 1995, Lloyd et al. 2000). When redshifts became available for long bursts the isotropic energy, $E_{\text{iso}}$, could be estimated from the fluence and the peak energy could be transformed into the source frame, $E_{pz}$, the so-called Amati relation, a correlation between $E_{\text{iso}}$ and $E_{pz}$ in the sense that more energetic bursts have a higher $E_{pz}$, was discovered using data from BeppoSAX, (Amati et al. 2002). This correlation has subsequently been confirmed and extended although there remain many significant outliers, including all short bursts. The physical origin of the correlation may be associated with the emission mechanisms operating in the fireball but the theoretical details are far from settled (see the discussion by Amati (2006) and references therein). More recently a tighter correlation between $E_{\text{iso}}$, $E_{pz}$ and the jet break time, $t_{\text{break}}$, measured in the optical afterglow has been reported (Ghirlanda et al. 2004). This is explained in terms of a modification to the Amati relation in which $E_{\text{iso}}$ is corrected to a true collimated energy, $E_\gamma$, using an estimate of the collimation angle derived from $t_{\text{break}}$. The details of the collimation correction depend on the density and density profile of the circumburst medium, Nava et al. (2006) and references therein. Multivariable regression analysis was performed by Liang & Zhang (2005) to derive a model-independent relationship, $E_{\text{iso}} \propto E_{pz}^{1.94} t_{\text{break}}^{-1.24}$, indicating that the rest-frame break time of the optical afterglow, $t_{\text{break}}$, was indeed correlated with the prompt emission parameters.

Other studies have concentrated on the properties of the isotropic peak (maximum) luminosity, $L_{\text{iso}}$ ergs s$^{-1}$, measured over some short time scale $\approx 1$ s, rather than the time integrated isotropic energy, $E_{\text{iso}}$. Schaefer (2003) noted a possible correlation between $L_{\text{iso}}$ and $E_{pz}$ and later Yonetoku et al. (2004) published such a correlation for 16 GRBs with firm redshifts. A correlation between $L_{\text{iso}}$ and the spectral lag was first identified by Norris et al. (2000) and explained in terms of the evolution of $E_{\text{peak}}$ with time. The shocked material responsible for the gamma-ray emission is expected to cool at a rate proportional to the gamma-ray luminosity and it has been suggested that $E_{\text{peak}}$ traces the cooling (Schaefer 2004). A similar correlation between $L_{\text{iso}}$ and the variability of the GRB ($V$) was described by Fenimore & Ramirez-Ruiz (2000), Ramirez & Fenimore (2000), and Reichart et al. (2001) and a related correlation between $E_{pz}$ and $V$ was described by Lloyd-Ronning & Ramirez-Ruiz (2002). The origin of the $L_{\text{iso}} - V$ relation is likely to be related to the physics of the relativistic shocks and the bulk Lorentz factor of the outflow. It could be that high $\Gamma_{\text{outflow}}$
results in high $L_{iso}$ and $V$ while lower luminosity and variability are expected if $\Gamma_{outflow}$ is low (see, for example, Mészáros et al. 2002). A rather bizarre correlation involving $L_{iso}$, $E_{pz}$ and variability was found by Firmani et al. (2006). They employed the “high signal” time, $T_{45}$, as formulated by Reichart et al. (2001) in their study of variability, and showed that $L_{iso} \propto E_{pz}^{1.62}T_{45}^{-0.49}$ for 19 GRBs with a spread much narrower than that of the Amati relation. There is currently no explanation for such a correlation although it may be connected with the spectral lag and variability correlations and the Amati relation.

The correlation between $E_{iso}$ and $E_{pz}$ supplemented by additional empirical information can be used in pseudo redshift indicators, for example Atteia (2003), Pelangeon & Atteia (2006), but the intrinsic spread in the correlation and uncertainty about the underlying physical interpretation introduce errors, typically of a factor $\sim 2$. It may be possible to reduce the errors by simultaneous application of several independent luminosity/energy correlations, and extension of the Hubble Diagram to high redshifts using GRBs has been attempted, see for example Schaefer (2007). However, it is not clear that the correlations briefly described above are truly independent and there may be some underlying principle or mechanism which connects them all together. Recently, and more controversially, Butler et al. (2007) have raised serious doubts about the validity of these correlations suggesting that it is likely that they are introduced by observational/instrumental bias and have nothing to do with the physical properties of the GRBs and hence they conclude that GRBs are probably useless as cosmological probes. Here we take a new look at the source frame spectral and temporal properties of a large number of GRBs for which we have redshifts in order to try and understand what really correlates with what and whether or not this can provide useful intrinsic information about the GRBs and what drives them. In this analysis we include the short-duration GRBs which may share a similar emission mechanism with long bursts despite probably having different progenitors.

2. Source frame spectra of the prompt emission

The profile of the prompt energy spectrum of all GRBs is well represented by a Band function (Band et al. 1993),

$$B(E) = E^{\alpha+1} \exp(-E/E_c), \quad E \leq E_c(\alpha - \beta)$$

$$B(E) = E^{\beta+1} \exp(\beta - \alpha)(\alpha - \beta)E_c\exp(\beta - \alpha), \quad E \geq E_c(\alpha - \beta) \quad (1)$$

where $\alpha$ and $\beta$ are the photon power law indices at low (X-ray) and high ($\gamma$-ray) energies respectively and $E_c$ keV is the high cut-off energy. Note that in the original formulation of Band et al. (1993) the photon number spectrum $N_E(E)$ was used. Here we introduce an
extra factor of $E$ and define $B(E)$ as the energy spectrum but retain $\alpha$ and $\beta$ as the photon indices. The observed total fluence is

$$F_{\text{tot}} = \int_{E_1}^{E_2} F(E) dE = N_{\text{tot}} \int_{E_1}^{E_2} B(E) dE$$

(2)
ergs cm$^{-2}$, where $N_{\text{tot}}$ is the normalisation in ergs cm$^{-2}$ keV$^{-1}$ at 1 keV and $E_1$ to $E_2$ is the observed energy band. Spectral fitting of the observed count spectrum will yield values for $\alpha$, $\beta$, $E_c$ and $N_{\text{tot}}$. The cut-off energy, $E_c$, is often converted to the peak energy of the $E.F(E)$ spectrum which is given by $E_p = (\alpha + 2)E_c$ and the normalisation may be expressed as the fluence, $F_{\text{tot}}$, rather than using the normalisation $N_{\text{tot}}$. However, the separation of the fluence into a normalisation term and a spectral integral is central to the development of the argument which follows. Table 1 gives the spectral parameters for 99 GRBs for which we have redshift values and a prompt light curve. The spectral parameters for bursts detected by BATSE, BeppoSAX, HETE-2 and Konus/WIND were taken from the references cited. The values for Swift bursts were derived from the BAT spectra supplemented by detections by INTEGRAL and Konus/WIND where available. Many of the Swift spectra ($\approx$ 40) are adequately fitted by a simple power law or a cut-off power law with $E_c$ fixed. For these bursts a cut-off power law model was used with $E_c = 150$ keV (corresponding to the upper limit of the BAT energy band). Providing the fitted $\alpha > -2$ the fitted function has a peak in $E.F(E)$ and a value for the peak energy can then be estimated. The spectra of 7 very soft Swift bursts with redshifts (GRB050406, GRB050416A, GRB050824, GRB051016B, GRB060512, GRB060926 and GRB070419A) gave $\alpha \leq -2$ and these were discarded because, for such spectra, we have no meaningful estimate of $E_p$. Such GRBs are normally designated as X-ray flashes (XRFs) and the exceptionally low (negative) $\alpha$ values may arise because we are actually observing the high energy tail ($\beta$) and not the lower energy power law in the Band function. Alternatively it may be that such soft spectra are the result of a second soft X-ray component which dominates in these objects.

The equivalent isotropic energy from the source is given by

$$E_{\text{iso}} = \frac{4\pi d_L^2 N_{\text{tot}}}{(1 + z)^{\alpha + 3}} I_{\text{bol}}(E_{pz}, \alpha, \beta)$$

(3)
ergs, where $d_L$ is the luminosity distance corresponding to the redshift $z$ under some cosmology, $I_{\text{bol}}(E_{pz}, \alpha, \beta)$ is the bolometric integral of the spectral energy profile in the source frame, $B_z$, taken over the wide energy band 1 keV to 10 MeV

$$I_{\text{bol}}(E_{pz}, \alpha, \beta) = \int_1^{10^4} B_z(E) dE$$

(4)
and $E_{pz} = E_p(1 + z)$ is the peak energy in the source frame. We can replace the first term in Equation 3 by the equivalent isotropic energy density, $Q_z$ ergs keV$^{-1}$ at 1 keV in the source
A factor \(1/(1+z)^{\alpha+2}\) arises because we have shifted the normalisation from 1 keV in observer frame to 1 keV in the source frame. The remaining factor of \(1/(1+z)\) accounts for the time-dilation of the duration over which the bursts are seen. The exponential term comes from the energy roll-off in the Band function and is always very close to 1 because \(E_{cz} = E_{pz}/(\alpha + 2)\) is much larger than 1 keV for all GRBs. It is pertinent to transform this to the isotropic energy density at the peak energy, \(E_{pz}\) keV, in the source frame,

\[
Q_{pz} = Q_z \exp[(\alpha + 2)(E^{-1}_{pz} - 1)]E^{\alpha+1}_{pz}
\]

(6)

ergs keV\(^{-1}\) so that the spectrum normalisation is specified at a characteristic energy in or close to the observed \(\gamma\)-ray energy band. We can then write Equation 3 as

\[
E_{iso} = Q_{pz}E_{wz},
\]

(7)

where

\[
E_{wz} = \exp(\alpha + 2)I_{bol}(E_{pz}, \alpha, \beta)E^{-(\alpha+1)}_{pz}
\]

(8)

keV is a characteristic photon energy which depends on the profile of the energy spectrum and the limits adopted for the integration and it serves to convert from an energy density \((Q_{pz} \text{ ergs keV}^{-1})\) at the peak of the \(E.F_z(E)\) spectrum to the total isotropic energy \((E_{iso} \text{ ergs})\). The isotropic energy spectrum in the source frame is given by

\[
F_z(E) = Q_{pz} \exp(\alpha + 2)E^{-(\alpha+1)}_{pz}B_z(E)
\]

(9)

ergs keV\(^{-1}\). The source frame spectra of the GRBs listed in Table 1 are shown in Figure 1 with the spectral energy density \(Q_{pz}\) marked at energy \(E_{pz}\) keV. In the majority of spectra the high energy spectral index is not measured but set to \(\beta = -2.3\) which is the approximate average found by BATSE. Figure 2 shows the corresponding \(E.F_z(E)\) spectra in ergs. We assumed a cosmology with \(H_0 = 71\) km s\(^{-1}\) Mpc\(^{-1}\), \(\Omega = 0.27\) and \(\Lambda = 0.73\) to calculate the luminosity distance \(d_L\).

Some of the redshifts for the GRBs listed in Table 3, in particular for 6 of the short bursts, are measured from a putative host galaxy rather than from an optical transient assumed to be associated with the GRB. The reliability of the redshifts for these short bursts is discussed by Troja et al. (2008). The probability of a chance association is < 5% for all the short bursts except for GRB061217 which is 39%.
3. The Amati relation

The Amati relation is a correlation between $E_{pz}$ and $E_{iso}$, first reported by Amati et al. (2002), and subsequently shown to be obeyed by the majority of long GRBs although there is a fairly large scatter. The top left panel of Figure 3 shows the histogram of isotropic energy values, $E_{iso}$, calculated using Equation 7 using the spectral parameters in Table 1 and redshift in Table 3. A large range of values for $E_{iso}$ is produced because of the spread in the isotropic energy density at the peak $Q_{pz}$, the peak energy $E_{pz}$ and the bolometric integral $I_{bol}$. The top right panel of Figure 3 shows the characteristic energy, $E_{wz}$, plotted against the peak energy values, $E_{pz}$. There is a tight correlation between these 2 parameters because of the form of the Band function. To a first crude approximation $E_{wz} = 4.3E_{pz}$ (the solid line in Figure 3) but the best fit correlation is significantly shallower ($E_{wz} \propto E_{pz}^{0.85}$) and the scatter evident in Figure 3 is introduced by differences in the photon indices, $\alpha$ and $\beta$. The ratio $E_{wz}/E_{pz}$ ranges from 2.7 to 6.5. In fact $E_{wz}$ is well approximated by a function of the form

$$E_{wz} \approx E_{fit} = E_{pz}^{c_0} \exp(c_1 - c_2\alpha - c_3\beta)$$

(10)

where the coefficients found by a least squares fitting procedure are $c_0 = 0.898, c_1 = 2.371, c_2 = 0.388, c_3 = -0.344$. A comparison of $E_{fit}$ and $E_{wz}$ for the GRBs listed in Table 1 is shown in the bottom left panel of Figure 3 and the distribution of the ratio $E_{wz}/E_{fit}$ is shown in the bottom right-hand panel. For the majority of objects the approximation, $E_{fit}$, is within ±10% of the value obtained by numerical integration. There are a few GRBs with a larger discrepancy but all are within ±20% which is a very small perturbation in comparison with the dynamic range of the $E_{wz}$ values.

Using $E_{wz} \approx E_{fit}$ we can express $E_{iso}$ as an explicit function of $E_{pz}$:

$$E_{iso} \approx Q_{pz}E_{pz}^{c_0} \exp(c_1 + c_2\alpha - c_3\beta).$$

(11)

The immediate origin of the Amati relationship is now clear. Given Equation 11 some degree of correlation between $E_{pz}$ and $E_{iso}$ is guaranteed. The nature and spread of this correlation will depend on the relationship between the flux density, $Q_{pz}$, and the peak energy, $E_{pz}$, and the distribution of photon indices $\alpha$ and $\beta$. It could be that $Q_{pz}$ and $E_{pz}$ are correlated in such a way to cancel the apparent dependence on $E_{pz}$ but this is highly unlikely. This correlation arises because the GRB spectral profile has the form of Band function (Equation 1) with a particular range of values for the photon indices, $\alpha, \beta$, and the energy $E_c$. So understanding where the Amati relation comes from is really the same as understanding why the spectra have this functional form in the first place.

