EVIDENCE FOR NEW RELATIONS BETWEEN GAMMA-RAY BURST PROMPT AND X-RAY AFTERGLOW EMISSION FROM 9 YEARS OF SWIFT

Dirk Grupe1,2, John A. Nousek1,2, Péter Veres2, Bin-Bin Zhang2,3, and Neil Gehrels4

1 Swift Mission Operation Center, 2582 Gateway Dr., State College, PA 16801, USA; dgrupe007@gmail.com
2 Department of Astronomy and Astrophysics, Pennsylvania State University, 525 Davey Lab, University Park, PA 16802, USA
3 Center for Space Plasma and Aeronautic Research (CSPAR), University of Alabama in Huntsville, Huntsville, AL 35899, USA
4 Astrophysics Science Division, Astroparticle Physics Laboratory, Code 661, NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA

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ABSTRACT

When a massive star explodes as a gamma-ray burst (GRB), information about the explosion is retained in the properties of the prompt and afterglow emission. We report on new relations between the prompt and X-ray afterglow emission of Swift-detected GRBs found from Burst Alert Telescope (BAT) and X-Ray Telescope data covering 2004 December to 2013 August (754 in total). These relations suggest that the prompt and afterglow emission are closely linked. In particular, we find very strong correlations between the BAT 15–150 keV $S_\text{z}$ and the break times before and after the plateau phase in the 0.3–10 keV X-ray afterglow light curves. We also find a strong anticorrelation between the photon index of the GRB prompt emission and the X-ray spectral slope of the afterglow. Moreover, anticorrelations exist between the rest-frame peak energy in the prompt emission $E_{\text{peak}, z}$ and the X-ray afterglow decay slope during the plateau phase and the break times after the plateau phase. The rest-frame break times before and after the plateau phase are also anticorrelated with the rest-frame 15–150 keV luminosity and the isotropic energy during the prompt emission. A principal component analysis suggests that the GRB properties are primarily driven by the luminosity/energy release in the 15–150 keV band. Luminosity functions derived at different redshifts from a log $N$–log $S$ analysis indicate that the density of bright bursts is significantly lower in the local universe than in the universe at $z \approx 3$, where the density of bright GRBs peaks. Using cluster analysis, we find that the duration of BAT-detected short GRBs is less than 1 s. We also present a catalog of all Swift onboard-detected bursts.

Key words: catalogs – gamma-ray burst: general

Online-only material: color figures, machine-readable table

1. INTRODUCTION

The Swift mission (Gehrels et al. 2004) has revolutionized the study of gamma-ray burst (GRB) afterglows. With Swift, it is possible for the first time to access the earliest phase of X-ray afterglows. In the pre-Swift era, observations of the X-ray afterglow were limited to the “normal” decay phase, typically starting about a day after detection of the burst. During the BATSE era, only a relatively small number of bursts were actually followed up by X-ray observatories such as BeppoSAX (Costa et al. 1999; De Pasquale et al. 2006). All this changed when Swift was launched in 2004 November. Swift is an autonomous robot, making it possible to observe X-ray afterglows starting typically 1 or 2 minutes after a trigger by the Swift Burst Alert Telescope (BAT; Barthelmy 2005). Over nearly 9 yr in orbit (as of 2013 August), Swift has discovered more than 800 GRBs, providing the largest sample of GRBs with observations of both prompt and afterglow emission. The prompt emission is likely the result of internal shocks produced in a newly formed jet (e.g., Mészáros 2006). Further models include photospheric emission with either baryon-dominated (Pe’er et al. 2006; Beloborodov 2010) or magnetically dominated (Drenkhahn & Spruit 2002; McKinney & Uzdensky 2012) ejecta. In addition, magnetic reconnection can be responsible for the prompt emission irrespective of photospheric emission (Thompson 1994; Zhang & Yan 2011).

For the afterglow, the external shock scenario (Mészáros & Rees 1997) is observationally the best-supported mechanism, with modifications involving jet opening angle effects (Rhoads 1999), the nature of the interstellar medium (wind or constant density profile; Panaitescu & Kumar 2000), and possible late energy injection (Rees & Mészáros 1998).

As shown by Nousek et al. (2006) and Zhang et al. (2006), X-ray afterglows typically display a canonical light curve characterized by a very steep initial decay followed by a much shallower slope, usually referred to as the “plateau phase.” After this plateau, we see the “normal” decay phase. The initial decay slope in the X-ray light curve is regarded as the tail of the prompt emission phase (Zhang et al. 2007, 2009b). The plateau phase marks the beginning of the afterglow phase, which is generally caused by external shocks when the jet starts to interact with the interstellar medium. Swift’s ability to observe GRBs in soft X-rays within minutes after the explosion has led to the discovery of flares in roughly one-third of all GRBs (e.g., Falcone et al. 2007; Margutti et al. 2011b). Not only has Swift revolutionized GRB studies, but the large number of bursts covered with multiwavelength observations and redshift measurements has also allowed, for the first time, very detailed statistical analysis of GRBs, including cosmological studies (e.g., Wanderman & Piran 2010).

Although a connection between the prompt and the afterglow emission of a GRB is expected within the standard fireball model (e.g., Mészáros 2006), in the early days of Swift there was no evidence for such a connection (Willingale et al. 2007) except for the fluences in the prompt and afterglow emission. As shown by Gehrels et al. (2008), based on the observations of GRBs detected during the first 2.5 yr of Swift, there is a strong correlation between the fluence in the 15–150 keV band and the flux density of the X-ray afterglow emission. O’Brien et al. (2006) showed that the Swift BAT and X-Ray Telescope (XRT; Burrows et al. 2005) light.
curves of the prompt and afterglow emission can typically be consistently connected. Recently, Margutti et al. (2013) performed a statistical analysis of all Swift-detected GRBs through 2010 December and found clear correlations between the energetics of the prompt and the afterglow emission, which also seem to suggest a universal scaling relation between short- and long-duration GRBs (Bernardini et al. 2012b; Nava et al. 2012). D’Avanzo et al. (2012) showed that X-ray afterglow luminosities at various times after the trigger correlate strongly with prompt emission properties such as the isotropic energy $E_{\text{iso}}$ and the peak energy in the high-energy spectrum, $E_{\text{peak}}$. Statistical analyses of the X-ray afterglow light curves had also previously been performed by Evans et al. (2009) and Racusin et al. (2009). While Evans et al. (2009) focused on automated analysis of the Swift XRT light curves, finding that about 40% of Swift bursts with X-ray observations GRBs had canonical light curves, Racusin et al. (2009) carried out an analysis of the spectral and temporal parameters of the Swift X-ray data. They found that different phases of the light curves are all consistent with closure relations that explain the various states of GRB afterglow light curves due to the jet geometry and physics, the environment around the GRB, and the electron density and cooling (e.g., Zhang & Meszaros 2004 and references therein).

One of the best-known relations between GRB properties is that of the peak energy in the γ-ray spectrum $E_{\text{peak}}$ with the isotropic energy $E_{\text{iso}}$ or the collimation-corrected energy $E_{\gamma}$, the Amati and Ghirlanda relations, respectively (Amati et al. 2002; Ghirlanda et al. 2004). Similar to these are the relations found by Yonetoku et al. (2004) and Schaefer (2007) between $E_{\text{peak}}$ and the burst luminosity.

Although various efforts have been made to link the energetics of the prompt and afterglow emission of GRBs (e.g., Margutti et al. 2013), what is still missing is a finding of correlations between prompt and afterglow properties, such as $T_{90}$, break times, or spectral slopes. While this effort was hampered at the beginning of the Swift mission because of the small number of bursts (Willingale et al. 2007), with almost 9 yr in orbit (as of 2013 August), the sample of Swift-detected GRBs has grown to more than 800, allowing new relations to be found among the prompt and afterglow emission parameters.

One motivation for this study comes from the relation we found between redshift and excess absorption seen in the observed X-ray spectra of GRB afterglows (Grupe et al. 2007). However, this method is rather limited, in the sense that it can only say that if a burst has a large amount of excess absorption, then it is a low-redshift burst. Our goal has been to find other means to distinguish between high- and low-redshift bursts more precisely and, finally, to estimate the redshift based on early available Swift data. Hydrogen column densities derived from X-ray observations were found, using canonical correlation analysis, to correlate with the properties of the prompt emission (Balázs & Veres 2011). The most sophisticated statistical analysis of Swift GRBs to date was performed by Morgan et al. (2012), who applied a random-forest algorithm to predict high-redshift bursts. By looking through the data of Swift-detected GRBs, we noticed several relations between prompt and afterglow properties that are not necessarily expected. In particular, we noted a strong relation of the BAT $T_{90}$ and 15–150 keV luminosity with the break times in the X-ray afterglow light curve (Grupe 2012).

Here we present a detailed analysis of the whole Swift-detected GRB data set and show that indeed there are many correlations that establish a tight relation between the prompt and afterglow emission in GRBs. This paper is organized as follows: In Section 2, we describe the sample selection and data analysis; in Section 3, we present the distributions and correlation analysis for the Swift-detected GRBs prompt and afterglow properties, followed by a discussion in Section 4. Throughout, spectral indices $\beta$ and light-curve decay indices $\alpha$ are defined as $F_{\nu} \propto \nu^{-\beta} t^{-\alpha}$. All errors are 1σ unless stated otherwise. Cosmological parameters such as luminosity distances and comoving volumes were derived from the Cosmology Calculator, by Wright (2006). For all of these values, we assumed the standard cosmology with $H_0 = 71$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_M = 0.27$, and $\Omega_{\Lambda} = 0.73$.

2. GRB SAMPLE AND OBSERVATIONS

2.1. Sample Selection

By the end of 2013 August, Swift had discovered 804 bursts. Of these, 40 GRBs were discovered through ground processing, and nine through the BAT Slew Survey. There is also one burst with no data available. Excluding these 50 bursts from the initial sample leaves a total of 754 Swift-detected, onboard-triggered bursts. In Appendix A, we present the whole catalog of these 754 GRBs as a machine-readable file that is available online. This file contains the GRB name, BAT trigger number, redshift, and BAT and XRT measured observed parameters. A full list of these parameters is given in Appendix A, in Table 9.

Figure 1 displays the total number of onboard-detected GRBs per year (triangles) and the number with spectroscopic redshift measurements (circles). In 663 cases, XRT observed the field on the target with XRT and the Ultraviolet/Optical Telescope (UVOT; Roming et al. 2005) within 300 s of the trigger. XRT did not observe the remaining 97 bursts, as a result of observing constraints due to the Sun, the Moon, or Earth. UVOT detected a total of 251 GRB afterglows out of 655 observations performed. In this paper, however, we focus on the high-energy properties of the bursts and leave the UVOT analysis for a later publication. Crucial to the analysis of physical parameters of GRBs are

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5 A full interactive table of all Swift bursts can be found at http://swift.gsfc.nasa.gov/docs/swift/archive/grb_table/.
redshift measurements. Through 2013 August, 232 of the 754 GRBs in our sample or their host galaxies had spectroscopic redshift measurements (about 31%). Burst redshifts were taken from GCN Circulars and the GRB redshift catalogs by Fynbo et al. (2009); Jakobsson et al. (2012) and Krühler et al. (2012). Note that in the pre-
Swift era, there were redshift measurements for only 43 bursts (Gehrels & Cannizzo 2013).

Of the 754 GRBs in our sample, 63 are short-duration and 690 are long-duration bursts (one early GRB did not have a T90 measurement), following the standard division at T90 = 2 s as defined by Kouveliotou et al. (1993). This is a significantly lower percentage than the ∼25% found in the BATSE GRB sample. The reason is purely a selection effect due to the lower energy range of the Swift BAT compared with BATSE. As we show below, the 2 s dividing line is too long for BAT-discovered bursts (see also Bromberg et al. 2013).

2.2. Observations and Data Reduction

The 0.3–10 keV X-ray count rate light curves and spectra were derived from the University of Leicester GRB repository Web site (Evans et al. 2007).6 The light curves were fitted using multisegment power-law models (e.g., Evans et al. 2009) in which periods of flares, in particular at early times after the explosion, were excluded from the analysis. In almost all cases (90%–95%), we made use of the Leicester online light-curve fitting routine, which is used by the Swift team to make predictions of the XRT count rate of an X-ray afterglow. In the remaining cases, we fitted the light curves manually in XSPEC. For these, we converted the light-curve file into spectrum (.pha) and response matrix (.rmf) files that can be read into XSPEC by applying the FTOOLS task “fx2xsp” to the light-curve ASCII file.

For most spectra, we used the photon counting mode data (Hill et al. 2004), which primarily cover the afterglow phase. We extracted source and background spectra and auxiliary response files provided by the GRB Web site at Leicester. These data typically cover the entire afterglow phase. The Windowed Timing mode data at the beginning of the light curves are often contaminated by emission from flares, which tends to be much harder than the afterglow emission (Falcone et al. 2007; Margutt et al. 2011a, 2011b). We did not rely on the automated fitting results from the Leicester repository. In the majority of cases, the automated routine uses a free “intrinsic” absorber, in the fit, which results in excess absorption with large uncertainties even if a spectrum is consistent with just the Galactic absorption column density. Therefore, all spectra were analyzed manually. In 2007 September, the substrate voltage on the Swift XRT detector was increased from 0 to 6 V (Godet et al. 2009). Accordingly, for all spectra we used the most current response files. For spectra obtained prior to 2007 August, we used the response file swxpc0t012s0_20070901v011.rmf, and after the end of 2007 August, the file swxpc0t012s6_20010101v013.rmf was used. All data were fitted to absorbed power-law models in XSPEC (Arnaud 1996). First we fitted the data with the absorption parameter fixed to the Galactic value derived from the H I maps by Kalberla et al. (2005). If this model did not result in an acceptable fit, we thawed the absorption parameter to search for excess absorption above the Galactic value as described in Grupe et al. (2007). For afterglows with spectroscopic redshifts, we determined the intrinsic absorption column density at the redshift of the GRB.

The parameters measured from the BAT data were derived from the BAT GRB analysis pages7 and BAT refined GCN Circulars and GCN (Barthelmy et al. 1995) burst reports. Whenever possible we also made use of the peak energy Epeak in the high-energy spectrum of a burst, primarily given by the Konus instrument on the Wind spacecraft (Aptekar et al. 1995) and the Fermi Gamma-Ray Burst Monitor (GBM; Meegan et al. 2009). Pre- Fermi (Atwood et al. 2009; Yamaoka et al. 2009), we used the Epeak measurement(s) from Konus and the Suzaku Wide-Band All-Sky Monitor published in GCN Circulars. After the Fermi launch, we used the GBM measurements when available, which now exist for roughly 50% of all bursts since the Fermi launch.

In the end, we derive T90, the 15–150 keV photon spectral slope Γ, and the 15–150 keV fluence from BAT, as well as the 0.3–10 keV X-ray spectral slope βX, the break times at the beginning and the end of the plateau phase (Tbreak1 and Tbreak2), the slope during the plateau phase αX2, and the “normal” decay slope αX3. For bursts with spectroscopic redshift measurements, the fluence was k-corrected (e.g., Humason et al. 1956; Oke & Sandage 1968) and T90, Tbreak1, and Tbreak2 were transformed into the rest frame. The rest-frame 15–150 keV luminosity is the mean isotropic luminosity during the time T90,z = T90/(1+z) determined from the k-corrected fluence. A complete description of each parameter is given in Appendix B.

3. RESULTS

One of the goals of this paper is to establish new connections between GRB prompt and afterglow emission properties. Therefore, we need to examine the data set by means of statistics. In this section, we first present the distributions of the observed and rest-frame parameters of Swift-detected GRBs. In particular, we look at differences between short- and long-duration GRBs. We then examine bivariate correlations among these parameters with the goal of finding evidence for connections between GRB prompt and afterglow phases. This is followed by a principal component analysis (PCA) to search for underlying properties that drive the observed parameters in GRBs. The section closes with a discussion of the GRB luminosity functions and a look into estimating the redshift of a burst, including an update on the relation between redshift and excess absorption (Grupe et al. 2007).

3.1. Distributions

The mean, standard deviation, and median of burst properties for all Swift-detected GRBs, as well as for long- and short-duration GRBs and high-redshift GRBs (z > 4.0), are listed in Table 1. We included high-redshift bursts in this table to examine whether these bursts appear to be somewhat special and have different properties than bursts at lower redshifts or bursts without redshift measurements. In this subsection, we present the distributions of T90, the break times in the X-ray light curves, the decay slopes, and the redshifts. All other distributions are given in Appendix C. In Figures 2–6, the statistical analyses of the distributions are visualized with three standard tools in data mining (e.g., Feigelson & Babu 2012; Torgo 2011; Crawley 2007):

- Histograms and kernel density estimators;
- Box plots; and
- Quartile–quartile (Q–Q) plots.

We explain the purpose of these statistical tools in Appendix C.

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6 At http://www.swift.ac.uk/xrt_curves/.

7 See http://swift.gsfc.nasa.gov/docs/swift/results/BATbursts/.
Table 1
GRB Properties in the Observed and Rest Frames

| Property | All GRBs | Long GRBs | Short GRBs |
|----------|----------|-----------|------------|
|          | Mean     | SD        | Median     | No. of GRBs | Mean     | SD        | Median     | No. of GRBs | Mean     | SD        | Median     | No. of GRBs |
| \( \Gamma_{\text{BAT}} \) | 1.614 ± 0.120 | 1.600 | 751 | 1.651 ± 0.140 | 1.620 | 687 | 1.205 ± 0.140 | 1.100 | 63 | 1.554 ± 0.160 | 1.600 | 18 |
| \( \beta_X \) | 1.002 ± 0.132 | 0.970 | 632 | 1.007 ± 0.140 | 0.970 | 592 | 0.934 ± 0.160 | 0.830 | 39 | 0.974 ± 0.140 | 0.171 | 0.960 | 18 |
| log \( T_90 \) | 1.435 ± 0.132 | 1.601 | 755 | 1.612 ± 0.150 | 1.681 | 690 | -0.501 ± 0.160 | -0.456 | 63 | 1.557 ± 0.154 | 1.354 | 18 |
| log \( T_{\text{break}-1} \) | 2.706 ± 0.193 | 2.638 | 384 | 2.705 ± 0.194 | 2.633 | 377 | 2.655 ± 0.170 | 2.568 | 6 | 2.792 ± 0.294 | 2.000 | 11 |
| log \( T_{\text{break}-2} \) | 3.258 ± 0.196 | 2.190 | 146 | 2.252 ± 0.164 | 2.178 | 144 | 2.725 ± 0.160 | 2.725 | 2 | 1.984 ± 0.285 | 1.881 | 11 |
| log \( T_{\text{break}-3} \) | 3.866 ± 0.197 | 3.897 | 417 | 3.917 ± 0.172 | 3.924 | 389 | 2.802 ± 0.160 | 2.566 | 19 | 3.987 ± 0.197 | 4.080 | 16 |
| \( \alpha_{\text{X}2} \) | 0.592 ± 0.039 | 0.620 | 539 | 0.597 ± 0.042 | 0.630 | 515 | 0.455 ± 0.030 | 0.500 | 23 | 0.582 ± 0.035 | 0.660 | 17 |
| \( \alpha_{\text{X}3} \) | 1.550 ± 0.074 | 1.380 | 475 | 1.499 ± 0.055 | 1.370 | 450 | 2.475 ± 0.080 | 1.660 | 25 | 1.591 ± 0.046 | 1.490 | 17 |
| log fluence \( b \) | -5.919 ± 0.676 | -5.907 | 752 | -5.813 ± 0.585 | -5.848 | 689 | -7.080 ± 0.499 | -7.134 | 63 | -5.880 ± 0.460 | -5.930 | 18 |
| log fluence-\( k \) | -5.560 ± 0.749 | -5.536 | 232 | -5.477 ± 0.679 | -5.491 | 217 | -6.761 ± 0.687 | -6.768 | 15 | -5.528 ± 0.568 | -5.586 | 18 |
| log \( L_{15-150\text{keV}} \) | 51.540 ± 1.240 | 51.678 | 231 | 51.603 ± 1.120 | 51.759 | 216 | 50.637 ± 1.210 | 51.111 | 15 | 53.158 ± 0.459 | 53.090 | 18 |
| log \( E_{\text{iso}} \) | 52.610 ± 1.272 | 52.856 | 231 | 52.782 ± 1.064 | 52.965 | 216 | 50.126 ± 1.458 | 50.472 | 15 | 53.928 ± 0.360 | 53.953 | 18 |
| \( E_{\text{peak}} \) | 254.1 ± 376.0 | 148.0 | 206 | 225.3 ± 246.4 | 143.0 | 193 | 686.4 ± 1108.0 | 370 | 13 | 154.4 ± 96.5 | 122.5 | 8 |
| \( E_{\text{peak},2} \) | 750.6 ± 5 | 893.2 | 104 | 669.2 ± 532.5 | 537.4 | 96 | 2008 ± 2947.9 | 933 | 6 | 966.4 ± 570.2 | 824.0 | 8 |
| log (\( \Delta N_{H} + 1 \)) | 0.606 ± 0.715 | 0.000 | 618 | 0.626 ± 0.715 | 0.000 | 578 | 0.377 ± 0.698 | 0.000 | 39 | 0.259 ± 0.160 | 0.000 | 18 |
| \( z \) | 2.018 ± 1.373 | 1.763 | 232 | 2.111 ± 1.363 | 1.950 | 217 | 0.681 ± 0.640 | 0.547 | 15 | 5.201 ± 1.080 | 4.860 | 18 |