Figure 4 shows the Amati relationship for the GRBs in Table 1. The correlation line shown (derived ignoring the obvious outliers) is $E_{pz} \propto E_{iso}^{0.46}$ consistent with Amati 2006,
$E_{pz} \propto E_{iso}^{0.5}$. All the short bursts are outliers with low $E_{iso}$ values compared with the long bursts of similar $E_{pz}$ value. The other notable outlier is GRB980425 (see Amati 2006). The XRFs (characterised by the hardness ratio of the low energy spectra, see below) all fall on the lower edge of the correlation with low $E_{pz}$ compared with $E_{iso}$. A more fundamental relationship is that between the flux density $Q_{pz}$ and the characteristic energy $E_{uwz}$ which is also shown in Figure 4. It appears that, disregarding the short bursts, the Amati correlation is tighter than this new relationship but this is deceptive. Unlike $E_{iso}$ and $E_{pz}$, $Q_{pz}$ and $E_{uwz}$ are independent and their product provides the isotropic energy $E_{iso}$ (Equation 7). We now have a correlation which goes beyond the simple fact that GRB spectra have the Band function profile. Crudely, $Q_{pz}$ is a measure of the height of the spectrum as plotted in Figure 1 and $E_{uwz}$ (which is itself a function of $E_{pz}$, $\alpha$ and $\beta$) is a measure of the characteristic photon energy. There is a weak correlation between these two quantities, $E_{uwz} \propto Q_{pz}^{0.3}$, as can be seen in Figures 4 and 1. However, the pattern of outliers is the same as for the Amati relationship. The short bursts, and the sub-luminous long burst, GRB980425, have significantly low $Q_{pz}$ values but $E_{uwz}$ values which are comparable to the gamut of long bursts. The bursts designated as XRFs (see below) all lie in the low tail of the $E_{uwz}$ range but have $Q_{pz}$ values which are similar to many long bursts.

4. The rate profile and luminosity time of the prompt emission

The analysis above has highlighted the well known problems associated with the Amati relation and other correlations involving $E_{iso}$. We now consider a way of converting $E_{iso}$ into a characteristic luminosity to see if this can improve the situation. The variety of time variability in the prompt emission from GRBs is astonishing. Some bursts consist of a single Fast Rise Exponential Decay (FRED) profile, other have multiple peaks, some are very spiky with rapid variations while others have a smoother profile. The luminosity is continually varying between bright, short peaks and low troughs and in some cases the flux drops below the detection threshold for a while before flaring up again. With such a range of behaviour defining some characteristic luminosity and/or duration is tricky. Reichart et al. (2001) showed that the peak luminosity correlated with a variability measure $V$ computed by taking the difference between the light curve and a smoothed version of the light curve where the smoothing or correlation time was the time taken to emit the brightest fraction $f$ of the flux, $T_{45}^F$. They showed that the most robust correlation was obtained for $f \approx 0.45$. The correlation of the peak luminosity with $T_{45}$ has been adopted by subsequent authors, for example Guidorzi et al. (2005), Firmani et al. (2006), but in all cases the peak luminosity must be defined using some small arbitrary bin size (typically 1 second) and the only connection between the total fluence and the peak luminosity is indirect, through the
The variability measure $V$ depends on the correlation of structures (peaks, troughs etc.) in the light curves. Here we try a different approach in which the sequence of features or events in the light curves is abandoned completely. We identify the time periods in which significant flux is measured and then construct a *rate profile* by sorting the sequence of count rate samples from these time periods into descending order to produce, for every GRB, a monotonically decreasing function, $f_s(t_s)$, where $t_s$ is sorted time. The total sum of all the samples should be the total count fluence and the profile is normalised by dividing by this fluence so that the integral under the profile is unity. Such a rate profile shows what fraction of the burst is spent at what fraction of the peak rate and has the general form shown schematically in Figure 5. Examples of these rate profiles are shown in Figures 6 and 8. The time periods in which significant flux is detected were found by successive correlation with boxcar functions of increasing width. It doesn’t matter if the total duration of these periods is a little larger than required to capture the total fluence because the small excess of samples in the tail can be dropped and the rest of the profile is unchanged. Remarkably the shape of these rate profiles is surprisingly similar for all GRBs and is insensitive to the time bin size used as long as it is not too large or too small. If the bin size is too large then there may be too few samples defining the profile, but we found that a number of bins $> 20$ was fine. Using excessively large time bins can also hide significant real structure in the fluctuations of the light curve and this should be avoided. At the other extreme, if the bins are too small the number of counts per bin may drop to single figures and the profile shape is again compromised. In practice all long bursts are well represented using $\approx 64$ ms bins while short bursts require $\approx 4$ ms bins or something similar.

The influence of statistical fluctuations (noise) on the rate profiles is rather strange. Because the integral is normalised to unity statistical fluctuations on the total fluence are not included. The profile reflects the distribution of the detected flux over a range of brightness but is not influenced by uncertainties in the total flux. The sorting of bins into decreasing brightness order also ensures the profiles are always smooth with the larger errors or distortion due to noise accumulating at the start and end of the profile. This is often most noticeable as a slight increase in gradient or curl over at the end of the profile. Although errors can be estimated for each of the samples, $d_i$, Chi-squared minimization using these errors cannot be employed for any function fitting because the sorting operation destroys the meaning of the errors. i.e. the scatter of the sorted data values about the fitted function is not governed directly by the errors on $d_i$. 

$T_{45}$ value.
Most profiles are well represented by an empirical function of the form

\[ f_s(t_s) = f_0 \left(1 - \left( \frac{t_s}{T_E} \right)^{1/C_L} \right)^{C_L} + f_E \]  

(12)

where \( T_E \) is the total emission time or duration of the profile, \( f_E \) is the level of the profile at \( T_E \) and represents the minimum detectable flux (or luminosity) and \( C_L \) is a luminosity index which describes the curvature. This function is illustrated in Figure 5. Because the profile integral is normalised to unity the peak value at the start is \( f_0 + f_E = 1/T_L \), where \( T_L \) is a luminosity time in seconds. The peak flux is then given by the fluence divided by the luminosity time, \( F_{\text{tot}}/T_L \) cts s\(^{-1}\) or, perhaps more intuitively, the peak flux multiplied by \( T_L \) is the total fluence. Because \( T_L \) is derived from the functional fit of all the data it does not depend strongly on the time bin size (as discussed above) and therefore the peak flux calculated using \( T_L \) is also not dependent on the binning. If \( C_L = 1 \) the profile is linear and if \( C_L > 1 \) the profile is concave and the fraction at high rate is smaller. If \( C_L < 1 \) the curvature would be negative but this is not seen for any GRBs. So \( C_L \) is a measure of the sharpness or spikiness of the profile.

We fitted all rate profiles with the function \( f_s \) given by Equation 12 finding the best fit values for the parameters \( T_L, C_L \) and \( f_E \) using a least squares statistic

\[ \Sigma = 100 N \Delta t^2 \sum (d_i - f_{si})^2 \]  

(13)

where \( N \) is the total number of samples, \( d_i \), of time width \( \Delta t \). Note \( T_E \) is fixed as the cumulative duration of all the significant samples detected, \( T_E = N \Delta t \). The \( \Sigma \) statistic has properties similar to reduced Chi-Squared, with typical values in the range 0.5-2.0 (set by the scaling factor of 100), independent of the number of samples \( N \) or the sample size \( \Delta t \). Table 2 provides a complete list of all the temporal parameters. This table also includes the instrument and a GRB classification using the usual observational definitions: Short bursts if \( T_{90} < 2 \text{ s} \) and X-ray Flashes (XRFs) if \( \text{fluence}(1-30 \text{ keV})/\text{fluence}(30-500 \text{ keV}) > 1 \).

Figure 6 shows examples of typical fits. Note that sorted time is scaled by \( 1/T_E \) and the \( f_s \) values by \( T_L \) so that both axes take the range 0-1. The top-right panels show GRB021211 which is a typical FRED burst and has a low curvature index, \( C_L = 1.28 \). The top-left and bottom right panels show GRB990510 and GRB070521 which have more complicated flaring structure but are well fitted with \( C_L \) values of 2.48 and 1.69 respectively. The remaining objects have short bright spikes and extended low level emission, a class discussed by Norris & Bonnell (2006). GRB050724 and GRB051221A are essentially short bursts followed by a low level, extended tail and the combination of these features produces large \( C_L \) values, 3.17 and 2.85 respectively. For GRB051221A, \( \Sigma = 3.22 \) which is rather high. In this case
the short spike followed by the extended tail produces an extra feature or wiggle in the rate profile which is not fitted by the simple $f_s$ function, Equation 12. For these and similar bursts a sample size of 4 ms was used to accommodate the profile of the initial short spike. The left-hand panel of Figure 7 shows the distribution of $\Sigma$ and $T_L$ values for all GRBs in Table 2. There is no correlation between the goodness of fit measured by $\Sigma$ and the luminosity time, $T_L$. The same is true for $\Sigma$ and the luminosity index $C_L$. Figure 8 shows the worst fits of rate profiles with large $\Sigma$ values. In all these GRBs the peak value, $1/T_L$, is a good approximation to the data peak but the fit is compromised by undulating features. GRB990705 and GRB061007 represent a small group of bursts which have flares that rise fast, are reasonably flat at the top and decay fast. These produce a characteristic S-feature in the profile. Only 12 rate profiles (out of 99) have $\Sigma > 2$ and only 3 of these have a substantial mis-match, GRB990705, GRB061007 and GRB061210. The latter is an extreme example of a short burst, $T_L = 0.03$ s, which has an extended low flux tail giving $T_{90} = 85.3$ s. We note that GRB991216 has a faint pre-cursor just visible on the lightcurve plot.

The combination of luminosity time, $T_L$, and curvature index, $C_L$, gives us information closely related to $T_{45}$. The right-hand panel of Figure 7 shows the correlation between $C_L$ and the ratio of $T_{45}$ calculated directly from the sample values $d_i$ and $T_L$ from the fitted function. $T_{45}$ could be calculated by integration of the fitted function using the parameters $T_L$, $C_L$, $f_E$ and $T_E$ and this would produce a smooth curve of $C_L$ vs. $T_{45}/T_L$ if $f_E$ were zero or constant. The parameter $C_L$, for example, could be replaced by $T_{45}$ and the fitted function would still be uniquely defined. The scatter in Figure 7 results from the small differences between the data and the fitted function and the value of $f_E$ which is generally much smaller than $1/T_L$ but different for each GRB. Error ranges for $T_L$ and $C_L$ were estimated assuming the statistic $\Sigma$ has properties similar to reduced Chi-Squared. The errors so derived are not statistically correct, because of the odd statistical nature of the sorted rate profile, and in some cases they are an over estimate as is evident from the scatter in Figure 7.

Although the minimum flux level, $f_E$, was included in the fitting it is a measure of the instrument sensitivity rather than some intrinsic property of the rate profile. If the noise level were lower the number of significant samples detected would increase, $T_E$ would get bigger and $f_E$ would decrease. The instrument would detect a slightly larger fluence, $F_{tot}$, and the fitted value of $T_L$ would increase a little, however, the peak flux level, $F_{tot}/T_L$, would remain unchanged and $C_L$ would be essentially the same. The analysis of the rate profile described above provides a robust estimate of the peak flux (or peak luminosity) using all the available light curve data and is not biased by the instrument sensitivity providing the burst detection significance is secure in the first instance. The error on the peak flux so estimated is dominated by the error on the fluence rather than any error associated with estimating the luminosity time, $T_L$. It is also unchanged by the choice of sample size, $\Delta t$, providing
the number of samples is sufficient to capture the details of the emission profile as already discussed above. We can never be sure that resampling a light curve with a smaller $\Delta t$ will not reveal a very short, bright, isolated spike which was hidden by the previous binning and this would compromise the shape of the profile, but such has not been seen in any of the GRB light curves analysed so far (about 250 including all Swift bursts to date).

Using the redshift, $z$, we can calculate the luminosity time in the source frame, $T_{Lz} = T_L/(1 + z)$ and 90% duration in the source frame, $T_{90z} = T_{90}/(1 + z)$. The peak luminosity multiplied by the $T_{Lz}$ gives the isotropic energy, $L_{iso}T_{Lz} = E_{iso}$ ergs. This simple property of $T_{Lz}$ makes it a highly significant measure of the burst duration and is why we chose to call it the luminosity time. Such a time is often introduced in theoretical discussions, see for example $t_j$ in Thompson et al. (2007) or $t_{burst}$ in Ghirlanda et al. (2007). Above we have described a method to calculate this time for every GRB.

5. Characterisation of the prompt emission in the source frame

The prompt emission of each GRB in the source frame is characterised by the peak energy density, $Q_{pz}$ ergs keV$^{-1}$, the characteristic photon energy, $E_{wz}$ keV (which embodies the photon indices $\alpha$, $\beta$ and the peak energy $E_{pz}$, Equation 8), the luminosity time, $T_{Lz}$ s, and the luminosity curvature, $C_L$. Figure 9 shows $T_{Lz}$ plotted against the standard measure of burst length $T_{90z}$ where the dashed line shows equality. For bursts consisting of a single smooth pulse then $T_{Lz} \approx T_{90z}$. If there is more structure in the light curve and, in particular, if there are periods when the flux drops to zero then $T_{Lz} < T_{90z}$. In some cases a short precursor pulse is followed by a long time gap before the main burst starts and then $T_{Lz} \ll T_{90z}$. So the ratio of the two times is a crude measure of the variability but this includes all time scales and long periods when no flux is detected and is not equivalent to the short time scale variability defined by Reichart et al. (2001). The top-right panel of Figure 9 shows the distribution of $T_{Lz}$. Two peaks containing the short-bursts, centred around 0.05 seconds, and long-bursts centred at 5 seconds, are clearly visible. The distribution of $C_L$ is shown in the lower left-hand panel of Figure 9. Most bursts are contained in a symmetrical peak centred on $C_L = 1.6$. The few bursts with $C_L > 2.2$ include the short bursts which have a long weak tail and bursts which exhibit several very short spikes on top of a more generally smooth emission. The bottom right-hand panel of Figure 9 shows the distribution of the Band lower photon spectral index, $\alpha$. Hard bursts have $\alpha > -1$ and softer bursts have $\alpha < -1$. We do not show the distribution of the high energy photon index, $\beta$, because this parameter is only available for a few bursts and in most cases it was set to $\beta = -2.3$ which is the approximate average found by BATSE.
The distributions of the remaining parameters, the characteristic photon energy, $E_{wz}$, and the peak energy density, $Q_{pz}$, are shown at the top of the Figure 10. $E_{wz}$ stretches over two decades from 100 keV to 10000 keV. $Q_{pz}$ has a much larger spread with a main peak spanning three decades and a low energy tail covering another three. Since the product of the two gives us $E_{iso}$, the range of isotropic energy is very large, as is evident from Figure 3 and the Amati relation plotted in Figure 4. The luminosity time, $T_{Lz}$, plotted against the peak energy density, $Q_{pz}$, is shown in the bottom left-hand panel of Figure 10. Short bursts have $Q_{pz} < 10^{48.5}$ while in general long bursts have larger $Q_{pz}$ values. The two notable exceptions are, as before, GRB980425 and GRB060218 which are long bursts with very low luminosity. Five short bursts with long tails that are classified as long because their $T_{90} > 2$, GRB050603, GRB050724, GRB061006, GRB061210 and GRB070714B have $T_{Lz}$ of 0.22, 0.38, 0.33, 0.02 and 0.48 s respectively and these sit below the main long grouping along with the shorts. The XRFs tend to have lower $Q_{pz}$ and lower $T_{Lz}$ values within the long burst population. The peak luminosity density of a burst is given by $Q_{pz}/T_{Lz}$ ergs keV$^{-1}$ s$^{-1}$. This has a much narrower distribution than either $Q_{pz}$ or $T_{Lz}$ with a 90% range just over 2 decades, $3.1 \times 10^{47} - 7.8 \times 10^{49}$ ergs keV$^{-1}$ s$^{-1}$, as is clear from the histogram in the bottom right-hand panel of Figure 10. Both short and long bursts have similar values of peak luminosity density (the short bursts are shown as the white histogram, all bursts are shown in the grey histogram).