Notes.

\( a \) Standard deviation.
\( b \) Observed fluence in the 15–150 keV BAT energy band in units of erg cm\(^{-2}\).
\( c \) The \( k \)-corrected 15–150 keV fluence in units of erg cm\(^{-2}\).
\( d \) Rest-frame 15–150 keV luminosity in units of erg s\(^{-1}\).
\( e \) The \( k \)-corrected isotropic energy \( E_{\text{iso}} \) in the 15–150 keV BAT band.
\( f \) Peak energy in units of keV.
\( g \) The excess absorption column density \( \Delta N_{H} \) above the Galactic value (see Grupe et al. 2007) is given in units of 10\(^{20}\) cm\(^{-2}\).
Figures 2 and 3 display the distributions of the BAT $T_{90}$ and the break times $T_{\text{break}1}$ and $T_{\text{break}2}$ before and after the plateau phase in the X-ray light curve. The observed times are given in Figure 2, and Figure 3 shows the values shifted into the rest frame. The median $T_{90}$ is 38 s for all Swift-detected GRBs and 46 s for long GRBs only. The density estimates for the $T_{90}$ distributions suggest that for Swift-detected GRBs we see a bimodal distribution, separating them into short and long bursts, as had been suggested based on the BATSE results (Kouveliotou et al. 1993). The division between the two groups, however, appears to lie at a shorter $T_{90}$ than for the BATSE-detected bursts, in agreement with the results of Bromberg et al. (2013): the observed $T_{90}$ distribution suggests that the dividing line between short and long bursts detected by BAT is on the order of 1 s. These short bursts also appear clearly as outliers in the $T_{90}$ box plot for all GRBs. In the rest frame (Figure 3), the median $T_{90}$ for all bursts (with redshifts) is 13.4 s, with 16.0 s for long and 0.27 s for short bursts.
Although the break times before the plateau phase of short and long bursts are all on the order of 500 s, there are significant differences in the break times after the plateau phase. While long GRBs show breaks after the plateau phase in the observed frame at about 8400 s after the trigger, short GRBs show a median break time after the plateau of 300 s. In the rest frame, the corresponding times are 150 s for the short and 3360 s for the long bursts. These break times before and after the plateau phase are comparable to those presented by Evans et al. (2009) and Margutti et al. (2013). It is interesting to note that from the relation between redshift and the length of the plateau phase reported by Stratta et al. (2009), one would naively expect short GRBs to have longer plateau phases than long GRBs, as they occur (as we show below) at lower redshifts. Note, however, that we do not have enough short bursts with redshift and break-time measurements to allow us to state reliable numbers.

Figure 4 displays the distributions of the X-ray light curve decay slopes during (top) and after (bottom) the plateau phase, $\alpha_{X2}$ and $\alpha_{X3}$. The distribution of $\alpha_{X2}$ is almost Gaussian, with an extended wing toward the very flat end of the distribution (see the Q–Q plot). Note that although this phase is commonly called the “plateau phase,” the median decay slope of all bursts is on the order of $\alpha_{X2} = 0.6$ and there is a large scatter in the distribution of decay slopes ($\sigma = 0.44$). Some plateau decay
slopes can be relatively steep, with $\alpha_{X2} > 1.0$. Our mean and median values of $\alpha_{X2}$ are slightly steeper than those found by Evans et al. (2009) and Margutti et al. (2013), 0.27 and 0.32, respectively. One reason why we found a slightly steeper decay slope during the plateau phase could be that we accept slopes with $\alpha_{X2} > 1.2$ (see Figure 4), which is not the case for the Margutti et al. (e.g., 2013) sample.

The distribution of the “normal” decay slopes after the plateau is shown in the bottom panels of Figure 4. Note again that the distribution of $\alpha_{X3}$ is quite broad and a significant number of bursts have decay slopes that exceed $\alpha_{X3} > 2.0$, which is typically assumed to be a decay slope after a jet break, particularly for short-duration GRBs. The mean and standard deviation of all GRBs of $\alpha_{X3}$ are 1.55 and 0.73 and the median value is 1.38, suggesting a non-Gaussian distribution. The median decay slope during the “normal” decay phase for long GRBs is 1.37. Note that there are three outliers in the $\alpha_{X3}$ distribution, all of which are short bursts (GRBs 051210, 120305A, and 120521A). These decay slopes are extreme, on the order of 7 or 8. With the median values as discussed...
et al. (2013), short bursts are less energetic than long bursts, and this effect means that low-fluence bursts must be short if they are to be detected, explaining the upper left of the diagram. On the other hand, the void at lower right might be of a physical nature.

There are two effects here:

1. A highly energetic (and high-fluence) burst requires a certain amount of time to release the energy; and
2. Related to this, short bursts, generally speaking, have lower luminosities/energies than long GRBs (e.g., Margutti et al. 2013).

Regarding the first point, the reason high-fluence bursts are seen with longer $T_{90}$ may be that there is some maximum flux (or luminosity) that can be generated by the burst. Therefore, a high-fluence burst would require a longer time span to release its energy than a low-fluence burst.

Second, detecting a short burst with high fluence requires that it occur close by. For example, the short GRB with the highest fluence ($1.16 \times 10^{-6}$ erg cm$^{-2}$) in our sample is GRB 051221A (Burrows et al. 2006), which has a redshift of $z = 0.547$, resulting in a luminosity distance of 3150 Mpc. To detect this GRB with a fluence of order $10^{-4}$ erg cm$^{-2}$, it would have to occur within 390 Mpc, equivalent to $z = 0.085$. Although this is not impossible, and Swift has detected a few bursts with redshifts lower than 0.085 (four, to be precise), the probability of detecting a relatively luminous short burst like GRB 051212A

above and listed in Table 1, we can construct a median GRB X-ray afterglow light curve. Figure 5 displays the observed median 0.3–10 keV X-ray flux (left) and rest-frame luminosity (right) light curves, constructed by using the median values for the break times before and after the plateau phase and the decay slopes $\alpha_{X2}$ and $\alpha_{X3}$. We used the median values for the fluxes and luminosities at the break time after the plateau phase [$F(T_{\text{break2}}) = 5 \times 10^{-12}$ erg s$^{-1}$ cm$^{-2}$ and $L(T_{\text{break2}}) = 1.7 \times 10^{42}$ erg s$^{-1}$] as the normalization points of the light curves.

The redshift distribution of the 232 Swift-detected bursts with spectroscopic redshift measurements is shown in Figure 6. The mean redshift of these bursts is $z = 2.018$, and the median $z = 1.76$, which is lower than that for the bursts detected during the first 2 yr of Swift operation ($z = 2.30$; Grupe et al. 2007). Recently, Coward et al. (2013) studied the evolution of the mean redshift of Swift-detected GRBs since 2005 and showed that it has decreased over the course of the mission. There is a significant difference in the redshift distributions of short and long GRBs, with short bursts being detected only at the lower end of the overall distribution. This is a selection effect. As shown by, e.g., Bernardini et al. (2012b) and Margutti et al. (2013), short bursts are less energetic than long bursts (see also below), resulting in a lower fluence. The cause of the different energetics of short and long GRBs is most likely their different progenitors (e.g., Salvaterra et al. 2008; Fong et al. 2013; Rowlinson et al. 2013), which then result in different redshift distributions. As a consequence, short bursts with lower energy appear to be undetectable at high redshifts.

### 3.2. Selection Effects

Before we start any discussion on the results of the correlation analysis from our sample, we need to be aware of any selection biases in the sample that may lead to nonphysical results. One of these is displayed in Figure 7, which shows the observed BAT 15–150 keV fluence and $T_{90}$ seems to be very strongly correlated with a Spearman rank order correlation coefficient $r_s = 0.667$ and a Student’s $T$ test value of $T_r = 22.85$. However, this is purely a selection effect, driven by the detector properties. We only detect low-fluence bursts when their energy is released in a relatively short amount of time. If the energy is spread over a longer time span, the signal will be dominated by noise and BAT will not be able to trigger on the event. This selection effect means that low-fluence bursts must be short if they are to be detected, explaining the upper left of the diagram. On the other hand, the void at lower right might be of a physical nature. There are two effects here:

1. A highly energetic (and high-fluence) burst requires a certain amount of time to release the energy; and
2. Related to this, short bursts, generally speaking, have lower luminosities/energies than long GRBs (e.g., Margutti et al. 2013).

Figure 6. Same as Figure 2, but for the redshift distribution of all Swift-detected GRBs with spectroscopic redshifts. (A color version of this figure is available in the online journal.)

Figure 7. Fluence in the 15–150 keV Swift BAT band vs. $T_{90}$. Short bursts are marked as blue triangles and high redshift bursts ($z > 3.5$) as red circles. (A color version of this figure is available in the online journal.)
at such a distance is low. This is mostly a consequence of the general space density of GRBs and their luminosity functions (see also Section 3.5) and the much smaller comoving volume at a redshift of 0.085 than at higher cosmological redshifts. Having a less luminous burst explode and detecting it with a fluence in the 10^{-4} erg cm^{-2} range would require an even smaller distance.

How does the $T_{90}$–fluence selection effect affect other correlations? We found a mild correlation between $T_{90}$ and the isotropic energy in the 15–150 keV BAT band. However, this correlation may mostly be driven by this selection effect.

Another question that may raise concerns is whether $T_{90}$ really is a good parameter to describe a burst. As pointed out by, e.g., Zhang (2012) and Qin et al. (2013), $T_{90}$ is strongly detector dependent. This is similar to a hardness ratio, which does not allow direct comparisons between different missions. However, as long as we use both parameters from samples using only data from the same detector, it may not be a problem. Still, for Swift BAT GRBs, we typically use the 2 s dividing line between short- and long-duration bursts defined by Kouveliotou et al. (1993) for GRBs detected by BATSE on the Compton Gamma Ray Observatory, which was operating at much higher energies than the Swift BAT. However, as pointed out in Section 3.1, the division between BAT-detected short- and long-duration GRBs occurs at earlier times. It has also recently been shown by Bromberg et al. (2013) that the cutoff line at 2 s between short- and long-duration GRBs detected by BAT is not a good choice and that it is more appropriate for Swift-discovered bursts to place the cutoff at around 0.8 s. We discuss this in more detail in Section 4.4.

There is another problem that has recently been pointed out by several authors: high-redshift bursts tend to have rather short $T_{90}$’s (Littlejohns et al. 2013; Tanvir et al. 2012; Kovecski 2012). GRB 090423 and GRB 080913 (e.g., Zhang et al. 2009a), which are the GRBs with the highest spectroscopically measured redshifts (8.2 and 6.7), had $T_{90}$ of 8.0 and 10.3 s, respectively, which in the rest frame suggests that these may be short bursts. However, the reason for these short $T_{90}$’s may not be a physical property of the bursts but rather a consequence of the detector threshold. Given that the flux light curve of the prompt emission observed from a high-redshift burst appears to be fainter than that of a low-redshift burst on average, a detector will trigger on the prompt emission later than for a low-redshift burst because the main part of the prompt emission light curve is below the detector threshold (Littlejohns et al. 2013). We basically observe the tip of the iceberg of the prompt emission of high-redshift bursts, with most lost in the noise. Nevertheless, the short duration of the observed prompt emission is not a general property of high-redshift bursts (e.g., GRB 050904, a burst at $z = 6.2$, had $T_{90} = 181.7$ s). The concern is how much this threshold effect influences the results from our Swift GRB sample. If there is a significant effect, we would expect to see a decrease of $T_{90}$ with increasing redshift. This relation is plotted for the observed and rest-frame $T_{90}$ in Figure 8; we do not observe such an effect. Therefore, we conclude that although some high-redshift bursts appear to have rather short prompt emission because of the detector threshold, the effect is not significant for the overall sample.

Nevertheless, there is another concern regarding high-redshift bursts (Coward et al. 2013). As mentioned at the beginning of this subsection, the fluence and $T_{90}$ are strongly correlated because of how BAT triggers on bursts. Although the mean and median fluences and $T_{90}$’s of all GRBs and of high-redshift bursts are essentially the same (Table 1), this picture changes when looking at the rest-frame parameters: we do not find very long $T_{90}$ GRBs at high redshifts, and high-redshift bursts are significantly more luminous and energetic in comparison with the total GRB sample. The same selection bias that affects long GRBs with low fluence excludes long high-redshift GRBs from detection. The problem here is that because of time dilation [$T = (1+z) \times T^\prime$], a rest-frame long burst becomes dramatically more so in the observed frame. This means that the fluence of these bursts will be smeared out over a longer time span, with the consequence that detector noise will leave the burst remain undetected. In other words, to detect a GRB with the Swift BAT at high redshift, its rest-frame $T_{90}$ needs to be relatively small and it has to be highly energetic. Consequently, the majority of high-redshift bursts are missed by BAT. As pointed out by Wanderman & Piran (2010), however, this prediction also strongly depends on the star formation rate at high redshifts.

3.3. Correlation Analysis

Throughout this subsection, we look at correlations between observed and rest-frame GRB prompt and afterglow emission parameters. In particular, we are interested in strong relations between prompt and afterglow properties. One goal is to be able to make predictions of the behavior of the X-ray afterglow...
Figure 9. Correlations between the 15–150 keV isotropic energy and X-ray afterglow decay slopes during and after the plateau phase, $\alpha_{X2}$ and $\alpha_{X3}$, respectively. Short bursts are marked with triangles and long bursts with circles.
(A color version of this figure is available in the online journal.)

Figure 10. Correlations between the BAT 15–150 keV photon index $\Gamma$ and the observed (left) and rest-frame (right) $T_{90}$. High-redshift bursts ($z > 3.5$) are marked with circles.
(A color version of this figure is available in the online journal.)

Based on the prompt emission properties. The correlations between these parameters are listed in Tables 2 and 3, using Spearman rank order correlation coefficients and Student’s $t$-tests. While Table 2 lists the correlation results for the observed parameters of all 754 GRBs in our sample, Table 3 lists only the correlations between the rest-frame parameters of the 232 GRBs with spectroscopic redshifts. In this subsection we will discuss only those correlations that are statistically significant, meaning that the probability of a correlation’s being due to chance is $P < 10^{-3}$. Correlations quoted in this subsection apply to the whole GRB sample unless noted otherwise. We primarily focus on those relations that clearly connect the prompt and the afterglow phase. Other relations are shown in Appendix D.

In addition to the Spearman coefficient, we also determined Kendall’s $\tau$ and the Pearson correlation coefficient; these are given in Tables 10 and 11 in Appendix D for all GRBs and for those GRBs with spectroscopic redshift measurements.

We have already mentioned (Section 3.1) that the photon spectral index in the 15–150 keV BAT energy band is flatter for short-duration GRBs than for long-duration GRBs (see also Figure 31 in Appendix C). Figure 10 shows the relation between $T_{90}$ in the observed and rest frames and the 15–150 keV photon index $\Gamma$. In the observed frame, there clearly are two groups of GRBs. This effect, however, becomes smeared out in the rest frame. The reason that the percentage of short-duration GRBs with spectroscopic redshifts is significantly lower than in long-duration GRBs is simply that they are much more difficult to follow up, because of their lower flux/fluence and faster decay slopes as compared with long-duration GRBs.

Early studies of Swift-detected GRBs noted a close connection between the energetics of the prompt and afterglow emission (e.g., O’Brien et al. 2006; Willingale et al. 2007; Gehrels et al. 2008), and more recent studies (e.g., Margutti et al. 2013) confirm these findings. The left panel of Figure 11 shows the correlation between the fluence in the 15–150 keV band during the prompt emission and the 0.3–10 keV fluence in the afterglow emission, and the right panel displays the luminosities.

Clearly, and as expected, the energetics of the prompt and afterglow emission are very strongly correlated: bursts with high 15–150 keV fluence in their prompt emission will have high X-ray luminosities/fluxes in the afterglows, and vice versa.

In this paper, we take a step beyond the energetics and ask what other prompt and afterglow properties are correlated. One of our main results is that there are clear correlations between the BAT 15–150 keV $T_{90}$’s and the break times in the X-ray afterglow light curves before and after the plateau phase. These
Table 2

|              | $\Gamma_{\text{BAT}}$ | $\beta_X$         | $\alpha_{X2}$     | $\alpha_{X3}$     | $T_{90}$  | $T_{\text{break1}}$ | $T_{\text{break2}}$ | 15-150 keV Fluence |
|--------------|-----------------------|-------------------|-------------------|-------------------|----------|---------------------|---------------------|-------------------|
| $\Gamma_{\text{BAT}}$ | ...                   | 632, 6.23 x 10^{-6} | 539, <10^{-8}    | 475, <10^{-8}    | 750, 0.0231 | 384, 0.1638         | 417, 0.0162         | 750, 1.85 x 10^{-4} |
| $\beta_X$    | +0.186, +4.557        | ...               | 539, 4.55 x 10^{-4} | 473, 2.71 x 10^{-4} | 631, 0.4148 | 384, 0.1459         | 417, 9.33 x 10^{-4} | 631, 0.7742        |
| $\alpha_{X2}$| -0.259, -6.215       | -0.150, -3.528    | ...               | 413, <10^{-8}    | 538, 7.2 x 10^{-7} | 383, 0.4634         | 414, 1.7 x 10^{-7} | 538, <10^{-8}      |
| $\alpha_{X3}$| -0.313, -7.181       | -0.167, -3.669    | +0.405, +8.980   | 475, 1 x 10^{-8} | 278, 0.0387 | 414, 1.97 x 10^{-6} | 475, 5.6 x 10^{-7} | 417, <10^{-8}      |
| $T_{90}$     | +0.083, +2.279        | +0.033, +0.816    | +0.212, +5.015   | +0.262, +5.903   | ...       | 383, <10^{-8}       | 417, <10^{-8}      | 752, <10^{-8}      |
| $T_{\text{break1}}$ | +0.071, +1.395    | -0.074, -1.457    | -0.038, -0.734   | +0.124, +2.077   | +0.328, +6.776 | ...                 | 277, <10^{-8}      | 383, 0.2121        |
| $T_{\text{break2}}$ | +0.118, +2.414     | +0.161, +3.334    | +0.254, +5.321   | +0.231, +4.825   | +0.495, +11.615 | +0.516, +9.994      | ...                 | 417, 7.49 x 10^{-5} |
| 15-150 keV fluence | -0.136, -3.758     | +0.011, +0.286    | +0.268, +6.450   | +0.227, +5.075   | +0.659, +23.99 | -0.064, -1.253     | +0.193, +3.999    | ...               |