The correlation shown in Figure 11 between the peak luminosity density and the characteristic photon energy in the source frame is the first GRB relationship to unify the short and the long bursts. If the peak luminosity density is multiplied by $E_{wz}$ the x-axis becomes the peak isotropic luminosity, $L_{iso}$ ergs s$^{-1}$. The correlation of $E_{wz}$ vs. $L_{iso}$ is shown in the right-hand panel of Figure 11 along with the best fit

$$\frac{E_{wz}}{396 \text{ keV}} = \left( \frac{L_{iso}}{10^{50} \text{ ergs s}^{-1}} \right)^{0.24}$$

(14)

which has a Pearson’s correlation coefficient of $r = 0.77$, Kendall’s $\tau = 0.54$, significance 7.9$\sigma$. Thus Figure 11 encapsulates a major result of this work, showing a high quality correlation of characteristic photon energy with peak isotropic luminosity for 99 GRBs including 8 short bursts and 7 XRFs. The correlation between $E_{wz}$ and $L_{iso}$ is similar to those reported by Yonetoku et al. (2004) and Firmani et al. (2006) but there are important differences. Here we have estimated the peak isotropic luminosity from the rate profile so we are not restricted to long bursts or a particular time bin size, and the peak energy, $E_{pz}$, is replaced by the characteristic photon energy, $E_{wz}$. We note that the correlation derived by Yonetoku et al. (2004) is significantly steeper, $E_{pz} \propto L_{iso}^{-0.5 \pm 0.1}$ but they used a rather small sample of 16 GRBs. We can identify 13 of these objects in our sample and we find they give $E_{pz} \propto L_{iso}^{0.4 \pm 0.06}$ with Pearson’s correlation coefficient $r = 0.81$, consistent with their result.
The same 13 objects also give $E_{wz} \propto L_{iso}^{0.31 \pm 0.04}$ with $r = 0.88$ so using $E_{wz}$ in place of $E_{pz}$ gives a slightly tighter correlation with a shallower slope which is consistent with our result obtained from the full sample of 99 bursts. Unlike the Firmani et al. relationship the present correlation does not contain $T_{45z}$. We tried including $T_{45z}$ in a Principle Components Analysis (PCA) but found no significant correlation or reduction in the scatter. We also looked for significant correlation with the curvature parameter $C_L$ (which is closely related to $T_{45z}$ as discussed above). No correlation was found which was surprising given that $C_L$ is a measure of variability and correlation between variability and luminosity is known (Reichart et al. 2001). This is probably because the variability, $V$, is associated with small time scales and correlation between successive peaks whereas $C_L$ involves no correlation and is a measure of variability/spikiness over all time scales. If we replace $E_{wz}$ by $E_{pz}$ in the PCA of the complete sample then $E_{pz} \propto L_{iso}^{0.27}$ with $r = 0.71$ and Kendall’s $\tau = 0.52$, significance 7.7$\sigma$ so, again, using $E_{wz}$ yields a tighter correlation with a shallower slope compared to $E_{pz}$. The small change in slope arises because the correlation of $E_{pz}$ with $E_{wz}$ is different from unity (see Figure 3).

For each burst we calculate $K_z$ which is a measure of its displacement perpendicular from the the best fit correlation line in the right-hand panel of Figure 11.

$$K_z = \left( \frac{E_{wz}}{1280 \text{ keV}} \right)^{0.74} \left( \frac{L_{iso}}{1.26 \times 10^{52} \text{ ergs s}^{-1}} \right)^{0.24}$$

$$= \left( \frac{E_{wz}}{1280 \text{ keV}} \right)^{0.74} \left( \frac{Q_{pz}}{1.97 \times 10^{49} \text{ ergs keV}^{-1}} \frac{2.00 \text{ s}}{T_L} \right)^{0.24}$$

This is a function of the ratio of the characteristic photon energy to the peak isotropic luminosity. The constants quoted in this definition are the mean values of the parameters so they represent the centre of the clustering of objects within the parameter space. The distribution of $K_z$ is plotted in Figure 12. The mean value is $\log_{10}(K_z) = 0$ or, equivalently, $K_z = 1$. Hard-dim bursts (including most short bursts) have $K_z > 1$, soft-bright bursts (including all XRFs) have $K_z < 1$. The distribution is approximately log-normal (the best fit Gaussian profile is shown in Figure 12) and has a rms width of $\sigma[\log_{10}(K_z)] = 0.19$. 90% of the GRBs (90 objects) are contained in the range $0.45 < K_z < 1.95$. The obvious outlier is GRB980425/SN1998bw which is either very sub-luminous or has an exceptionally high peak energy for such a dim burst. Under the hypothesis that $K_z$ is constant, $\chi^2 = 418$ with 97 degrees of freedom and the mean of the estimated errors on $\log 10(K_z)$ is 0.12 so there is clear evidence for intrinsic scatter in $K_z$ with an estimated 90% range of $0.57 < K_z < 1.75$. The largest uncertainties arise from the estimation of $E_{wz}$ because this depends on $E_{pz}$ and the photon indices $\alpha, \beta$. The mean value of $K_z$ for the pre-Swift bursts is $-0.05$ and for Swift bursts is 0.02 so they are statistically indistinguishable. The distribution for pre-Swift
bursts, plotted as the white histogram in Figure 12, sits symmetrically within the total distribution. The right-hand panel of Figure 12 shows \(\log_{10}(K_z)\) as a function of redshift, \(z\). There is no obvious trend. The objects with the smallest errors that contribute most to the high \(\chi^2\) show no dependence on redshift. Table 3 provides a complete listing of the rest frame parameters and associated errors.

6. Discussion

Within the new parameterisation of the temporal and spectral properties of the prompt GRB emission the three important quantities are the characteristic energy in the source frame, \(E_{wz}\) keV (Equation 8), the energy density at the peak of the \(E.F_z(E)\) spectrum, \(Q_{pz}\) ergs kev\(^{-1}\) (derived from the total fluence, Equations 2, 5 and 6) and the luminosity time, \(T_{Lz}\) s, derived from the rate profile. The ratio \(Q_{pz}/T_{Lz}\) gives us the peak luminosity density in ergs keV\(^{-1}\) s\(^{-1}\) where “peak” corresponds to both the maximum in the \(E.F_z(E)\) spectrum and the maximum flux level in the light curve. The instantaneous maximum brightness of the prompt emission is characterised by a function of the photon energy/peak luminosity ratio \(K_z\) given in Equation 15. This is not a constant but it covers a remarkably small dynamic range compared with the constituent parameters, \(E_{wz}\), \(Q_{pz}\) and \(T_{Lz}\). Given the measurement errors it is difficult to make an accurate estimate of the intrinsic dynamic range but it is certainly less than 0.5 < \(K_z\) < 2.0 and this holds for 98 GRBs in the sample of 99 we have analysed including long, short and XRFs, the exception being GRB980425.

6.1. Is \(K_z\) intrinsic?

We might wonder whether the narrow range in \(K_z\) is an artefact of the observational data or something intrinsic to the nature of the GRB emission? An artificial tightness of the energy-luminosity correlation could arise in several ways; the observed quantities may be correlated by some property of the instrumentation/measurement, the measured positions of GRBs in the energy-luminosity plane could be incorrect because of some systematic error/bias introduced by or inherent in the data analysis or GRBs from certain areas in the plane may be selectively missed. Spectral analysis of \textit{Swift} long GRBs and possible biases in the fitted parameters are discussed by Cabrera et al. (2007). They confirm the Amati relation and conclude that it is very unlikely to be an artifact of selection effects. If this is the case then the same can be said of the \(E_{wz} - L_{iso}\) relationship. Conversely, functional biases in the spectral parameters of GRBs are considered by Massaro et al. (2007). They found that the \(E_{iso}\) vs. \(E_p\) relation is biased and that similar correlations like \(L_{iso}\) vs. \(E_p\) will
also be affected by functional biases introduced by spectral fitting. The measured quantities in the observer frame which map to $E_{\text{wz}}$ and $Q_{\text{pz}}/T_L$ are the peak energy, $E_p$ keV, and the spectral energy density at the peak

$$f_p = \frac{N_{\text{tot}}}{T_L} \exp[-(\alpha + 2)]E_p^{\alpha+1}$$  \hspace{1cm} (16)$$
ergs cm$^{-2}$ keV$^{-1}$ s$^{-1}$. These are plotted in the top left-hand panel of Figure 13. There is no tight clustering or significant correlation. Pearson’s correlation coefficient is $r = 0.27$ and Kendall’s $\tau = 0.12$, significance $1.8\sigma$. The 90% range of $f_p$ is $4.1 \times 10^{-10} - 3.1 \times 10^{-8}$ ergs cm$^{-2}$ keV$^{-1}$ s$^{-1}$ and the 90% range of the observed peak energy is $36 - 417$ keV, both one to two orders of magnitude. Using the redshift to transform these into $Q_{\text{pz}}/T_L$ and $E_{\text{wz}}$ produces the distributions shown in Figures 10 and 11. These quantities have slightly narrower distributions in the source frame with 90% ranges of $2.0 \times 10^{47} - 7.8 \times 10^{49}$ ergs keV$^{-1}$ s$^{-1}$ and $391 - 3490$ keV respectively. Finally they combine in $K_z$ which has a rather narrow 90% range of $0.45 - 1.95$ and some of this is attributable to the measurement errors. It is very unlikely that some systematic error or bias in the measured quantities which have a large dynamic range and are not correlated conspires to give such a tight correlation and we conclude that $K_z$ encodes real, useful, information about the source frame properties of the prompt emission. The rate profile fitting not only provides us with the peak flux density level but also the minimum detected flux density

$$f_m = N_{\text{tot}} E \exp[-(\alpha + 2)]E_p^{\alpha+1}$$  \hspace{1cm} (17)$$
ergs cm$^{-2}$ keV$^{-1}$ s$^{-1}$. The top right-hand panel of Figure 13 shows $f_m$ vs. $f_p$. There is some clustering of the weaker bursts along the line $f_p \approx 5f_m$ and clearly the area above this line in the top left corner is below the threshold. It could be that we are preferentially missing hard-dim bursts while soft-dim bursts are detected but redshift works in our favour because the distant dim bursts are redshifted into the lower observation energy band where the sensitivity is higher and time dilation stretches the light curve so we have longer to detect the emission. We are undoubtedly missing low luminosity bursts especially at high redshift. The lower panels of Figure 13 shows $L_{\text{iso}}$ and $E_{\text{wz}}$ plotted vs. redshift. The hard (high $E_{\text{wz}}$) and most luminous (high $L_{\text{iso}}$) sources are seen at all redshifts while the softer, weaker sources are only seen at low redshifts, entirely as one would expect, but as we can see from Figure 12 there is no obvious difference in the distribution of $K_z$ as a function of $z$. There is no reason to suspect that absence of dim bursts too weak to detect is biasing the distribution in the photon energy-luminosity plane.

Our conclusions are somewhat different from Butler et al. (2007). The combination of recent *Swift* detections with pre-*Swift* results confirms the general correlation between $E_{\text{pz}}$ and $E_{\text{iso}}$ (the Amati relation) but the spread is indeed large and many bursts, including all
the short bursts, are extreme outliers from the bulk correlation of the long bursts. Such a correlation is, in part, a simple consequence of the shape of a typical GRB spectrum (the Band function) but the spread and presence of many outliers renders this correlation insensitive in testing of cosmological world models. There is a clustering of events in the ratio of fluence/duration (effectively luminosity), however, we think the root of the problem is not observational bias or sensitivity thresholding but rather that the Amati relation (and similar correlations involving $E_{iso}$) are looking at the wrong parameter space. Yes, this is the demise of the existing pre-Swift high-energy correlations, but if we re-cast them in terms of the instantaneous peak luminosity and we replace $E_{pz}$ by $E_{wz}$, which combines the spectral parameters $E_{pz}$, $\alpha$ and $\beta$, then they reappear in a new light. The quantities in the observer frame are not correlated, the short and dim bursts are no longer outliers in the source frame correlation and there is no difference between Swift and pre-Swift detections.

6.2. Correlations involving evolution of parameters

All the analysis presented here involves average spectral and temporal properties of the prompt emission. $E_{wz}$ and $Q_{pz}$ are derived from the time-integrated spectra and $T_{Lz}$ is estimated from the full energy band light curves. We know that GRB spectra evolve with time and the light curves are different in different energy bands. In general the spectra soften as the burst proceeds, $\alpha$ increases and $E_p$ decreases with time (e.g. Goad et al. 2007, Page et al. 2007). The light curves are shorter and more spikey at high energies than they are at low energies (Reichart et al. 2001). The lag-luminosity (Norris et al. 2000) and variability-luminosity (Reichart et al. 2001) correlations are testament to this temporal-spectral evolution. In this work we have estimated the hardness and brightness of just the peak emission. If instrumentation could follow the evolution of the characteristic energy and luminosity through the light curve each burst would form a track on the energy-luminosity density plane which may run from top right to bottom left with $K_z \sim \text{constant}$. The lag and variability correlations may provide a means by which scatter can be introduced in $K_z$ although physical reasons for this are not immediately apparent. Further analysis and better quality data are required to explore the evolution of $K_z$ through individual bursts.

6.3. Emission processes

The correlation between the hardness and brightness of GRB spectra, previously in the form of the Amati relation and now the correlation between $E_{wz}$ and $Q_{pz}/T_{Lz}$, is a challenge to theoretical modelling of the prompt emission. Within the standard fireball picture there
are many variants involving internal and external shocks in which synchrotron emission, inverse Compton scattering and photospheric emission feature, and the fireball itself may be dominated by kinetic energy or magnetic energy (Poynting flux). The initial problem is to predict a spectrum which has the general form of the Band function with a spectral break or curvature characterised by some energy, \( E_c \), \( E_p \) or \( E_{\text{wz}} \), and the second problem is to predict the coupling between the characteristic energy or hardness of the spectrum and the luminosity (see the review by Zhang & Mészáros 2002).