**Notes.** Values below the diagonal list the Spearman rank order correlation coefficient $r_s$ and the Student’s $t$-test value $T_t$. Values above the diagonal list the number of GRBs in the correlation and the probability $P$ that the result was drawn from a random distribution.
Table 3

Spearman Rank Order Correlation and Student’s t-test ($T_s$) for the Rest-frame Parameters of GRBs with Spectroscopic Redshifts

|         | $\Gamma_{\text{BAT}}$ | $\beta_X$ | $\alpha_X^2$ | $\alpha_X^3$ | $T_{90,x}$ | $T_{\text{break}1,x}$ | $T_{\text{break}2,x}$ | $L_{15-150\text{keV}}$ | $E_{\text{iso}}$ | $E_{\text{peak},x}$ |
|---------|------------------------|-----------|---------------|---------------|-------------|------------------------|------------------------|-----------------------|----------------|-------------------|
| $\Gamma_{\text{BAT}}$ | ... | 230, 1.68 $\times 10^{-3}$ | 208, 6.95 $\times 10^{-5}$ | 188, 1.68 $\times 10^{-4}$ | 232, 0.1360 | 144, 0.1991 | 175, 0.047 | 231, $<10^{-8}$ | 231, $4 \times 10^{-8}$ | 104, $1.12 \times 10^{-5}$ |
| $\beta_X$ | +0.206, +3.179 | ... | ... | 208, 0.011 | 188, 2.75 $\times 10^{-4}$ | 230, 0.2813 | 144, 0.2133 | 175, 4.61 $\times 10^{-4}$ | 229, 0.0500 | 229, 0.0701 | 103, 0.1557 |
| $\alpha_X^2$ | -0.272, -4.064 | -0.175, -2.556 | ... | 175, 1.96 $\times 10^{-5}$ | 208, 0.0197 | 143, 0.4256 | 175, 0.1557 | 207, 0.0702 | 207, 1.22 $\times 10^{-3}$ | 98, 4.12 $\times 10^{-3}$ |
| $\alpha_X^3$ | -0.271, -3.839 | -0.262, -3.708 | +0.317, +4.393 | ... | 188, 9.06 $\times 10^{-3}$ | 115, 0.2404 | 174, 0.5166 | 188, 0.0225 | 188, 2.98 $\times 10^{-5}$ | 87, 0.0122 |
| $T_{90,x}$ | +0.098, +1.496 | +0.072, +1.082 | +0.162, +2.351 | +0.190, +2.637 | ... | 144, 4.53 $\times 10^{-6}$ | 175, $<10^{-8}$ | 231, 7.64 $\times 10^{-6}$ | 231, 2.64 $\times 10^{-3}$ | 104, 0.757 |
| $T_{\text{break}1,x}$ | +0.108, +1.291 | +0.104, +1.246 | -0.067, -0.799 | -0.111, -1.183 | +0.371, +4.767 | ... | 115, $<10^{-8}$ | 143, $<10^{-8}$ | 143, $<10^{-8}$ | 65, 0.2841 |
| $T_{\text{break}2,x}$ | +0.151, +2.004 | +0.262, +3.573 | +0.108, +1.425 | +0.050, +0.651 | +0.439, +6.421 | +0.628, +8.568 | ... | 175, 1.00 $\times 10^{-8}$ | 175, 0.0110 | 82, 0.1623 |
| $L_{15-150\text{keV}}$ | -0.370, -6.032 | -0.130, -1.972 | +0.126, +1.816 | +0.166, +2.295 | -0.290, -4.579 | -0.587, -8.614 | -0.413, -5.956 | ... | 231, $<10^{-8}$ | 103, 6.88 $\times 10^{-8}$ |
| $E_{\text{iso}}$ | -0.351, -5.678 | -0.120, -1.815 | +0.222, +3.264 | +0.300, +4.284 | +0.197, +3.048 | -0.472, -6.357 | -0.192, =2.57 | +0.850, +24.415 | ... | 103, 1.06 $\times 10^{-6}$ |
| $E_{\text{peak},x}$ | -0.416, -4.616 | -0.141, -1.433 | +0.287, +2.938 | +0.268, +2.560 | -0.031, -0.309 | -0.136, -1.086 | -0.155, -1.405 | +0.426, +4.735 | +0.459, +5.188 | ... |

Notes. Values below the diagonal list the Spearman rank order correlation coefficient $r_s$ and the Student’s t-test value $T_s$. Values above the diagonal list the number of GRBs in the correlation and the probability $P$ that the result was drawn from a random distribution.
The left panel of Figures 12 and 13 show the observed values, while the right panels display the values in the rest frame of the burst. Although there is a large scatter in all these relations, there are clearly correlations: GRBs with long $T_{90}$ start their X-ray afterglow plateau phase at later times and end the plateau phase later than GRBs with shorter $T_{90}$. Between $T_{90}$ and the break time before the plateau phase, $T_{\text{break,1}}$, we found for the...
observed values a Spearman rank order correlation \( r_s = 0.328 \) and Student’s \( t \)-test value \( T_s = 6.776 \) (\( N = 384 \) GRBs), which imply a probability \( P < 10^{-8} \) of a random result; for the values in the rest frame, \( r_s = 0.371 \) and \( T_s = 4.767 \) (\( N = 144 \)), for which \( P = 4.5 \times 10^{-6} \). The relationship between the prompt and afterglow emission is especially strong between \( T_{90} \) and the break time after the plateau phase, \( T_{break,2} \). For the observed values, we found \( r_s = 0.495, T_s = 11.615 \) (\( N = 417 \)) with \( P < 10^{-8} \), and \( r_s = 0.439, T_s = 6.421 \) (\( N = 175 \)) with \( P < 10^{-8} \) for the times in the rest frame. What the relations between \( T_{90} \) and the break times in the X-ray light curves suggest is that there seems to be a strong connection between the prompt and the afterglow emission. A relation between long \( T_{90} \) and later afterglow break times allows one, in principle, to make predictions of the behavior of the X-ray afterglow light curve based on prompt emission properties. If this is true, then we would also expect to see a correlation between the spectral slopes in the BAT 15–150 keV band and the 0.3–10 keV X-ray band.

The correlation between the BAT 15–150 keV hard X-ray photon index \( \Gamma \) and the X-ray energy spectral slope \( \beta_X \) is displayed in Figure 14. Again, although there is a large scatter in this relation, the two properties are clearly correlated, and this is another hint that the prompt and afterglow phases are clearly linked. GRBs with steep spectral in the 15–150 keV band also show steeper X-ray spectra. The Spearman rank order correlation coefficient is \( r_s = 0.179 \) with \( T_s = 4.560 \) (632 GRBs) and a probability \( P = 6.32 \times 10^{-6} \) of a random result. We also checked whether there is any (anti-) correlation between spectral indices and the rest-frame break times before and after the plateau phase. We could not find any significant correlation between these properties (Table 2). There is a weak trend between the X-ray spectral slope and \( T_{break,2} \), for bursts with later break times to have steeper X-ray spectra, but the probability is 1.5% that this is just a random result.

The BAT 15–150 keV photon index \( \Gamma \) also strongly anticorrelates with the decay slopes during the plateau and normal decay phases, \( \alpha_{X2} \) and \( \alpha_{X3} \). The decay slope during the plateau phase anticorrelates with \( \Gamma \) with \( r_s = -0.260, T_s = -6.232 \), and a probability of a random distribution \( P < 10^{-8} \) (539 GRBs); for the "normal" decay slope \( \alpha_{X1}, r_s = -0.313, T_s = -7.154, \) and \( P < 10^{-8} \) (475 GRBs). These relations are displayed in Figure 15. Again, these clearly link the prompt with the afterglow emission: bursts with steeper 15–150 keV spectra have flatter decay slopes during the plateau and normal decay phases. These relations can be used to estimate the behavior of the X-ray light curve.

We noticed strong correlations between the fluence in the 15–150 keV BAT energy band and the decay slopes in the X-ray light curve \( \alpha_{X2} \) and \( \alpha_{X3} \), as shown in Figure 16. We find Spearman rank order correlation coefficients \( r_s = 0.270 \) and 0.225, Student’s \( t \)-test values of 6.482 (for 538 GRBs) and 5.043 (475 GRBs), and probabilities of a random result of \( P < 10^{-8} \) and \( P < 5.6 \times 10^{-7} \) for the fluence versus \( \alpha_{X2} \) and \( \alpha_{X3} \) correlations, respectively. These relations become apparent in our \textit{Swift} GRB sample as a consequence of the large number of bursts. Although this is purely phenomenological and most likely due to selection effects, we can still take advantage of these relations to predict the behavior of the X-ray light curve. Note that for the relations of luminosity and isotropic energy with \( \alpha_{X2} \) and \( \alpha_{X3} \), there are only trends that bursts with higher fluence in the BAT energy band decay faster in X-rays (see Table 3).
The next step is to see whether the luminosity in the prompt emission also anticorrelates with the break times in the X-ray light curve. As shown in Figure 17, this is indeed the case for both the break times before and after the plateau phase, \( T_{\text{break1},z} \) and \( T_{\text{break2},z} \) respectively. In the first case, the Spearman correlation coefficient and Student’s \( t \)-test values are \( r_s = -0.587 \) and \( T_{\text{r}} = -8.614 \), with \( P < 10^{-8} \) (143 GRBs), and for the break time after the plateau phase, \( r_s = -0.413 \) and \( T_{\text{r}} = -5.956 \) with \( P = 1 \times 10^{-8} \) for all GRBs (\( N = 175 \)) and \( r_s = -0.433 \), \( T_{\text{r}} = -6.187 \) with \( P < 10^{-8} \) for the long GRBs (\( N = 168 \)). This is a real anticorrelation between the prompt luminosity and the afterglow emission light curve break times. The same cannot necessarily be said, however, for the connection found by, e.g., Dainotti et al. (2008) between the break time after the plateau phase \( T_{\text{break2},z} \) and the luminosity at \( T_{\text{break2},z} \), which are strongly anticorrelated. The problem is that \( T_{\text{break2}} \) and \( L_{0.3-10\text{keV}}(T_{\text{break2}}) \) are not independent parameters. Because the decay slope of the “plateau” phase is not \( 0^8 \), a later break time will automatically result in a lower flux/luminosity. Although there is a strong correlation between \( T_{\text{break2},z} \) and the luminosity at \( T_{\text{break2},z} \) as reported by Dainotti et al. (2008) in our sample (\( r_s = -0.559, T_{\text{r}} = -8.785, P < 10^{-8} \)), there is also a strong anticorrelation with the flux at that time. As a consequence, any possible physical cause for this relation cannot be disentangled from the fact that at later times a burst will automatically appear to be fainter than at earlier times.