With a kinetic energy dominated outflow and a simple synchrotron model generated by internal shocks, incorporating a peak in the electron energy one expects \( E_{pz} \propto \Gamma^{-2}t_{\text{var}}^{-1}L^{1/2} \) where \( \Gamma \) is the bulk Lorentz factor, \( t_{\text{var}} \) is the typical variability time scale associated with the internal shocks and \( L \) is the luminosity (Zhang & Mészáros 2002). This is consistent with the Amati relation if \( L \propto E_{\text{iso}} \) (which is not the case if we include both short and long bursts as shown above) and there is a constancy of both \( \Gamma \) and \( t_{\text{var}} \) across all bursts, which seems unlikely (Rees & Mészáros 2005). The relationship \( E_{\text{wz}} \propto L_{\text{iso}}^{0.25} \) derived here and shown to hold for all bursts is significantly flatter than the Amati relation. If the Lorentz factor depends on luminosity, \( \Gamma \propto L^{\beta} \), then we can choose \( \beta \approx 1/8 \) to match the observed correlation providing \( t_{\text{var}} \) is independent of luminosity and approximately constant for all bursts. It is not obvious why the Lorentz factor should have such a specific and low dependence on luminosity and, again, why \( t_{\text{var}} \) should be constant when the burst durations \( (T_{90z} \text{ or } T_{Lz}) \) have such a large dynamic range. Within this model the radius at which the emission occurs is given by \( r \sim ct_{\text{var}}\Gamma^2 \) so if we assume typical values of \( t_{\text{var}} \sim 0.01 \text{ s} \) and \( \Gamma \sim 300, r \sim 3 \times 10^{13} \text{ cm} \). Furthermore, by considering the onset of X-ray afterglows observed by Swift Kumar et al. (2007) estimate that emission originates at much larger radii, between \( 10^{15} \) and \( 10^{16} \text{ cm} \), and suggest that synchrotron/inverse Compton parameters cannot account for the prompt emission.

Alternatively, we can consider a thermal origin for the peak in the \( E, F(E) \) spectrum and the correlation of the characteristic energy with luminosity, see for example Rees & Mészáros (2005), Ryde (2005) and Ghirlanda et al. (2007). If the photosphere of the expanding fireball has radius \( R_0 \), Lorentz factor \( \Gamma_0 \), a blackbody spectral component with temperature \( T_{bb} \) and isotropic luminosity fraction \( \varepsilon_{bb} \) of the total isotropic luminosity \( L_{\text{iso}} \), then the observed temperature, \( T_{\text{obs}} = (4/3)\Gamma_0 T_{bb} \), is given by

\[
\frac{T_{\text{obs}}}{1460 \text{ keV}} = \left( \frac{\Gamma_0}{10^7 \text{ cm}} \frac{10^7 \text{ cm}}{R_0} \right)^{1/2} \left( \frac{\varepsilon_{bb}L_{\text{iso}}}{10^{52} \text{ ergs s}^{-1}} \right)^{1/4}
\]

(18) Thompson (2006). This is just the Stefan-Boltzmann law modified to account for the relativistic expansion rate of the photosphere and it matches the observed correlation if \( E_{\text{wz}} \propto T_{\text{obs}} \) and \( \varepsilon_{bb}^{1/2} \Gamma_0 / R_0 \) is approximately constant for all bursts. The observed spectrum
is not a single temperature blackbody. If $\varepsilon_{bb} << 1$ then any single temperature blackbody component is diluted by non-thermal (possibly power law or inverse Compton) components which combine to give the Band function. If $\varepsilon_{bb} \sim 1$ the observed spectrum must result from the summation of a large number of thermal components with a spread of temperatures that give an average of $T_{\text{obs}}$, (for example, in a manner similar to that described by Ruffini et al. 2004). We can re-arrange Equation 18 as

$$\left( \frac{\varepsilon_{bb}^{1/2} \Gamma_0 10^7 \text{ cm}}{R_0} \right)^{1/2} = \left( \frac{T_{\text{obs}}}{1460 \text{ keV}} \right) \left( \frac{L_{\text{iso}}}{10^{52} \text{ ergs s}^{-1}} \right)^{-1/4}$$

(19)

If $T_{\text{obs}} \sim E_{\text{wz}}$ this is essentially the same as the definition of the photon energy- luminosity quasi-constant, $K_z$, and so, under this interpretation, the scatter in the correlation arises from variations in the fireball dimension, $R_0$, the Lorentz factor, $\Gamma_0$, or the blackbody luminosity fraction, $\varepsilon_{bb}$. If $K_z = 1$ then we have an average fireball with $R_0/(\varepsilon_{bb}^{1/2} \Gamma_0) \approx 10^7$ cm. If $K_z > 1$ the fireball has a higher than average $\varepsilon_{bb}^{1/2} \Gamma_0$ and/or a smaller radius, $R_0$. If $K_z < 1$ the fireball has a low $\varepsilon_{bb}^{1/2} \Gamma_0$ and/or large radius. With $\Gamma_0 = 300$ and $\varepsilon_{bb} = 1$ then $R_0 \approx 3 \times 10^9$ cm which is the thermalization radius (i.e. the radius of the jet or fireball photosphere) estimated by Thompson, Mészáros & Rees (2007). This radius is much smaller than estimates arising from the internal shock model or recent estimates involving the onset of the X-ray afterglow (see above) so independent estimates of the radius of the prompt emission and/or the Lorentz factor may help to discriminate between thermal and internal shock models. We also note that baryonic photospheres are governed by physical argument (Mészáros et al. 2002) such that the ratio $R_0/\Gamma_0$ is constrained and the relationship between $\varepsilon_{bb}^{1/2} \Gamma_0/R_0$ and $K_z$ may not be as simple as we have indicated.

6.4. $K_z$ as a cosmological probe

We can write $K_z$ in terms of a ratio of measured quantities in the observer frame, $K$, a function of redshift, $C(z)$, and a constant, $K_0$, which depends only on the mean values of the observed quantities for all GRBs

$$K_z = K_0 K C(z)$$

(20)

Using the approximation to $E_{\text{wz}}$ from Equation 10 and the expression for $K_z$, Equation 15, the observed ratio is

$$K = \frac{E_p^{0.74 c_0} \exp(c_1 - c_2 \alpha - c_3 \beta^{0.74}) f_p^{-0.24}}{\alpha}$$

(21)

and the redshift function is

$$C(z) = (1 + z)^{0.74 c_0 + 0.24} d_L^{-0.48}.$$  

(22)
$C(z)$ is plotted in Fig. 14 taking the luminosity distance (calculated from $z$) in units of $10^{28}$ cm. For $z < 1$ the $d_L$ term dominates because at low $z$ there is little redshift of the peak energy, $E_p$, but the inverse square law has a dramatic effect on the intrinsic brightness. For $z > 1$ $C(z)$ is only slowly varying because the two terms nearly cancel. Because the conversion from the measured ratio, $K$, to the intrinsic ratio, $K_z$ is almost independent of $z$ if $z > 1$ the $E_{wz} - Q_{pz}/T_{Lz}$ correlation is almost useless as a pseudo redshift indicator. Even if the intrinsic scatter in $K_z$ were very low the ratio would have to be measured with very high accuracy to enable redshift to be estimated from the observed ratio, $K$.

Because $C(z)$ varies little for $z > 1$ and the majority of GRBs fall into this redshift range we can randomly shuffle all the redshift values ($z > 1$) and the correlation between peak luminosity and characteristic energy remains essentially unchanged. We don’t need to know which GRBs have which redshift but the range and magnitude of the redshift values are important because they determine the absolute values (and ranges) of $E_{iso}$, $L_{iso}$ and $E_{wz}$. The same situation applies to the Amati relation. If we assume $E_{pz}E_{iso}^{-0.5} = constant$ then the redshift factor, $C(z)$, has the form shown by the dotted curve in Fig. 14. This, too, is fairly flat for $z > 1$ and shuffling the redshift values leaves the Amati relation intact. The sensitivity of any putative pseudo redshift indicator which involves $E_{iso}$ or $L_{iso}$ can be assessed in a similar way using the approximation to $E_{iso}$, Equation 11, and calculating the appropriate $C(z)$ function.

We have the rather bizarre situation that the measured redshifts coupled with properties of the Band function give us the characteristic energy-peak luminosity relation (and the Amati relation) but we can’t use an individual $K$ ratio measurement to predict the redshift for a particular GRB. Things would be a little better at low redshifts ($z < 1$) if the intrinsic scatter could be explained. If the dominant emission mechanism is non-thermal then the coupling of the Lorentz factor of the expansion with the luminosity and the variability time associated with the internal shocks may be the root cause of intrinsic scatter. If thermal processes dominate then the ratio $R_0/\Gamma_0$ may vary as discussed above. Because we can identify classes which fall predominately at $K_z > 1$ (shorts) and $K_z < 1$ (XRFs) there is some hope that additional parameters which distinguish these classes may serve to narrow the distribution. In the above discussion we made no mention of collimation or beaming of the outflow. Since the Amati relation involving $E_{iso}$ has been transformed into the present universal correlation involving $L_{iso}$ the simple beaming argument that underpinned the Ghirlanda relation (Ghirlanda et al. 2004) is not directly applicable and currently there is no simple physical model which links collimation to scatter in peak luminosity or the characteristic photon energy. However, it is not unreasonable to suppose that collimation may introduce scatter in the peak luminosity, and that correlation of $K_z$ with afterglow parameters such as optical jet break times $t_{break}$ or the time of the start of the final X-ray afterglow, $T_a$ (Willingale et
al. 2007), may be fruitful.

7. Conclusion

The equivalent isotropic energy, $E_{\text{iso}}$ ergs, of a GRB can be expressed as the product of two source frame terms, a characteristic photon energy, $E_{wz}$ keV, calculated from the shape of the spectrum across the range 1-10000 keV and the energy density at the peak of the $E.F_z(E)$ spectrum, $Q_{pz}$ ergs keV$^{-1}$. The relationship between $E_{wz}$ and $E_{pz}$ (Equation 10) and the correlation trend between $E_{wz}$ and $Q_{pz}$ gives rise to the Amati relation. By stacking the samples of a GRB light curve into descending order we can construct a rate profile. The functional form of such rate profiles is common to the vast majority of bursts. Fitting the profile gives us a luminosity time, $T_{Lz}$ s, a measure of the burst duration which can be used to convert the energy density at the peak to a luminosity density at peak, $Q_{pz}/T_{Lz}$ ergs keV$^{-1}$ s$^{-1}$. We can calculate the peak equivalent isotropic luminosity as a product $L_{iso} = E_{wz}Q_{pz}/T_{Lz} = E_{iso}/T_{Lz}$ ergs s$^{-1}$.

$E_{wz}$ is a characteristic photon energy or a measure of the colour or hardness of the burst and $Q_{pz}/T_{Lz}$ is a measure of the instantaneous peak luminosity. We have gathered and analysed sufficient spectral and temporal data from 99 bursts to produce the relation between $E_{wz}$ vs. $Q_{pz}/T_{Lz}$ and $E_{wz}$ vs. $L_{iso}$, shown in Figure 11, which constitutes the closest thing we have to an intrinsic colour-magnitude diagram for the peak emission from GRBs, $E_{wz} \propto L_{iso}^{0.25}$. All bursts are clustered such that we can construct an intrinsic colour-magnitude quasi constant $K_z$, which is a function of the source frame characteristic photon energy/peak luminosity ratio given by Equation 15. The range of equivalent isotropic energy that drives the expanding fireball is very large, 6 orders of magnitude (Figure 3), but the instantaneous hardness/brightness of the peak emission covers a very small intrinsic dynamic range, $\approx 4$.

The existence and form of $K_z$ indicates that the physical mechanism for the Gamma-ray production at the photosphere of the fireball is common to all bursts and is probably thermal although many other possibilities are not ruled out. If the prompt spectra are dominated by thermal photons the scatter in $K_z$ may be attributed to variations in the size and/or Lorentz factor of the fireball. XRFs have low $\Gamma_0$ and/or large radii. Short bursts have high $\Gamma_0$ and/or small radii. The relation between $T_{Lz}$ vs. $Q_{pz}$ clearly separates short from long, but both classes have the same instantaneous peak hardness/brightness.

We gratefully acknowledge funding for Swift at the University of Leicester by STFC. We thank the authors of the BATSE (http://coss.cgsf.nasa.gov/docs/cgro/batse), HETE
(http://space.mit.edu/HETE) and BeppoSAX (http://www.asdc.asi.it/grb_wfc) websites which gave us access to the prompt lightcurves of pre-Swift bursts. We also thank B. Zhang, N. Butler and C. Guidorzi for valuable comments/discussions.

REFERENCES

Atteia J.-L., 2003, A&A 407, L1-L4
Atteia J.-L., 2005, ApJ 626, 292
Amati L. et al., 2002, A&A, 390, 81
Amati L., 2006, MNRAS 372, 233
Amati et al., 2006b, astro-ph/0611189
Amati L., Della Valle, M., Frontera F., Malesani D., Guidorzi C., Montanari E. and Pian E., 2007, A&A, 463, 913
Band D. et al., 1993, ApJ 413, 281
Butler N.R., Kocevski D., Bloom J.S., Curtis J.L., 2007, arXiv0706.1275B
Barthelmy S.D. et al., 2005, Nature, 438, 994
Bloom J.S., Frail D.A. and Kulkarni S.R., 2003, ApJ 594, 674
Burrows D.N. et al., 2006, ApJ 653, 468
Cabrera, J.I., Firmani, C., Avila-Reese, V., Ghirlanda, G., Ghisellini, G., Nava, L., 2007, arXiv:0704.0791v3
Campana S. et al, A&A, 454, 113
Fenimore, E.E. and Ramirez-Ruiz, E., 2000, ArXiv Astrophysics e-prints, astro-ph.04176F
Firmani C., Ghisellini G., Avila-Reese V., Ghirlanda G., 2006, MNRAS, 370, 185
Frail D.A. et al., 2001, ApJ, 562, L55
Friedman A.S. & Bloom J.S., 2005, ApJ 627, 1
Galassi M. et al., 2004, GCN 2770
Ghirlanda G., Ghisellini G. and Lazzati D., 2004, ApJ 616, 331
Ghirlanda G., Bosnjak Z., Ghisellini G., Tavecchio F., Firmani C., 2007, MNRAS, 379, 73
Golenetskii S. et al., 2005, GCN 3474, GCN 3518, GCN 4150, GCN 4238, GCN 4394, GCN 5264
Guidorzi C., Frontera F., Montanari E., Rossi F., Amati L., Gomboc A., Hurley K., Mundell C.G., 2005, MNRAS, 363, 315
Goad M.R. et al., 2007, A&A, 468, 103
Liang E. & Zhang B., 2005, ApJ 633, 611
Kumar P., McMahon E., Panaitescu A., Willingale R., O’Brien P., Burrows D., Cummings J., Gehrels N., Holland S., Pandey S.B., Vanden Berk D., Zane S., 2007, MNRAS, 376, 57
Lloyd N.M., Petrosian V. & Mallozzi R.S., 2000, ApJ 534, 227
Lloyd-Ronning, N. M. and Ramirez-Ruiz, E., 2002, ApJ, 576, 101-106
Mészáros P., Ramirez-Ruiz E., Rees M.J. & Zhang B., 2002, ApJ, 578, 812
Mallozzi R.S., Paciesas W.S., Pendleton G.N., Briggs M.S., Peece R.D., Meegan C.A., Fishman G.J., 1995, ApJ, 454, 597
Massaro, F., Cutini, S., Concitore, M.L., Tramacere, A., 2007, arXiv:0710.2226v1
Nava L., Ghisellini G., Ghirlanda G., Tavecchio F., Firmani C., 2006, A&A, 450, 471 Cabrera J.I., Firmani C. and Avila-Reese V., 2007, MNRAS, submitted
Norris J.P., Marani G.F., Bonnell J.T., 2000, ApJ, 534, 248
Norris J.P. & Bonnell J.T., 2006 ApJ, 643, 266
Page K.L. et al. 2007, ApJ, 663, 1125
Pelangeon A. & Atteia J.-L., 2006, GCN 4442
Piro L. et al., 2005, ApJ, 623, 314
Ramirez-Ruiz, E. & Fenimore, E.E., 2000, ApJ 539, 712-717
Rees M.J. & Mészáros P., 2005, ApJ, 628, 847
Reichart D.E., Lamb D.Q., Fenimore E.E, Ramirez-Ruiz E., Cline T.L., Hurley K., 2001, ApJ 552, 57

Romano P. et al., 2006, A&A, 456, 917

Ruffini R., Bianco, C.L., Xue S-S., Chardonnet P., Fraschetti, F., Gursadyan V., Int.J.Mod.Phys.D, 13, 843

Ryde F., 2005, ApJ, 625, L95

Schaefer B.E., 2003, ApJ, 583, L71-L74

Schaefer B.E., 2004 ApJ, 602, 306

Schaefer B.E., 2007, ApJ, 660, 16

Sakamoto T. et al., 2005, ApJ 629, 211

Thompson, C., 2006, ApJ, 651, 333

Thompson, C., Mészáros P., Rees M.J., 2007, ApJ, 666, 1012

Troja, E., King, A.R., O’Brien, P.T., Lyons, N., Cusumano, G., 2008, MNRAS, accepted, arXiv:0711.3034

Villasenor J.S. et al., 2005, Nature 437, 855

Willingale R. et al., 2007, ApJ 662, 1093

Yonetoku D., Murakami T., Nakamura T., Yamazaki R., Inoue A.K., Ioka K., 2004, ApJ, 609, 935

Zhang B. & Mészáros P., 2002, ApJ, 581, 1236
Fig. 1.— The 1 keV to 10 MeV source frame spectra of GRBs listed in Table 1. The observed energy band is shown as the solid line in each case. $Q_{p,z}$ values are marked; solid dots for long GRBs, solid stars for short GRBs and solid triangles for XRFs.
Fig. 2.— The 1 keV to 10 MeV $E.F_z(E)$ source frame spectra of GRBs listed in Table 1. The observed band is shown as the solid line in each case. $E_{pz}Q_{pz}$ values are marked at the peak energy $E_{pz}$; solid dots for long GRBs, solid stars for short GRBs and solid triangles for XRFs.
Fig. 3.— Top panels: The distribution of $E_{\text{iso}}$ and the correlation of $E_{\text{wz}}$ vs. $E_{\text{pz}}$ for GRBs listed in Table 1; solid dots for long GRBs, solid stars for short GRBs, solid triangles for XRFs. The solid line is $E_{\text{wz}} = 4.3E_{\text{pz}}$ rather than the best fit correlation which is a shallower (see text). Bottom panels: Comparison of the functional fit, $E_{\text{fit}}$, and the value, $E_{\text{wz}}$, calculated by numerical integration of the Band function over the interval 1-10000 keV for the GRBs in Table 1. The right-hand panel shows the distribution of the ratio of $E_{\text{wz}}/E_{\text{fit}}$. 
Fig. 4.— Left-hand panel: The Amati relation for the GRBs in Table 1. Right-hand panel: $E_{wz}$ vs. $Q_{pz}$ for the same GRBs. Solid dots for long GRBs, solid stars for short GRBs, solid triangles for XRFs.

Fig. 5.— The rate profile function, Equation 12.
Fig. 6.— Typical prompt emission light curves and the corresponding rate profiles. The light curves have been smoothed with a boxcar function of width $T_{45}$ for display purposes.

Fig. 7.— Left-hand panel: The distribution of luminosity times, $T_L$ s, and the $\Sigma$ statistic from the fit. Right-hand panel: The correlation between rate profile index $C_L$ and the ratio of $T_{45}$ derived directly from the data and $T_L$ derived from the profile function fit.
Fig. 8.— Light curves and the corresponding rate profiles for which the fit statistic $\Sigma$ is high. The light curves have been smoothed with a boxcar function of width $T_{45}$ for display purposes.
Fig. 9.— Top panels: The correlation between luminosity time $T_{Lz}$ and $T_{90z}$ and the distribution of $T_{Lz}$. The dashed line indicates the equality $T_{Lz} = T_{90z}$. Bottom panels: The distributions of luminosity curvature index $C_L$ and photon index $\alpha$ for the GRBs in Table 1.
Fig. 10.—Top panels: The distributions of $E_{wz}$ keV and $Q_{pz}$ ergs keV$^{-1}$. Bottom panels: The correlation of $T_{Lz}$ s vs. $Q_{pz}$ and the distribution of the peak luminosity density, $Q_{pz}/T_{Lz}$ ergs keV$^{-1}$ s$^{-1}$. The distribution for short bursts is shown as the white histogram.
Fig. 11.— Left-hand panel: The correlation between characteristic energy $E_{\text{wz}} \text{ keV}$ and the peak luminosity density $Q_{pz}/T_{Lz} \text{ keV s}^{-1} \text{ s}^{-1}$. Right-hand panel: $E_{\text{wz}} \text{ keV}$ vs. the peak isotropic luminosity, $L_{\text{iso}} = E_{\text{wz}}Q_{pz}/T_{Lz} \text{ ergs s}^{-1}$. In both plots solid dots for long GRBs, solid stars for short GRBs, solid triangles for XRFs. The object with the largest $E_{\text{wz}}$, 8600 keV, is GRB050904.

Fig. 12.— The distribution of the photon energy/peak luminosity ratio $K_z$ corresponding to the scatter about the correlation line in the right-hand panel of Figure 11. The white histogram shows the distribution of the 26 pre-Swift bursts. The curve is the best fit Gaussian distribution. The right-hand panel shows $K_z$ vs. redshift $z$; solid dots for long GRBs, solid stars for short GRBs, solid triangles for XRFs. The horizontal dashed lines indicate the 90% range. The objects with unusually high $K_z$ are GRB980425/SN1998bw at low $z$ and GRB050904 at high $z$. 
Fig. 13.— Top panels: Observer frame parameters $E_p$ and minimum observed flux density, $f_m$, plotted against the peak flux density, $f_p$. The solid line represents $f_p = f_m$. Bottom panels: Source frame parameters, peak luminosity $L_{iso}$ and characteristic energy $E_{wz}$ plotted vs. redshift $z$; solid dots for long GRBs, solid stars for short GRBs, solid triangles for XRFs.
Fig. 14.— The redshift dependence, $C(z)$, in $K_z$. The data points show the $C(z)$ values for the GRBs in Table 1. The dashed curve is the redshift dependence of the Amati relation which is included for comparison.
Table 1. Observed spectral parameters; α, low photon index, \( E_p \), peak energy keV (if no error quoted then calculated assuming fixed \( E_{\text{cut}}, E_p = (\alpha + 2) \times 150 \) keV), \( \beta \), high photon index (if no error quoted then fixed at average of -2.3), \( F_{\text{tot}} \), fluence ergs cm\(^{-2} \), \( E_1 \) to \( E_2 \), observed energy band keV. References: (0) Swift BAT ibid., (1) Golenetskii et al., 2005, (2) Villasenor et al., 2005, (3) Barthelmy et al. 2005, Amati et al. 2006, Campana et al. 2006, (4) Golenetskii et al., 2005, (5) Golenetskii et al. 2005, Burrows D.N. et al. 2006, (6) Romano et al., 2006, (7) Amati et al. 2007, Montanari & Pian 2007, (8) Amati et al. 2007, Golenetskii et al. 2006, (9) Page et al. 2007, (10) Ghirlanda et al. 2004, (11) Friedman & Bloom 2005, (12) Sakamoto et al. 2005, (13) Atteia et al. 2005, (14) Piro et al. 2005, Amati 2007, (15) Galassi et al. 2004, Amati 2007, (16) Schaefer 2007, Firmani et al. 2006, (17) Golenetskii et al. 2007.

| GRB    | α      | \( E_p \)  | \( \beta \)  | \( F_{\text{tot}} \) | \( E_1 \) | \( E_2 \) | refs |
|--------|--------|-----------|-----------|----------------|--------|--------|------|
| 970228 | -1.54 ± 0.08 | 115 ± 38  | -2.50 ± 0.40 | (11.0 ± 1.0) \times 10^{-6} | 40     | 700    | 10   |
| 970508 | -1.71 ± 0.10 | 79 ± 23   | -2.20 ± 0.25 | (1.8 ± 0.3) \times 10^{-6} | 40     | 700    | 10   |
| 971214 | -0.76 ± 0.10 | 155 ± 30  | -2.70 ± 1.10 | (8.8 ± 0.9) \times 10^{-6} | 40     | 700    | 10   |
| 980425 | -1.27 ± 0.13 | 118 ± 24  | -2.30       | (3.8 ± 0.4) \times 10^{-6} | 20     | 2000   | 10   |
| 980613 | -1.43 ± 0.20 | 93 ± 43   | -2.70 ± 0.60 | (1.0 ± 0.2) \times 10^{-6} | 40     | 700    | 10   |
| 980703 | -1.31 ± 0.14 | 255 ± 51  | -2.30 ± 0.14 | (23.0 ± 0.2) \times 10^{-6} | 20     | 2000   | 10   |
| 990123 | -0.89 ± 0.08 | 781 ± 62  | -2.45 ± 0.97 | (3.0 ± 0.4) \times 10^{-4} | 40     | 700    | 10   |
| 990506 | -1.37 ± 0.15 | 283 ± 57  | -2.15 ± 0.38 | (1.9 ± 0.2) \times 10^{-4} | 20     | 2000   | 10   |
| 990510 | -1.23 ± 0.05 | 163 ± 16  | -2.70 ± 0.40 | (1.9 ± 0.2) \times 10^{-5} | 40     | 700    | 10   |
| 990705 | -1.05 ± 0.20 | 189 ± 15  | -2.20 ± 0.10 | (7.5 ± 0.8) \times 10^{-5} | 40     | 700    | 10   |
| 990712 | -1.88 ± 0.07 | 65 ± 11   | -2.48 ± 0.56 | (0.6 ± 0.3) \times 10^{-5} | 40     | 700    | 10   |
| 991216 | -1.23 ± 0.13 | 318 ± 64  | -2.18 ± 0.39 | (1.9 ± 0.2) \times 10^{-4} | 20     | 2000   | 10   |
| 010921 | -1.49 ± 0.16 | 106 ± 21  | -2.30       | (10.0 ± 1.0) \times 10^{-6} | 30     | 700    | 10   |
| 011121 | -1.42 ± 0.14 | 217 ± 26  | -2.30       | (96.6 ± 1.0) \times 10^{-6} | 40     | 700    | 14   |
| 011211 | -0.84 ± 0.09 | 59 ± 8    | -2.30       | (5.1 ± 0.2) \times 10^{-6} | 40     | 700    | 14   |
| 021004 | -1.01 ± 0.19 | 80 ± 35   | -2.30 ± 0.46 | (2.6 ± 0.6) \times 10^{-6} | 2      | 400    | 11   |
| 021211 | -0.85 ± 0.09 | 47 ± 9    | -2.37 ± 0.42 | (2.2 ± 0.2) \times 10^{-6} | 30     | 400    | 10   |
| 030115A| -1.28 ± 0.14 | 83 ± 37   | -2.20 ± 0.40 | (2.3 ± 0.3) \times 10^{-6} | 2      | 400    | 16   |
| 030226 | -0.95 ± 0.10 | 108 ± 22  | -2.30       | (6.4 ± 0.6) \times 10^{-6} | 30     | 400    | 10   |
| 030323 | -0.80 ± 0.20 | 53 ± 30   | -2.30       | (1.2 ± 0.3) \times 10^{-6} | 2      | 400    | 13   |
| 030328 | -1.00 ± 0.11 | 110 ± 22  | -2.30       | (2.6 ± 0.2) \times 10^{-5} | 30     | 400    | 10   |
| 030429 | -1.10 ± 0.20 | 35 ± 10   | -2.30       | (0.8 ± 0.1) \times 10^{-6} | 2      | 400    | 12   |
| 040924 | -1.17 ± 0.05 | 125 ± 12  | -2.30       | (2.7 ± 0.1) \times 10^{-6} | 20     | 500    | 16   |
| 041006 | -1.37 ± 0.10 | 63 ± 13   | -2.30       | (7.0 ± 0.5) \times 10^{-6} | 30     | 400    | 15   |
| 050126 | -1.06 ± 0.20 | 158 ± 20  | -2.30       | (8.4 ± 0.8) \times 10^{-7} | 15     | 150    | 0    |
| 050315 | -1.76 ± 0.06 | 36        | -2.30       | (3.2 ± 0.1) \times 10^{-6} | 15     | 150    | 0    |
| 050318 | -1.34 ± 0.20 | 47 ± 9    | -2.30       | (10.8 ± 0.8) \times 10^{-7} | 15     | 150    | 0    |
| 050319 | -1.66 ± 0.15 | 51        | -2.30       | (1.3 ± 0.1) \times 10^{-5} | 15     | 150    | 0    |
| 050401 | -1.11 ± 0.07 | 132 ± 16  | -2.30       | (8.2 ± 0.3) \times 10^{-6} | 15     | 150    | 0    |
| 050505 | -0.99 ± 0.20 | 102 ± 0   | -2.30       | (2.5 ± 0.2) \times 10^{-6} | 15     | 150    | 0    |
| 050509B| -1.04 ± 0.20 | 144       | -2.30       | (0.9 ± 0.2) \times 10^{-8} | 15     | 150    | 0    |
Table 1—Continued