Note that the anticorrelations between the prompt emission luminosity and the isotropic energy and break times in the X-ray afterglow light curve can be used as a diagnostic to determine whether a redshift measured for a galaxy in the direction of the burst is actually associated with the burst or just a random galaxy in the line of sight. A good example here is GRB 051109B (Tagliaferri et al. 2005). This burst had an observed \( T_{90,2} = 15 \pm 1 \) s and a fluence of \((2.7 \pm 0.4) \times 10^{-7} \) erg cm\(^{-2}\) (Hullinger et al. 2005), with break times in the “X-ray light curve at \( T_{\text{break1}} = 200 \) s and \( T_{\text{break2}} = 1430 \) s. Perley et al. (2005) reported a galaxy in the direction of this burst and measured a redshift of \( z = 0.080 \). Is this galaxy associated with the burst or not? The answer is that this association is most unlikely. At the redshift of the galaxy, the luminosity distance is \( D_L = 360 \) Mpc, which results in a 15–150 keV luminosity \( L_{15-150\text{keV}} = 3 \times 10^{47} \) erg s\(^{-1}\) cm\(^{-2}\) and an isotropic energy \( E_{\text{iso}} = 4 \times 10^{48} \) erg. These values are far off the relations shown in Figure 17 and Figure 41 in Appendix D. We can therefore conclude that the galaxy found by Perley et al. (2005) at \( z = 0.08 \) is not associated with GRB 051109B and is just a random foreground galaxy. As pointed out by Campisi & Li (2008), with the increasing magnitude limits of newer telescopes, the chance of coincidence of a GRB with a foreground galaxy at redshifts \( z < 1.5 \) is on the order of several percent.

### 3.4. Principal Component Analysis

So far, we have only looked at bivariate correlations, and we have found strong correlations between GRB prompt and afterglow properties. One further step is statistical analysis in a multidimensional parameter space. The goal here is to search for any underlying fundamental property driving these relations. One of the standard tools in multivariate analysis that may answer this question is PCA (Pearson 1901). The idea of PCA is to reduce the number of significant sample parameters to a small number that capture most of the variance in the data. For example, in active galactic nuclei the measured parameters are primarily driven by the mass of the central black hole and the Eddington ratio \( L/L_{\text{Edd}} \) (see, e.g., Grupe 2004; Boroson 2002). In a mathematical sense, the PCA searches for eigenvalues and eigenvectors in a correlation coefficient matrix. Good descriptions of the application of PCA in astronomy have been provided by Francis & Wills (1999) and Boroson & Green (1992).

We applied a PCA to the bursts in our sample for which the following input parameters were available: \( \log T_{90,2}, \log T_{\text{break2},z}, \alpha_{X2}, \beta_X, \Gamma, \) and the rest-frame 15–150 keV luminosity (175 GRBs in total). The reason we did not include all properties listed in Table 3 is that some of these have obvious correlations, such as \( T_{\text{break1}} \) and \( T_{\text{break2}} \). We want the input properties to be as independent as possible. We applied the PCA implemented in the statistical package R (e.g., Crawley 2007; The R-Team 2009). All input parameters were normalized by \( \lambda_{\text{norm}} = x - \bar{x} \text{mean}/s\text{d}(x) \), where \( s\text{d}(x) \) is the standard deviation of the parameter \( x \). The results are summarized in Table 4. The first two eigenvectors from the PCA account for 60% of the variance of the sample. The most dominant of these, eigenvector 1, accounts for almost 40% of the variance. It strongly correlates

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8 In fact, the median decay slope during the plateau phase is 0.6.
Figure 17. Relations of the $k$-corrected BAT luminosity (top) and the BAT photon index $\Gamma$ (bottom) with the break times before and after the X-ray afterglow plateau phase. Short bursts are marked with triangles.

(A color version of this figure is available in the online journal.)

Table 4

| Property                        | EV 1     | EV 2     | EV 3     | EV 4     | EV 5     | EV 6     |
|---------------------------------|----------|----------|----------|----------|----------|----------|
| Proportion of variance          | 0.3742   | 0.2366   | 0.1316   | 0.1007   | 0.08319  | 0.07377  |
| Cumulative proportion           | 0.3742   | 0.6108   | 0.7423   | 0.8430   | 0.92623  | 1.00000  |
| $\log T_{90,z}$                  | -0.3959  | 0.4782   | -0.2098  | 0.2080   | 0.7193   | -0.0997  |
| $\log T_{\text{break, } z}$     | -0.4859  | 0.2924   | 0.2970   | 0.1528   | -0.4977  | -0.5650  |
| $\alpha_{X2}$                   | 0.1043   | 0.6931   | -0.0393  | -0.6379  | -0.1961  | 0.2486   |
| $\Gamma_{\text{BAT}}$           | -0.3830  | -0.3865  | -0.5170  | -0.5799  | 0.0193   | -0.3163  |
| $\beta_X$                       | -0.4105  | -0.2349  | 0.7128   | -0.3458  | 0.2755   | 0.2698   |
| $\log L_{15-150 \text{ keV}}$   | 0.5303   | 0.0277   | 0.3016   | -0.2658  | 0.3468   | -0.6605  |

Note. These are GRBs with canonical light curves and spectroscopic redshift measurements.

with the 15–150 keV rest-frame luminosity and anticorrelates with all other parameters except the decay slope during the plateau phase, $\alpha_{X2}$. This may suggest that eigenvector 1 in our sample represents the 15–150 keV luminosity. In order to test this hypothesis, we excluded the 15–150 keV luminosity from the input parameters and ran another PCA on the sample. The results of this PCA are listed in Table 5. This analysis agrees with the PCA that included the 15–150 keV luminosity.

Using the second analysis, we calculated the first eigenvector for each GRB and plotted them versus the 15–150 keV luminosity and isotropic energy, as shown in Figure 18. If the conclusion that GRBs are primarily driven by their energetics is correct, then the relation between eigenvector 1 and energy also has to hold for energies determined independently by other missions. We used the bolometric energies listed in Nava et al. (2012) for about 30 GRBs. This relation is displayed in the right panel of Figure 18. Although the number of GRBs is small, they still follow the trend expected from our PCA. We can conclude that eigenvector 1 in our GRB sample represents the rest-frame 15–150 keV luminosity, the isotropic energy, or both, which seem to be the strongest drivers for the prompt and afterglow emission properties in our sample. Note that Margutti et al. (2013) came to a similar conclusion using $E_{\gamma, \text{iso}}$, $E_{\text{peak}}$, $L_{\text{peak}}$, $T_{90,z}$, and the isotropic energy in the X-ray band as input parameters of their PCA of their GRB sample (R. Margutti 2013, private communications). Although one has to be very careful...
The luminosity function is usually defined as
\[ \Phi(L, z) = \Phi^*(L_{\text{break}}(z)) \left( \frac{L}{L_{\text{break}}(z)} \right)^a + \left( \frac{L}{L_{\text{break}}(z)} \right)^b, \]
where \( \Phi^* \) is the number density at the break luminosity \( L_{\text{break}}(z) \) and \( a \) and \( b \) are the slopes of the luminosity function before and after the break.

The problem with GRBs in the pre-Swift era was that redshift measurements existed for only a handful of bursts. At the time, it was only possible to discuss the GRB luminosity function in a theoretical context (e.g., Kumar & Piran 2000). This has changed since Swift, and luminosity functions have been derived from Swift bursts (e.g., Schmidt 2009; Wanderman & Piran 2010; Cao et al. 2011; Salvaterra et al. 2008, 2012).

The log \( N-\log S \) diagram from the 15–150 keV fluence in the BAT band is shown in Figure 19. This diagram contains the observed 15–150 keV fluence (754 bursts), as well as the rest-frame \( k \)-corrected fluence (232 bursts). The parameters of the log \( N-\log S \) function are \( N^* = (1.733 \pm 0.018) \times 10^{-2} \),

\[ a = (7.41 \pm 2.06) \times 10^{-3}, \quad b = 1.185 \pm 0.018, \] and the break fluence \( S_{\text{break}} = (1.339 \pm 0.031) \times 10^{-6} \).

We constructed luminosity functions in six redshift intervals, as displayed in Figure 20. The parameters for the fits to the GRB luminosity functions displayed in that figure are listed in Table 6.

We noticed that the slope of the high-luminosity end of the luminosity functions with \( L > L_{\text{break}} \) becomes steeper with increasing redshift, as shown in Figure 21. This is the opposite of what has been reported by Richards et al. (2006) for quasars in the Sloan Digital Sky Survey, for which the high-luminosity end of the luminosity function becomes flatter with increasing redshift. As expected, the luminosity where the luminosity function breaks, \( L_{\text{break}} \), shifts to higher luminosities with increasing redshift. The number of GRBs per cubic gigaparsec, however, decreases with increasing redshift.