| GRB     | $\alpha$  | $E_p$   | $\beta$  | $F_{tot}$                  | $E_1$ | $E_2$ | refs |
|---------|-----------|---------|----------|-----------------------------|-------|-------|------|
| 050525A | $-0.87 \pm 0.07$ | $82 \pm 4$ | $-2.30$  | $(15.3 \pm 0.2) \times 10^{-6}$ | 15    | 150   | 0    |
| 050603  | $-0.81 \pm 0.04$ | $349 \pm 28$ | $-2.30$  | $(6.4 \pm 0.2) \times 10^{-6}$ | 15    | 150   | 1    |
| 050709  | $-0.53 \pm 0.13$ | $83 \pm 10$ | $-2.30$  | $(4.0 \pm 0.4) \times 10^{-7}$ | 2     | 400   | 2    |
| 050724  | $-1.80 \pm 0.17$ | $30 \pm 2.30$ | $1.0 \pm 0.1 \times 10^{-6}$ | 15    | 150   | 3    |
| 050730  | $-1.15 \pm 0.10$ | $127 \pm 2.30$ | $(2.4 \pm 0.2) \times 10^{-6}$ | 15    | 150   | 0    |
| 050802  | $-1.15 \pm 0.10$ | $127 \pm 2.30$ | $(2.0 \pm 0.2) \times 10^{-6}$ | 15    | 150   | 0    |
| 050803  | $-1.05 \pm 0.08$ | $142 \pm 2.30$ | $(2.2 \pm 0.1) \times 10^{-6}$ | 15    | 150   | 0    |
| 050814  | $-1.61 \pm 0.13$ | $58 \pm 2.30$ | $(2.0 \pm 0.2) \times 10^{-6}$ | 15    | 150   | 0    |
| 050820A | $-0.97 \pm 0.09$ | $246 \pm 96$ | $-2.30$  | $(3.4 \pm 0.2) \times 10^{-6}$ | 15    | 150   | 0    |
| 050904  | $-1.07 \pm 0.14$ | $413 \pm 140$ | $-2.30$  | $(4.8 \pm 0.2) \times 10^{-6}$ | 15    | 150   | 0    |
| 050908  | $-1.50 \pm 0.12$ | $75 \pm 2.30$ | $(4.8 \pm 0.5) \times 10^{-7}$ | 15    | 150   | 0    |
| 050922C | $-1.04 \pm 0.05$ | $130 \pm 37$ | $-2.30$  | $(16.2 \pm 0.5) \times 10^{-7}$ | 15    | 150   | 0    |
| 051022  | $-1.18 \pm 0.04$ | $510 \pm 35$ | $-2.30$  | $(26.1 \pm 0.9) \times 10^{-5}$ | 20    | 2000  | 4    |
| 051109A | $-1.23 \pm 0.15$ | $157 \pm 111$ | $-2.30$  | $(2.2 \pm 0.3) \times 10^{-6}$ | 15    | 150   | 4    |
| 051109B | $-0.89 \pm 0.20$ | $41 \pm 32$  | $-2.30$  | $(2.6 \pm 0.4) \times 10^{-7}$ | 15    | 150   | 0    |
| 051111  | $-1.04 \pm 0.05$ | $211 \pm 50$ | $-2.30$  | $(4.1 \pm 0.1) \times 10^{-6}$ | 15    | 150   | 0    |
| 051221A | $-1.08 \pm 0.04$ | $402 \pm 72$ | $-2.30$  | $(11.5 \pm 0.3) \times 10^{-7}$ | 15    | 150   | 5    |
| 060108  | $-1.65 \pm 0.12$ | $52 \pm 2.30$ | $(3.7 \pm 0.4) \times 10^{-7}$ | 15    | 150   | 0    |
| 060115  | $-1.09 \pm 0.20$ | $62 \pm 18$  | $-2.30$  | $(1.7 \pm 0.2) \times 10^{-6}$ | 15    | 150   | 0    |
| 060124  | $-1.66 \pm 0.17$ | $193 \pm 49$ | $-2.30$  | $(4.6 \pm 0.5) \times 10^{-7}$ | 15    | 150   | 6    |
| 060206  | $-1.38 \pm 0.19$ | $75 \pm 22$  | $-2.30$  | $(8.3 \pm 0.4) \times 10^{-7}$ | 15    | 150   | 0    |
| 060210  | $-1.18 \pm 0.12$ | $123 \pm 2.30$ | $(7.7 \pm 0.4) \times 10^{-6}$ | 15    | 150   | 0    |
| 060218  | $-0.24 \pm 0.20$ | $30 \pm 20$  | $-2.30$  | $(1.6 \pm 0.2) \times 10^{-6}$ | 15    | 150   | 7    |
| 060223A | $-1.44 \pm 0.09$ | $83 \pm 2.30$ | $(6.7 \pm 0.5) \times 10^{-7}$ | 15    | 150   | 0    |
| 060418  | $-1.38 \pm 0.04$ | $230 \pm 46$ | $-2.30$  | $(8.3 \pm 0.3) \times 10^{-6}$ | 15    | 150   | 0    |
| 060502A | $-1.07 \pm 0.05$ | $139 \pm 2.30$ | $(2.3 \pm 0.1) \times 10^{-6}$ | 15    | 150   | 0    |
| 060502B | $-0.92 \pm 0.20$ | $162 \pm 2.30$ | $(4.0 \pm 0.5) \times 10^{-8}$ | 15    | 150   | 0    |
| 060510B | $-1.48 \pm 0.20$ | $89 \pm 6$   | $-2.30$  | $(4.1 \pm 0.2) \times 10^{-6}$ | 15    | 150   | 0    |
| 060522  | $-1.21 \pm 0.12$ | $118 \pm 2.30$ | $(1.1 \pm 0.1) \times 10^{-6}$ | 15    | 150   | 0    |
| 060526  | $-1.74 \pm 0.16$ | $39 \pm 2.30$ | $(1.3 \pm 0.2) \times 10^{-6}$ | 15    | 150   | 0    |
| 060604  | $-1.59 \pm 0.20$ | $61 \pm 2.30$ | $(0.4 \pm 0.1) \times 10^{-6}$ | 15    | 150   | 0    |
Table 1—Continued

| GRB      | $\alpha$     | $E_p$  | $\beta$ | $F_{\text{tot}}$       | $E_1$ | $E_2$ | refs |
|----------|--------------|--------|---------|-------------------------|-------|-------|------|
| 060605   | $-0.93 \pm 0.11$ | 160    | $-2.30$ | $(7.0 \pm 0.9) \times 10^{-7}$ | 15    | 150   | 0    |
| 060607A  | $-1.05 \pm 0.20$ | 131    | $-2.30$ | $(2.6 \pm 0.1) \times 10^{-6}$ | 15    | 150   | 0    |
| 060614   | $-1.66 \pm 0.03$ | 68     | $-2.30$ | $(20.4 \pm 0.4) \times 10^{-6}$ | 15    | 150   | 8    |
| 060707   | $-0.58 \pm 0.20$ | 60     | $-2.30$ | $(1.6 \pm 0.2) \times 10^{-6}$ | 15    | 150   | 0    |
| 060714   | $-1.64 \pm 0.08$ | 54     | $-2.30$ | $(2.8 \pm 0.2) \times 10^{-6}$ | 15    | 150   | 0    |
| 060729   | $-1.51 \pm 0.11$ | 73     | $-2.30$ | $(2.6 \pm 0.2) \times 10^{-6}$ | 15    | 150   | 0    |
| 060801   | $-0.01 \pm 0.19$ | 298    | $-2.30$ | $(8.0 \pm 1.0) \times 10^{-8}$ | 15    | 150   | 0    |
| 060814   | $-1.43 \pm 0.16$ | 257    | $-2.30$ | $(14.6 \pm 0.2) \times 10^{-6}$ | 15    | 150   | 0    |
| 060904B  | $-1.40 \pm 0.11$ | 90     | $-2.30$ | $(1.6 \pm 0.1) \times 10^{-6}$ | 15    | 150   | 0    |
| 060906   | $-1.71 \pm 0.08$ | 43     | $-2.30$ | $(2.2 \pm 0.1) \times 10^{-6}$ | 15    | 150   | 0    |
| 060908   | $-0.85 \pm 0.16$ | 153    | $-2.30$ | $(2.8 \pm 0.1) \times 10^{-6}$ | 15    | 150   | 0    |
| 060912   | $-1.45 \pm 0.06$ | 82     | $-2.30$ | $(13.5 \pm 0.6) \times 10^{-7}$ | 15    | 150   | 0    |
| 060927   | $-0.93 \pm 0.20$ | 72     | $-2.30$ | $(11.3 \pm 0.7) \times 10^{-7}$ | 15    | 150   | 0    |
| 061004   | $-1.46 \pm 0.07$ | 80     | $-2.30$ | $(5.7 \pm 0.3) \times 10^{-7}$ | 15    | 150   | 0    |
| 061006   | $-0.62 \pm 0.20$ | 664    | $-2.30$ | $(1.4 \pm 0.1) \times 10^{-6}$ | 15    | 150   | 17   |
| 061007   | $-0.62 \pm 0.02$ | 407    | $-2.30$ | $(44.4 \pm 0.6) \times 10^{-6}$ | 15    | 150   | 0    |
| 061110A  | $-1.35 \pm 0.09$ | 97     | $-2.30$ | $(10.6 \pm 0.8) \times 10^{-7}$ | 15    | 150   | 0    |
| 061121   | $-1.05 \pm 0.02$ | 557    | $-2.30$ | $(13.7 \pm 0.2) \times 10^{-6}$ | 15    | 150   | 9    |
| 061201   | $-0.33 \pm 0.15$ | 873    | $-2.30$ | $(3.3 \pm 0.3) \times 10^{-7}$ | 15    | 150   | 0    |
| 061210   | $-1.19 \pm 0.20$ | 121    | $-2.30$ | $(1.1 \pm 0.2) \times 10^{-6}$ | 15    | 150   | 0    |
| 061217   | $-0.38 \pm 0.20$ | 243    | $-2.30$ | $(4.2 \pm 0.7) \times 10^{-8}$ | 15    | 150   | 0    |
| 061222B  | $-1.71 \pm 0.20$ | 40     | $-2.30$ | $(2.2 \pm 0.2) \times 10^{-6}$ | 15    | 150   | 0    |
| 070110   | $-1.24 \pm 0.08$ | 114    | $-2.30$ | $(1.6 \pm 0.1) \times 10^{-6}$ | 15    | 150   | 0    |
| 070208   | $-1.50 \pm 0.20$ | 75     | $-2.30$ | $(0.4 \pm 0.1) \times 10^{-6}$ | 15    | 150   | 0    |
| 070318   | $-1.07 \pm 0.06$ | 139    | $-2.30$ | $(2.5 \pm 0.1) \times 10^{-6}$ | 15    | 150   | 0    |
| 070411   | $-1.35 \pm 0.07$ | 97     | $-2.30$ | $(2.7 \pm 0.2) \times 10^{-6}$ | 15    | 150   | 0    |
| 070506   | $-0.89 \pm 0.20$ | 53     | $-2.30$ | $(2.1 \pm 0.2) \times 10^{-7}$ | 15    | 150   | 0    |
| 070508   | $-0.87 \pm 0.02$ | 169    | $-2.30$ | $(19.6 \pm 0.3) \times 10^{-6}$ | 15    | 150   | 0    |
| 070521   | $-0.89 \pm 0.03$ | 166    | $-2.30$ | $(8.0 \pm 0.2) \times 10^{-6}$ | 15    | 150   | 0    |
| 070529   | $-1.11 \pm 0.12$ | 133    | $-2.30$ | $(2.6 \pm 0.2) \times 10^{-6}$ | 15    | 150   | 0    |
| 070611   | $-1.44 \pm 0.18$ | 83     | $-2.30$ | $(3.9 \pm 0.6) \times 10^{-7}$ | 15    | 150   | 0    |
| GRB    | $\alpha$  | $E_p$ | $\beta$ | $F_{\text{tot}}$        | $E_1$ | $E_2$ | refs |
|--------|-----------|-------|---------|------------------------|-------|-------|------|
| 070612A| $-1.41 \pm 0.07$ | 88    | $-2.30$ | $(10.6 \pm 0.6)10^{-6}$ | 15    | 150   | 0    |
| 070714B| $-1.04 \pm 0.15$  | 144   | $-2.30$ | $(6.4 \pm 0.9)10^{-7}$  | 15    | 150   | 0    |
| 070721B| $-0.86 \pm 0.08$  | 171   | $-2.30$ | $(3.0 \pm 0.2)10^{-6}$  | 15    | 150   | 0    |
| 070724A| $-1.51 \pm 0.20$  | 73    | $-2.30$ | $(2.8 \pm 0.7)10^{-8}$  | 15    | 150   | 0    |
| 070802 | $-1.42 \pm 0.18$  | 87    | $-2.30$ | $(2.5 \pm 0.5)10^{-7}$  | 15    | 150   | 0    |
| 070810A| $-1.82 \pm 0.10$  | 26    | $-2.30$ | $(6.1 \pm 0.7)10^{-7}$  | 15    | 150   | 0    |
Table 2. Observed temporal parameters; $T_{90}$ secs, luminosity time $T_L$ secs, luminosity index $C_L$, luminosity profile fitting statistic $\Sigma$. Errors were estimated by assuming $\Sigma$ was distributed as $\chi^2$.

| GRB     | instr | class | $T_{90}$ | $T_L$     | $C_L$   | $\Sigma$ |
|---------|-------|-------|----------|-----------|---------|----------|
| 970228  | SAX   | Long  | 80.0     | $9.7 \pm 0.6$ | $2.41 \pm 0.07$ | 1.55     |
| 970508  | SAX   | Long  | 20.0     | $4.2 \pm 0.1$  | $2.01 \pm 0.03$ | 1.55     |
| 971214  | SAX   | Long  | 35.0     | $10.6 \pm 0.2$ | $1.52 \pm 0.02$ | 1.31     |
| 980425  | SAX   | Long  | 37.4     | $16. \pm 1.$   | $1.54 \pm 0.13$ | 0.94     |
| 980613  | BATSE | Long  | 20.0     | $12. \pm 1.$   | $1.32 \pm 0.21$ | 1.19     |
| 980703  | BATSE | Long  | 102      | $20.0 \pm 0.4$ | $1.56 \pm 0.03$ | 0.30     |
| 990123  | SAX   | Long  | 100.0    | $22.7 \pm 0.2$ | $1.94 \pm 0.01$ | 1.37     |
| 990506  | BATSE | Long  | 220      | $14.00 \pm 0.10$ | $2.35 \pm 0.01$ | 1.83     |
| 990510  | SAX   | Long  | 75.0     | $5.23 \pm 0.06$ | $2.48 \pm 0.01$ | 1.23     |
| 990705  | SAX   | Long  | 42.0     | $26.8 \pm 0.9$ | $1.64 \pm 0.03$ | 6.51     |
| 990712  | SAX   | XRF   | 20.0     | $4.1 \pm 0.3$  | $2.80 \pm 0.08$ | 4.67     |
| 991216  | BATSE | Long  | 24.9     | $3.89 \pm 0.04$ | $2.59 \pm 0.01$ | 4.59     |
| 010921  | HETE-2| Long  | 24.6     | $12.3 \pm 0.4$ | $1.26 \pm 0.05$ | 0.35     |
| 011121  | SAX   | Long  | 37.0     | $18.9 \pm 0.6$ | $2.14 \pm 0.04$ | 3.10     |
| 011211  | SAX   | Long  | 270      | $133. \pm 5.$   | $1.26 \pm 0.06$ | 0.99     |
| 021004  | HETE-2| Long  | 49.7     | $11.4 \pm 0.7$ | $1.62 \pm 0.10$ | 0.39     |
| 021211  | HETE-2| Long  | 2.4      | $2.0 \pm 0.2$  | $1.28 \pm 0.09$ | 0.44     |
| 030115A | HETE-2| Long  | 36.0     | $8.4 \pm 0.4$  | $1.73 \pm 0.08$ | 0.28     |
| 030226  | HETE-2| Long  | 76.8     | $27.3 \pm 0.9$ | $1.60 \pm 0.06$ | 0.32     |
| 030323  | HETE-2| Long  | 19.6     | $2.9 \pm 0.8$  | $1.36 \pm 0.28$ | 0.20     |
| 030328  | HETE-2| Long  | 140      | $45.8 \pm 0.7$ | $1.66 \pm 0.02$ | 0.27     |
| 030429  | HETE-2| Long  | 24.6     | $5.8 \pm 0.7$  | $2.13 \pm 0.19$ | 0.94     |
| 040924  | HETE-2| Long  | 5.0      | $1.13 \pm 0.07$ | $2.05 \pm 0.08$ | 3.40     |
| 041006  | HETE-2| Long  | 24.6     | $13.1 \pm 0.4$ | $1.37 \pm 0.04$ | 1.63     |
| 050126  | Swift | Long  | 25.7     | $7.7 \pm 0.4$  | $1.65 \pm 0.09$ | 0.39     |
| 050315  | Swift | XRF   | 96.0     | $21.6 \pm 0.5$ | $1.62 \pm 0.04$ | 0.14     |
| 050318  | Swift | Long  | 31.3     | $5.3 \pm 0.3$  | $1.40 \pm 0.09$ | 1.11     |
| 050319  | Swift | Long  | 149      | $4.0 \pm 0.3$  | $1.93 \pm 0.11$ | 0.68     |
| 050401  | Swift | Long  | 33.3     | $6.1 \pm 0.2$  | $1.78 \pm 0.05$ | 0.19     |
| 050505  | Swift | Long  | 63.0     | $11.4 \pm 0.4$ | $1.50 \pm 0.08$ | 0.19     |
| 050509B | Swift | Short | 0.07     | $0.043 \pm 0.005$ | $1.61 \pm 0.20$ | 0.47     |
Table 2—Continued

| GRB   | instr | class | $T_{90}$ | $T_L$     | $C_L$     | $\Sigma$ |
|-------|-------|-------|----------|-----------|-----------|----------|
| 050525A | Swift | Long  | 8.8      | 3.9 ± 0.1 | 1.58 ± 0.03 | 1.45     |
| 050603  | Swift | Long  | 13.0     | 0.84 ± 0.02 | 2.74 ± 0.03 | 0.38     |
| 050709  | HETE-2| Short | 0.22     | 0.056 ± 0.004 | 2.26 ± 0.08 | 3.19     |
| 050724  | Swift | XRF   | 152      | 0.48 ± 0.02 | 3.17 ± 0.06 | 0.32     |
| 050730  | Swift | Long  | 155      | 25.8 ± 0.8  | 1.81 ± 0.06 | 0.25     |
| 050802  | Swift | Long  | 30.9     | 6.1 ± 0.3   | 1.59 ± 0.09 | 0.22     |
| 050803  | Swift | Long  | 89.0     | 14.3 ± 0.5  | 1.85 ± 0.05 | 0.12     |
| 050814  | Swift | Long  | 144      | 11.1 ± 0.6  | 1.74 ± 0.11 | 0.12     |
| 050820A | Swift | Long  | 240      | 11.6 ± 0.2  | 1.75 ± 0.03 | 0.16     |
| 050904  | Swift | Long  | 173      | 57. ± 1.    | 1.62 ± 0.04 | 0.28     |
| 050908  | Swift | Long  | 20.3     | 5.5 ± 0.3   | 1.45 ± 0.09 | 0.15     |
| 050922C | Swift | Long  | 4.1      | 1.81 ± 0.07 | 1.65 ± 0.05 | 0.89     |
| 051022  | Konus | Long  | 197      | 10.9 ± 0.3  | 1.81 ± 0.04 | 4.91     |
| 051109A | Swift | Long  | 37.0     | 2.9 ± 0.2   | 2.00 ± 0.13 | 0.28     |
| 051109B | Swift | Long  | 15.0     | 1.9 ± 0.2   | 1.79 ± 0.16 | 0.31     |
| 051111  | Swift | Long  | 42.6     | 13.4 ± 0.3  | 1.66 ± 0.04 | 0.11     |
| 051221A | Swift | Short | 1.40     | 0.118 ± 0.003 | 2.85 ± 0.03 | 3.22     |
| 060108  | Swift | Long  | 14.4     | 4.4 ± 0.3   | 1.46 ± 0.11 | 0.22     |
| 060115  | Swift | Long  | 141      | 17.5 ± 0.6  | 1.78 ± 0.06 | 0.35     |
| 060124  | Swift | Long  | 321      | 4.1 ± 0.3   | 1.58 ± 0.13 | 0.41     |
| 060206  | Swift | Long  | 7.7      | 3.3 ± 0.1   | 1.42 ± 0.05 | 0.22     |
| 060210  | Swift | Long  | 220      | 24.9 ± 0.6  | 1.92 ± 0.04 | 0.61     |
| 060218  | Swift | Long  | 2100     | 20.4 ± 0.9  | 1.82 ± 0.09 | 0.12     |
| 060223A | Swift | Long  | 11.4     | 4.7 ± 0.3   | 1.36 ± 0.10 | 0.14     |
| 060418  | Swift | Long  | 95.8     | 16.5 ± 0.3  | 1.93 ± 0.02 | 1.05     |
| 060502A | Swift | Long  | 32.0     | 12.0 ± 0.4  | 1.38 ± 0.06 | 0.77     |
| 060502B | Swift | Short | 0.13     | 0.058 ± 0.006 | 2.41 ± 0.13 | 0.60     |
| 060510B | Swift | Long  | 276      | 57. ± 1.    | 1.65 ± 0.04 | 0.24     |
| 060522  | Swift | Long  | 69.3     | 9.1 ± 0.4   | 1.77 ± 0.09 | 0.10     |
| 060526  | Swift | XRF   | 298      | 6.7 ± 0.3   | 2.39 ± 0.07 | 0.72     |
| 060604  | Swift | Long  | 7.8      | 2.3 ± 0.2   | 1.49 ± 0.24 | 0.14     |
Table 2—Continued

| GRB     | instr  | class | $T_{90}$ | $T_L$   | $C_L$  | $\Sigma$ |
|---------|--------|-------|----------|---------|--------|----------|
| 060605  | Swift  | Long  | 14.8     | 7.9 ± 0.4 | 1.46 ± 0.09 | 0.15 |
| 060607A | Swift  | Long  | 100      | 15.2 ± 0.4 | 1.88 ± 0.04 | 0.18 |
| 060614  | Swift  | Long  | 108      | 26.7 ± 0.4 | 2.13 ± 0.02 | 4.70 |
| 060707  | Swift  | Long  | 66.2     | 10.0 ± 0.5 | 1.72 ± 0.09 | 0.11 |
| 060714  | Swift  | Long  | 115      | 23.0 ± 0.6 | 1.62 ± 0.05 | 0.20 |
| 060729  | Swift  | Long  | 112      | 17.2 ± 0.5 | 1.59 ± 0.05 | 0.44 |
| 060801  | Swift  | Short | 0.49     | 0.20 ± 0.01 | 1.70 ± 0.11 | 0.51 |
| 060814  | Swift  | Long  | 128      | 25.5 ± 0.3 | 2.17 ± 0.01 | 1.25 |
| 060904B | Swift  | Long  | 190      | 4.9 ± 0.2 | 2.17 ± 0.04 | 0.53 |
| 060906  | Swift  | XRF   | 43.5     | 12.1 ± 0.4 | 1.67 ± 0.07 | 0.61 |
| 060908  | Swift  | Long  | 19.0     | 9.1 ± 0.3 | 1.09 ± 0.06 | 0.31 |
| 060912  | Swift  | Long  | 6.0      | 1.53 ± 0.06 | 2.02 ± 0.05 | 1.57 |
| 060927  | Swift  | Long  | 10.0     | 3.9 ± 0.1 | 1.92 ± 0.05 | 0.44 |
| 061004  | Swift  | Long  | 6.2      | 2.4 ± 0.1 | 1.89 ± 0.07 | 0.28 |
| 061006  | Swift  | Long  | 129      | 0.47 ± 0.01 | 3.12 ± 0.03 | 1.26 |
| 061007  | Swift  | Long  | 74.2     | 23.2 ± 0.2 | 1.90 ± 0.01 | 5.04 |
| 061110A | Swift  | Long  | 44.6     | 13.4 ± 0.5 | 1.57 ± 0.07 | 0.33 |
| 061121  | Swift  | Long  | 81.3     | 5.34 ± 0.06 | 2.58 ± 0.01 | 1.28 |
| 061201  | Swift  | Short | 0.76     | 0.22 ± 0.01 | 1.96 ± 0.07 | 0.55 |
| 061210  | Swift  | Long  | 85.3     | 0.030 ± 0.001 | 4.29 ± 0.04 | 13.4 |
| 061217  | Swift  | Short | 0.21     | 0.15 ± 0.01 | 1.76 ± 0.16 | 0.08 |
| 061222B | Swift  | XRF   | 40.0     | 10.7 ± 0.5 | 1.70 ± 0.08 | 0.43 |
| 070110  | Swift  | Long  | 87.3     | 18.1 ± 0.6 | 1.63 ± 0.07 | 0.25 |
| 070208  | Swift  | Long  | 47.7     | 2.9 ± 0.3 | 1.69 ± 0.17 | 1.12 |
| 070318  | Swift  | Long  | 119      | 12.7 ± 0.3 | 1.91 ± 0.04 | 0.14 |
| 070411  | Swift  | Long  | 116      | 27.0 ± 0.8 | 1.66 ± 0.05 | 0.26 |
| 070506  | Swift  | Long  | 4.3      | 2.1 ± 0.1 | 1.39 ± 0.12 | 0.55 |
| 070508  | Swift  | Long  | 20.8     | 6.59 ± 0.09 | 2.07 ± 0.02 | 1.30 |
| 070521  | Swift  | Long  | 38.4     | 12.2 ± 0.2 | 1.69 ± 0.03 | 0.42 |
| 070529  | Swift  | Long  | 108      | 8.5 ± 0.4 | 1.90 ± 0.09 | 0.29 |
| 070611  | Swift  | Long  | 13.2     | 2.6 ± 0.2 | 1.67 ± 0.18 | 0.28 |
| GRB      | instr | class | $T_{90}$ | $T_L$   | $C_L$   | $\Sigma$ |
|----------|-------|-------|----------|---------|---------|----------|
| 070612A  | Swift | Long  | 359      | 32.4 ± 0.9 | 1.91 ± 0.05 | 0.27     |
| 070714B  | Swift | Long  | 63.9      | 0.48 ± 0.02 | 2.87 ± 0.07 | 0.55     |
| 070721B  | Swift | Long  | 345      | 12.5 ± 0.4 | 1.87 ± 0.05 | 0.40     |
| 070724A  | Swift | Short | 0.40      | 0.11 ± 0.01 | 1.75 ± 0.16 | 0.66     |
| 070802   | Swift | Long  | 16.9      | 3.5 ± 0.3 | 1.74 ± 0.15 | 0.27     |
| 070810A  | Swift | XRF   | 10.9      | 4.1 ± 0.2 | 1.18 ± 0.10 | 0.46     |
Table 3. Source frame parameters; $z$ redshift, values from tabulations in Amati (2006), Ghirlanda et al. (2004) and http://swift.gsfc.nasa.gov/docs/swift/archive/grb_table/.
References for all the Swift redshifts are provided on this WWW data table. $E_{\text{wz}}$ keV, $Q_{pz}$ ergs keV$^{-1}$, $T_{Lz}$ s, photon energy/peak luminosity ratio $K_z$.