Now another step is to look at the rates at which GRBs occur in a space volume per year, as shown in Figure 22. This rate contains both long and short bursts. The way we estimated these numbers is by taking the number of Swift-discovered bursts with spectroscopic redshift measurements per redshift interval and assuming the same underlying redshift distribution for the remaining Swift bursts. This number was then multiplied by the ratio of the whole sky in square degrees to the BAT sky coverage. This plot suggests that the GRB rate is significantly higher in the current universe than it was at early times. This, however, is a very naive picture. The number of bursts with spectroscopic

Table 5
| Property                        | EV 1   | EV 2   | EV 3   | EV 4   | EV 5   |
|--------------------------------|--------|--------|--------|--------|--------|
| Proportion of variance         | 0.3525 | 0.2836 | 0.1497 | 0.1172 | 0.09717|
| Cumulative proportion          | 0.3525 | 0.6360 | 0.7857 | 0.9028 | 1.00000|
| log \( T_{\text{break}1} \)    | -0.4680| 0.4521 | -0.3117| 0.4303 | -0.5424|
| log \( T_{\text{break}2} \)    | -0.5854| 0.2565 | 0.2216 | 0.1604 | 0.7188 |
| \( \alpha_{X2} \)              | 0.0790 | 0.6985 | -0.0738| -0.7073| -0.0044|
| \( \Gamma_{\text{BAT}} \)      | -0.4048| -0.4096| -0.7159| -0.3758| 0.1210 |
| \( \beta_{X} \)                | -0.5179| -0.2719| 0.5795 | -0.3842| -0.4176|

Figure 18. Eigenvector 1 vs. rest-frame 15–150 keV luminosity (left) and isotropic energy in the 15–150 keV BAT band (middle) in our GRB sample. Eigenvector 1 was determined based on the five parameters used in the PCA listed in Table 5. The right panel displays eigenvector 1 vs. the bolometric energy derived by Nava et al. (2012) for comparison.

(A color version of this figure is available in the online journal.)

Figure 19. log \( N-\log S \) diagram for Swift-detected GRBs. Triangles show the observed fluence in the 15–150 keV BAT band and circles the \( k \)-corrected 15–150 keV fluence.

(A color version of this figure is available in the online journal.)

3.5. GRBs in a Cosmological Context

While log \( N-\log S \) tests and luminosity functions are standard tools in quasar cosmology studies (e.g., Richards et al. 2006; Ross et al. 2012), they have only been applied to GRBs in a few recent studies. The luminosity function is usually defined as

\[ \Phi(L, z) = (\frac{L}{L_{\text{break}}(z)})^a + (\frac{L}{L_{\text{break}}(z)})^b, \]
Figure 20. Luminosity functions of Swift-discovered GRBs in different redshift intervals. The fitted parameters to these luminosity functions and the number of GRBs in each are listed in Table 6.

Table 6

| Redshift Interval | No. of GRBs | $a^a$  | $b^a$  | $\Phi^a b$ | $L_{\text{break}}^a\text{c}$ |
|------------------|------------|--------|--------|------------|-------------------------------|
| $<0.5$           | 21         | $+0.117 \pm 0.016$ | $0.836 \pm 0.179$ | $0.630 \pm 0.074$ | $3.36 \pm 1.27 \times 10^{49}$ |
| 0.5–1.0          | 44         | $-0.036 \pm 0.166$ | $0.774 \pm 0.183$ | $0.433 \pm 0.195$ | $(2.81 \pm 3.49) \times 10^{50}$ |
| 1.0–2.0          | 61         | $-0.001 \pm 0.011$ | $0.948 \pm 0.074$ | $0.133 \pm 0.008$ | $(2.35 \pm 0.36) \times 10^{51}$ |
| 2.0–3.0          | 59         | $-0.024 \pm 0.023$ | $0.921 \pm 0.078$ | $0.127 \pm 0.011$ | $(9.21 \pm 2.13) \times 10^{51}$ |
| 3.0–4.0          | 27         | $-0.090 \pm 0.149$ | $1.211 \pm 0.224$ | $0.068 \pm 0.019$ | $(1.85 \pm 0.95) \times 10^{52}$ |
| $>4.0$           | 18         | $-0.107 \pm 0.040$ | $1.309 \pm 0.059$ | $0.014 \pm 0.001$ | $(9.11 \pm 1.07) \times 10^{52}$ |

Notes. The luminosity functions are shown in Figure 20.

$^a$ The fit parameters are defined by $\Phi(L, z) = \Phi^a(L_{\text{break}})/(L/L_{\text{break}})^a + (L/L_{\text{break}})^b$.

$^b$ GRB density at the break luminosity $L_{\text{break}}$ in units of GRBs per Gpc$^3$.

$^c$ Break luminosity in units of erg s$^{-1}$.

redshifts is biased against high-redshift bursts. Therefore, we cannot necessarily assume that the redshift distribution of the Swift bursts without redshift measurements is the same as for those with redshift measurements.

Another way to tackle this problem is to look only at the space density of the most luminous bursts. This is shown in Figure 22.

Figure 21. Slope $b$ of the luminosity functions (see Table 6) for bursts with $L > L_{\text{break}}$ vs. redshift.

Figure 22. Total rate of GRBs per year and per cubic gigaparsec derived from the number of Swift-detected GRBs.

Figure 23. Here we consider only those bursts with luminosity $L_{15–150\text{keV}} > 10^{52}$ erg s$^{-1}$. What can be seen is that the number of Swift-detected bursts per cubic gigaparsec decreases significantly in the local universe. This is similar to the “cosmic downsizing” that is known for bright quasars (e.g., Richards...
et al. 2006). If real, then we should also see this effect in a luminosity–redshift plot. The 15–150 keV luminosity is shown versus redshift in Figure 24, and indeed there are no bursts with $L_{15–150\text{keV}} > 3 \times 10^{52}$ erg s$^{-1}$ at redshifts less than 1.5. Note that the peak quasar density is roughly at a redshift of $z = 2.75$ (see, e.g., Richards et al. 2006), similar to that of our GRB sample. This result is consistent with what has been found by Wanderman & Piran (2010). The space density of GRBs thus decreases with increasing redshift. However, one should keep in mind that this may also be a selection effect. Because high-redshift bursts are those that are not detected in the UVOT, often no one wants to take the risk of sacrificing valuable observing time on a burst that is simply too faint and not necessarily highly redshifted. As we show below, bursts with redshift measurements tend to be brighter than those without. Nevertheless, the result shown in Figure 23 agrees with the cosmic star formation history (e.g., Hopkins & Beacom 2006).

### 3.6. Redshift Predictions

Spectroscopic redshift measurements exist for 232 Swift onboard-discovered bursts. The problems with obtaining GRB redshifts are that (1) the afterglows are faint to begin with, often fainter than 20 mag in $R$, and (2) they decay fast. So, an optical observer has to decide quickly if it is worth spending valuable telescope time on a newly discovered burst. The capability to detect GRB afterglows in the optical and near-infrared by either spectroscopic or photometric measurements has significantly increased in recent years, especially with the arrival of X-shooter at the ESO Very Large Telescope and GROND at the ESO/MPI 2.2 m telescope in La Silla (Greiner et al. 2008; Krühler et al. 2011). In order to predict GRB redshifts, ideally one would look for a relation between a redshift-dependent (or distant-dependent) parameter and a redshift-independent parameter. This can be based purely on selection effects. In the past it has been suggested (Grupe et al. 2007) that bursts with significant excess absorption column densities above the Galactic value are low-redshift bursts. Ukwatta et al. (2010) found an anticorrelation between the spectral lag times in the BAT data and the isotropic luminosity. Recently, Morgan et al. (2012) suggested a statistical method that applies a random-forest technique to predict high-redshift GRBs. To date, this is the most advanced method for predicting whether a burst is at high redshift based on Swift data.

Let us start with an update to the redshift–excess absorption relation presented in Grupe et al. (2007). At that time, the Swift GRB sample only contained about 50 GRBs. The new sample presented here contains more than four times as many bursts with spectroscopic redshift measurements. Figure 25 shows the relation between log$(1+z)$ and log$(1+\Delta N_H)$, illustrating that in principle this method still holds. The only exception is the burst with the highest redshift, GRB 090423, for which we obtained an excess absorption column density of $5.8 \times 10^{20}$ cm$^{-2}$. Equation (1) in Grupe et al. (2007) would have predicted a redshift of $z < 6.6$, which, however, would still have been a high-redshift burst. Note also that the errors on the absorption column density for this burst are rather large and, within the errors, GRB 090423 is still within the prediction.

In order to obtain a better discriminator for high-redshift bursts, we have to extend our simple relation between redshift and $\Delta N_H$. One discriminator here is a detection in the Swift UVOT. If the excess absorption is consistent with zero, this means it is either a high-redshift burst or a low-redshift burst with no significant X-ray absorption. In the latter case, this means that the burst will most likely not be reddened significantly in the optical/UV, so it should be detectible by UVOT. If UVOT does not detect the burst, this makes it a high-redshift candidate.
The next discriminators come from the BAT data. Figure 26 displays the relation between redshift and the photon index $\Gamma$ in the BAT band (left) and the observed 15–150 keV fluence (right). As can be seen, steep BAT spectra only occur in bursts with $z < 4$. This is a simple selection effect. As shown in Figure 27, there is a strong anticorrelation between the BAT photon index $\Gamma_{\text{BAT}}$ and the fluence in the 15–150 keV band. As shown in the right panel of Figure 26, bursts with fluences higher than $10^{-5}$ erg cm$^{-2}$ are only seen in GRBs with $z < 4$. Because of this and the anticorrelation between $\Gamma_{\text{BAT}}$ and the 15–150 keV fluence, we can observe GRBs with steep 15–150 keV spectra only in bursts with relatively low redshifts.