| GRB     | $z$  | $E_{\text{wz}}$  | $Q_{pz}$       | $T_{Lz}$       | $K_z$  |
|---------|------|------------------|----------------|----------------|-------|
| 970228  | 0.695| 930 ± 321        | $(0.3 \pm 0.1)10^{50}$ | $5.7 \pm 0.3$ | 1.21 ± 0.96 |
| 970508  | 0.835| 908 ± 279        | $(0.9 \pm 0.3)10^{49}$ | $2.30 \pm 0.06$ | 1.16 ± 0.83 |
| 971214  | 3.420| 1984 ± 432       | $(1.5 \pm 0.4)10^{50}$ | $2.41 \pm 0.04$ | 0.98 ± 0.50 |
| 980425  | 0.009| 553 ± 125        | $(1.7 \pm 0.5)10^{45}$ | $16. \pm 1$    | 0.20 ± 0.10 |
| 980613  | 1.096| 810 ± 383        | $(0.7 \pm 0.4)10^{49}$ | $5.7 \pm 0.7$  | 1.03 ± 1.13 |
| 980703  | 0.966| 2060 ± 461       | $(3.4 \pm 0.9)10^{49}$ | $10.2 \pm 0.2$ | 0.51 ± 0.26 |
| 990123  | 1.600| 5739 ± 732       | $(7.0 \pm 1.4)10^{50}$ | $8.72 \pm 0.09$ | 0.37 ± 0.11 |
| 990506  | 1.307| 3003 ± 675       | $(3.7 \pm 1.1)10^{50}$ | $6.07 \pm 0.04$ | 0.65 ± 0.34 |
| 990510  | 1.619| 1541 ± 216       | $(1.3 \pm 0.2)10^{50}$ | $2.00 \pm 0.02$ | 1.27 ± 0.42 |
| 990705  | 0.843| 1488 ± 190       | $(1.7 \pm 0.4)10^{50}$ | $14.5 \pm 0.5$ | 0.91 ± 0.29 |
| 990712  | 0.430| 606 ± 119        | $(1.3 \pm 0.7)10^{49}$ | $2.9 \pm 0.2$  | 1.79 ± 0.91 |
| 991216  | 1.020| 2736 ± 614       | $(2.4 \pm 0.7)10^{50}$ | $1.92 \pm 0.02$ | 0.83 ± 0.44 |
| 010921  | 0.450| 783 ± 173        | $(1.2 \pm 0.4)10^{49}$ | $8.5 \pm 0.3$  | 1.09 ± 0.57 |
| 011121  | 0.360| 1397 ± 218       | $(4.3 \pm 0.9)10^{49}$ | $13.9 \pm 0.5$ | 0.73 ± 0.27 |
| 011211  | 2.140| 737 ± 124        | $(1.4 \pm 0.3)10^{50}$ | $43 \pm 2$     | 1.37 ± 0.54 |
| 021004  | 2.335| 1076 ± 482       | $(0.4 \pm 0.2)10^{50}$ | $3.4 \pm 0.2$  | 1.26 ± 1.31 |
| 021211  | 1.010| 371 ± 80         | $(3.1 \pm 0.8)10^{49}$ | $1.0 \pm 0.1$  | 4.33 ± 2.19 |
| 030115A | 2.500| 1371 ± 626       | $(0.3 \pm 0.2)10^{50}$ | $2.4 \pm 0.1$  | 1.03 ± 1.09 |
| 030226  | 1.980| 1253 ± 284       | $(0.9 \pm 0.2)10^{50}$ | $9.2 \pm 0.3$  | 1.03 ± 0.54 |
| 030323  | 3.370| 896 ± 448        | $(0.4 \pm 0.3)10^{50}$ | $0.7 \pm 0.2$  | 2.13 ± 2.45 |
| 030328  | 1.520| 1110 ± 248       | $(2.6 \pm 0.7)10^{50}$ | $18.2 \pm 0.3$ | 1.26 ± 0.65 |
| 030429  | 2.650| 559 ± 169        | $(0.3 \pm 0.1)10^{50}$ | $1.6 \pm 0.2$  | 2.63 ± 1.87 |
| 040924  | 0.859| 998 ± 138        | $(0.9 \pm 0.1)10^{49}$ | $0.61 \pm 0.04$ | 1.40 ± 0.45 |
| 041006  | 0.716| 527 ± 120        | $(0.4 \pm 0.1)10^{50}$ | $7.6 \pm 0.2$  | 2.10 ± 1.12 |
| 050126  | 1.290| 1448 ± 237       | $(0.7 \pm 0.2)10^{49}$ | $3.3 \pm 0.2$  | 0.64 ± 0.25 |
| 050315  | 1.949| 653 ± 176        | $(1.3 \pm 0.4)10^{50}$ | $7.3 \pm 0.2$  | 2.23 ± 1.39 |
| 050318  | 1.440| 550 ± 118        | $(2.4 \pm 0.7)10^{49}$ | $2.2 \pm 0.1$  | 2.37 ± 1.21 |
| 050319  | 3.240| 1223 ± 553       | $(0.6 \pm 0.3)10^{50}$ | $0.94 \pm 0.06$ | 1.60 ± 1.68 |
| 050401  | 2.900| 2012 ± 316       | $(1.9 \pm 0.3)10^{50}$ | $1.56 \pm 0.05$ | 1.11 ± 0.41 |
| 050505  | 4.270| 2006 ± 201       | $(1.0 \pm 0.2)10^{50}$ | $2.16 \pm 0.09$ | 0.90 ± 0.23 |
| 050509B | 0.225| 742 ± 221        | $(0.4 \pm 0.2)10^{46}$ | $0.035 \pm 0.004$ | 0.67 ± 0.47 |
Table 3—Continued

| GRB     | $z$   | $E_{wz}$   | $Q_{pz}$   | $T_{L,z}$  | $K_z$   |
|----------|-------|------------|------------|------------|---------|
| 050730   | 3.970 | 2457 ± 142 | 0.257      | 0.9 ± 0.2  | 0.048 ± 0.003 | 2.32 ± 0.85 |
| 050724   | 2.057 | 230 ± 115  | 0.2 ± 0.2  | 0.38 ± 0.02 | 4.71 ± 5.42  |
| 050730   | 3.970 | 2457 ± 142 | 0.257      | 0.9 ± 0.2  | 0.048 ± 0.003 | 2.32 ± 0.85 |
| 050802   | 1.710 | 1426 ± 220 | 0.7 ± 0.1  | 5.2 ± 0.2  | 0.58 ± 0.21  |
| 050803   | 0.422 | 846 ± 110  | (3.1 ± 0.5)10^{48} | 10.1 ± 0.3 | 0.72 ± 0.22  |
| 050814   | 5.300 | 1962 ± 683 | (1.3 ± 0.5)10^{48} | 1.76 ± 0.09 | 1.02 ± 0.82  |
| 050820A  | 2.612 | 3086 ± 1243| 0.6 ± 0.2  | 3.20 ± 0.07 | 0.49 ± 0.45  |
| 050904   | 6.290 | 8602 ± 3035| (1.3 ± 0.5)10^{48} | 7.8 ± 0.2  | 0.18 ± 0.14  |
| 050908   | 3.350 | 1612 ± 419 | (1.7 ± 0.5)10^{48} | 1.27 ± 0.06 | 0.87 ± 0.52  |
| 050922C  | 2.198 | 1622 ± 489 | (2.9 ± 0.9)10^{48} | 0.57 ± 0.02 | 1.14 ± 0.80  |
| 051022   | 0.800 | 3435 ± 416 | (1.6 ± 0.2)10^{48} | 6.0 ± 0.2  | 0.48 ± 0.13  |
| 051109A  | 2.346 | 2152 ± 1076| (0.4 ± 0.3)10^{48} | 0.85 ± 0.07 | 0.83 ± 0.95  |
| 051109B  | 0.080 | 197 ± 98   | (0.4 ± 0.3)10^{48} | 1.8 ± 0.2  | 1.73 ± 2.00  |
| 051111   | 1.549 | 2040 ± 524 | (0.4 ± 0.1)10^{48} | 5.2 ± 0.1  | 0.60 ± 0.36  |
| 051221A  | 0.547 | 2352 ± 482 | (1.8 ± 0.4)10^{48} | 0.077 ± 0.002 | 0.67 ± 0.32 |
| 060108   | 2.030 | 898 ± 320  | (1.1 ± 0.4)10^{48} | 1.44 ± 0.08 | 1.36 ± 1.12  |
| 060115   | 3.530 | 1156 ± 355 | (0.8 ± 0.3)10^{48} | 3.9 ± 0.1  | 1.32 ± 0.94  |
| 060124   | 2.297 | 3441 ± 939 | (0.5 ± 0.2)10^{48} | 1.24 ± 0.08 | 0.32 ± 0.20  |
| 060206   | 4.050 | 1731 ± 534 | (0.4 ± 0.1)10^{48} | 0.65 ± 0.02 | 1.09 ± 0.78  |
| 060210   | 3.910 | 2384 ± 422 | (2.3 ± 0.5)10^{48} | 5.1 ± 0.1  | 0.77 ± 0.32  |
| 060218   | 0.030 | 130 ± 65   | (0.5 ± 0.4)10^{48} | 19.8 ± 0.9 | 1.63 ± 1.88  |
| 060223A  | 4.410 | 2110 ± 399 | (2.8 ± 0.6)10^{48} | 0.86 ± 0.05 | 0.80 ± 0.35  |
| 060418   | 1.489 | 2511 ± 561 | (0.6 ± 0.1)10^{48} | 6.6 ± 0.1  | 0.51 ± 0.26  |
| 060502A  | 1.510 | 1403 ± 159 | (2.5 ± 0.3)10^{48} | 4.8 ± 0.2  | 0.81 ± 0.21  |
| 060502B  | 0.287 | 838 ± 218  | (2.8 ± 1.0)10^{48} | 0.045 ± 0.004 | 0.85 ± 0.52 |
| 060510B  | 4.900 | 2479 ± 308 | (1.7 ± 0.4)10^{48} | 9.6 ± 0.2  | 0.60 ± 0.18  |
| 060522   | 5.110 | 2836 ± 515 | (0.4 ± 0.1)10^{48} | 1.49 ± 0.07 | 0.59 ± 0.25  |
| 060526   | 3.210 | 997 ± 498  | (0.8 ± 0.5)10^{48} | 1.58 ± 0.08 | 1.84 ± 2.11  |
| 060604   | 2.680 | 1212 ± 606 | (0.1 ± 0.1)10^{48} | 0.62 ± 0.06 | 1.28 ± 1.47  |
| GRB     | $z$  | $E_{wz}$     | $Q_{pz}$     | $T_{Lz}$     | $K_z$  |
|---------|-----|-------------|--------------|--------------|-------|
| 060605  | 3.800 | 2696 ± 386  | $(1.9 \pm 0.4) \times 10^{49}$ | 1.64 ± 0.07 | 0.51 ± 0.17 |
| 060607A | 3.082 | 2037 ± 654  | $(0.6 \pm 0.2) \times 10^{50}$ | 3.73 ± 0.10 | 0.72 ± 0.54 |
| 060614  | 0.125 | 436 ± 218   | $(0.4 \pm 0.3) \times 10^{49}$ | 23.7 ± 0.3  | 1.24 ± 1.43 |
| 060707  | 3.430 | 980 ± 490   | $(0.8 \pm 0.7) \times 10^{50}$ | 2.3 ± 0.1   | 1.73 ± 1.99 |
| 060714  | 2.710 | 1117 ± 272  | $(1.1 \pm 0.3) \times 10^{50}$ | 6.2 ± 0.2   | 1.31 ± 0.74 |
| 060729  | 0.540 | 589 ± 144   | $(0.8 \pm 0.2) \times 10^{49}$ | 11.2 ± 0.3  | 1.24 ± 0.71 |
| 060801  | 1.130 | 1924 ± 265  | $(0.9 \pm 0.2) \times 10^{48}$ | 0.095 ± 0.006 | 0.67 ± 0.23 |
| 060814  | 0.840 | 2175 ± 792  | $(0.4 \pm 0.2) \times 10^{50}$ | 13.9 ± 0.1  | 0.47 ± 0.39 |
| 060904B | 0.703 | 745 ± 155   | $(0.7 \pm 0.2) \times 10^{49}$ | 2.88 ± 0.09 | 1.27 ± 0.62 |
| 060906  | 3.685 | 1204 ± 353  | $(1.4 \pm 0.4) \times 10^{50}$ | 2.59 ± 0.09 | 1.55 ± 1.05 |
| 060908  | 2.430 | 1887 ± 404  | $(0.5 \pm 0.1) \times 10^{50}$ | 2.66 ± 0.08 | 0.81 ± 0.41 |
| 060912  | 0.937 | 795 ± 117   | $(1.0 \pm 0.2) \times 10^{49}$ | 0.79 ± 0.03 | 1.69 ± 0.58 |
| 060927  | 5.600 | 1765 ± 475  | $(0.7 \pm 0.2) \times 10^{50}$ | 0.59 ± 0.02 | 1.25 ± 0.79 |
| 061004  | 3.300 | 1670 ± 273  | $(1.9 \pm 0.4) \times 10^{49}$ | 0.55 ± 0.03 | 1.02 ± 0.39 |
| 061006  | 0.438 | 2986 ± 888  | $(2.5 \pm 0.9) \times 10^{48}$ | 0.328 ± 0.008 | 0.42 ± 0.29 |
| 061007  | 1.261 | 2895 ± 319  | $(3.9 \pm 0.4) \times 10^{50}$ | 10.28 ± 0.08 | 0.61 ± 0.16 |
| 061110A | 0.758 | 809 ± 138   | $(0.5 \pm 0.1) \times 10^{49}$ | 7.6 ± 0.3   | 0.88 ± 0.35 |
| 061121  | 1.314 | 4347 ± 674  | $(0.8 \pm 0.1) \times 10^{50}$ | 2.31 ± 0.03 | 0.40 ± 0.14 |
| 061201  | 0.835 | 4285 ± 1870 | $(0.3 \pm 0.1) \times 10^{49}$ | 0.118 ± 0.005 | 0.38 ± 0.38 |
| 061210  | 0.410 | 758 ± 210   | $(1.6 \pm 0.6) \times 10^{48}$ | 0.021 ± 0.001 | 2.62 ± 1.71 |
| 061217  | 0.287 | 1088 ± 183  | $(0.4 \pm 0.1) \times 10^{47}$ | 0.12 ± 0.01 | 0.56 ± 0.23 |
| 061222B | 3.360 | 1032 ± 115  | $(1.4 \pm 0.4) \times 10^{50}$ | 2.4 ± 0.1   | 1.84 ± 0.51 |
| 070110  | 2.352 | 1621 ± 235  | $(3.2 \pm 0.6) \times 10^{49}$ | 5.4 ± 0.2   | 0.72 ± 0.24 |
| 070208  | 1.170 | 832 ± 416   | $(0.5 \pm 0.3) \times 10^{49}$ | 1.3 ± 0.1   | 1.24 ± 1.43 |
| 070318  | 0.840 | 1058 ± 125  | $(1.2 \pm 0.2) \times 10^{49}$ | 6.9 ± 0.2   | 0.84 ± 0.23 |
| 070411  | 2.950 | 1721 ± 253  | $(0.7 \pm 0.1) \times 10^{50}$ | 6.8 ± 0.2   | 0.77 ± 0.26 |
| 070506  | 2.310 | 717 ± 358   | $(0.8 \pm 0.5) \times 10^{49}$ | 0.65 ± 0.05 | 1.86 ± 2.14 |
| 070508  | 0.820 | 1181 ± 119  | $(8.7 \pm 0.9) \times 10^{49}$ | 3.62 ± 0.05 | 1.33 ± 0.31 |
| 070521  | 0.553 | 1012 ± 104  | $(1.8 \pm 0.2) \times 10^{49}$ | 7.8 ± 0.2   | 0.94 ± 0.22 |
| 070529  | 2.500 | 1845 ± 309  | $(0.5 \pm 0.1) \times 10^{50}$ | 2.4 ± 0.1   | 0.83 ± 0.33 |
| 070611  | 2.040 | 1234 ± 415  | $(0.8 \pm 0.3) \times 10^{49}$ | 0.86 ± 0.08 | 1.03 ± 0.81 |
Table 3—Continued

| GRB      | $z$   | $E_{wz}$   | $Q_{pz}$            | $T_{Lz}$ | $K_z$      |
|----------|-------|------------|---------------------|----------|------------|
| 070612A  | 0.617 | 702 ± 108  | (3.7 ± 0.7)10^{49}  | 20.0 ± 0.6| 1.27 ± 0.46|
| 070714B  | 0.920 | 1121 ± 208 | (3.4 ± 0.9)10^{48}  | 0.25 ± 0.01| 1.24 ± 0.54|
| 070721B  | 3.626 | 2702 ± 330 | (0.8 ± 0.1)10^{50}  | 2.71 ± 0.08| 0.62 ± 0.18|
| 070724A  | 0.457 | 558 ± 279  | (0.7 ± 0.4)10^{47}  | 0.074 ± 0.007| 1.36 ± 1.57|
| 070802   | 2.450 | 1420 ± 463 | (0.6 ± 0.3)10^{49}  | 1.02 ± 0.08| 0.82 ± 0.63|
| 070810A  | 2.170 | 552 ± 276  | (0.4 ± 0.2)10^{50}  | 1.29 ± 0.07| 2.92 ± 3.37|