The question is whether we can find a combination of observed parameters that can be correlated with a redshift-dependent (or distance-dependent) property. To explore this question, we performed a PCA on the three prompt emission parameters, $T_{90}$, fluence, and $\Gamma$. We then determined eigenvector 1 for each long-duration GRB and plotted this against the isotropic energy $E_{\text{iso}}$. This relation is shown in Figure 28. For the 216 long GRBs with spectroscopic redshifts in the sample, this is a strong anticorrelation, with a Spearman rank order correlation coefficient $r_s = -0.572$ and $T_s = -10.15$, with a probability $P < 10^{-8}$ that this is just a random distribution. This means that if we calculate eigenvector 1 for a newly discovered burst based on the BAT input parameters, we should be able to predict the isotropic energy in the BAT band. Nevertheless, there is a lot of scatter in this relation, which prevents a clear statement of the redshift of the burst. We examined this plot a bit further for selected high- and low-redshift bursts. These are shown with circles and triangles, respectively. Clearly, they form distinct groups in this diagram. For a given eigenvector 1, high-redshift bursts show higher isotropic energies than do low-redshift bursts.

If we can find another discriminator between low- and high-redshift bursts, then we will know in which group a newly discovered GRB belongs and can use the eigenvector 1 of the burst to obtain an estimate of the isotropic energy. With this estimate and knowledge of the $T_{90}$ value, we can then estimate the distance to the burst and its redshift. Discriminators for high- and low-redshift bursts are (1) whether the X-ray spectrum shows strong excess absorption and (2) whether the afterglow is detected in the UVOT or not. Table 8 lists the mean, standard deviation, and median of observed prompt and afterglow properties of low-redshift ($z < 1.0$), intermediate-
redshift (1.0 < z < 3.5), and high-redshift (z > 3.5) long bursts. Besides low-redshift bursts’ showing enhanced excess absorption column densities, we find that high-redshift bursts tend to have flatter 15–150 keV photon indices, steeper later-time afterglow decay slopes, and lower fluences than low-redshift bursts.

As an example, we can estimate the redshift of GRB 051109B, the burst that was suggested to be associated with a nearby galaxy (Perley et al. 2005); as we showed in Section 3.3, this is most likely not the case and the redshift is probably much larger. Applying the method described above, we calculated an eigenvector 1 of +1.9 for this burst.9 From Figure 28, we can place this burst in the vicinity of $E_{iso} \approx 3 \times 10^{51}$ erg. The fluence of this burst was $2.7 \times 10^{-7}$ erg cm$^{-2}$. Therefore, the luminosity distance is roughly $D_L = 10$ Gpc, which, using the Cosmology Calculator (Wright 2006), corresponds to a redshift $z \approx 1.5$.

4. DISCUSSION

The main motivation for our project is to search for relationships between GRB prompt and afterglow properties that suggest a close connection between these two phases. With Swift, it is possible for the first time to perform statistical analyses on the rest-frame physical parameters of GRBs. Only since the launch of Swift have optical/near-IR observatories been able to obtain spectroscopic redshifts for a significant number of GRBs. About 30% of all Swift-discovered bursts have such redshifts. As recent papers by Margutti et al. (2013), Bernardini et al. (2012b), Nava et al. (2012), and Liu et al. (2010) have shown, there is a close link between the energetics of the prompt and afterglow emission. The study presented here has found new relations that support the connection between the prompt and afterglow phases.

4.1. Correlation Analysis

As shown in Section 3.3, there are several correlations between the prompt and afterglow properties of GRBs. We found the following.

1. The length of the prompt emission (i.e., $T_{90}$) correlates strongly with the break time after the plateau phase, which is essentially the length of the X-ray afterglow plateau phase.
2. The spectral slopes of the 15–150 keV prompt emission and the 0.3–10 keV X-ray afterglow emission are closely correlated.
3. The X-ray afterglow decay slopes are anticorrelated with the 15–150 keV spectral slope of the prompt emission.
4. The X-ray afterglow decay slopes correlate with the rest-frame peak energy $E_{peak}$ at high energies in the prompt emission.
5. The X-ray afterglow decay slopes also depend strongly on the energy/luminosity of the burst.

The mechanism underlying the plateau phase is poorly understood. In X-ray afterglow observations, there is no change in the spectral slope from the plateau phase to the normal decay phase, and in most cases, the plateau flux joins smoothly with the normal afterglow (Liang et al. 2007). On the other hand, the correlation between $T_{90}$ and $T_{break,2}$ points to the fact that the plateau is of internal origin, related to the central engine of the bursts. The fact that the spectrum does not change during $T_{break,2}$ points to its being determined by either a geometric or a hydrodynamic effect. A similar correlation for a much smaller number of GRBs was found by Liang et al. (2007).

This correlation suggests an approximate relation $T_{90} \propto T_{break,2}$. Since there is significant scatter in the data, we venture only qualitative interpretation.

There are many theories in the literature addressing the origin of the plateau phase (for a review, see Zhang 2007). The timescale of the plateau can be constrained by these. However, in most of these models it is difficult to link the prompt duration $T_{90}$ to the plateau duration. One of the most discussed models is that of refreshed shocks (Rees & Mészáros 1998; Zhang et al. 2006), in which the forward shock is energized either by a smoothly decaying central engine luminosity ($L \propto t^{-\alpha}$) or by a distribution of instantaneously ejected masses with a distribution of Lorentz factors down to few tens (Granot & Kumar 2006; Ghisellini et al. 2007). Models for the plateau phase include changes in microphysical parameters with time (Ioka et al. 2006), emission by a distribution of ejecta Lorentz factors (Granot & Kumar 2006), a strong reverse-shock contribution (Genet et al. 2007; Uhlem & Beloborodov 2007), and anisotropic jet structure (Eichler & Granot 2006; Toma et al. 2006).

One class of models explaining the plateau phase invokes energy injection from magnetars (Dai & Lu 1998; Zhang & Mészáros 2001) into the forward shock, similar to refreshed shocks. These can reproduce the flattening in the X-ray light curve (Dall’Osso et al. 2011; Bernardini et al. 2012a). The supply of energy is provided by the spin-down energy of a newly born magnetar. In these scenarios, the collapse to a black hole is delayed by the magnetar phase (Lyons et al. 2010). In relation to short GRBs, the injection of spin-down energy by a magnetar, and thus the plateau phase, can be linked to gravitational wave emission (Rowlinson et al. 2013; Corsi & Mészáros 2009). In these models, the prompt emission is tentatively explained with processes local to the outflow (e.g., magnetic dissipation or shocks close to the magnetar wind photosphere; Metzger et al. 2011), which cannot be readily related to the length of the plateau phase in the afterglow.

The most straightforward way of interpreting the $T_{90}$–$T_{break}$ correlation is the model by Kumar et al. (2008), which addresses both the prompt emission and the plateau phase. In this model, the X-ray luminosity is driven by the mass accretion rate. They envisage a massive star with a core and an envelope. Part of the core collapses to form a black hole, and accretion of the remainder of the core produces the prompt phase. The density drops sharply from the outermost parts of the core to the inner part of the envelope, producing the steep decay part. The envelope is subsequently accreted. The duration of accretion is roughly the fallback time, $t_{fb} \propto M(<r)^{-1/2} \times r^{3/2}$, where $M(<r)$ is the mass within radius $r$, generally dominated by the black hole mass. Thus $T_{90}$ corresponds to the core accretion time and $T_{break,2}$ to the envelope accretion in this model, and the $T_{90}$–$T_{break,2}$ correlation results in $r_{envelope} \propto r_{core}$. The drawback of this scenario is that it predicts a steep decay at the end of the plateau phase corresponding to the outer radius of the star. This is only observed in a few cases.

A natural explanation can be given for the correlation if the reverse shock is at the origin of the plateau. The details of such an interpretation are described, e.g., by Genet et al. (2007); Uhlem & Beloborodov (2007). The prompt duration ($T_{90}$) is defined as the active phase of the central engine (e.g., in a photospheric model), and this also defines the width of the ejecta. The plateau duration in this scenario corresponds to the time required for the

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9 See Appendix E for how to calculate eigenvector 1.
The gamma-ray luminosity $L$ anticorrelates with the plateau break time $T_{\text{break},2}$. This can be understood in terms of an approximate energy conservation. For a universal ratio between the prompt and plateau luminosities, an increase in energy emission in the prompt phase will result in a smaller emitted energy in the plateau, similar to having a constant energy reservoir.

There is a similar observed anticorrelation between $T_{\text{break},2}$ and the luminosity at the end of the plateau (Dainotti et al. 2008; Bernardini et al. 2012a), which we can tentatively understand within the framework of the magnetar model as follows: both the prompt and the afterglow luminosity depend on some positive power of the magnetic field (e.g., $L_{\text{plateau}} \propto B^2$), while the spin-down timescale, which is related to $T_{\text{break},2}$, is proportional to $B^{-2}$. This would qualitatively explain the anticorrelation. Other properties such as the neutron star radius or the rotation period are all redshift indicators, because of the large scatter in these relations (see Figure 9). As we explain below (Section 4.3), it seems that these (anti-) correlations are primarily driven by the luminosity/energy of the burst. What is interesting among these relations are those of the decay slopes of the X-ray afterglow emission with the rest-frame energy $E_{\text{peak}}$ and the energy and luminosity of the burst. While the energy, luminosity, and rest-frame $E_{\text{peak}}$ are all redshift (or distance) dependent, the decay slopes are not. In principle, we do a have redshift indicator. However, at this point we cannot use the slopes $\alpha_{X2}$ and $\alpha_{X3}$ as redshift indicators, because of the large scatter in these relations (see Figure 9). As discussed below, machine learning techniques may be the solution to taking advantage of these redshift-indicator relations.

### 4.2. Multivariate Analysis

With $\log T_{\text{break},2}$, $\log T_{\text{break},1}$, $\log T_{\text{break},0}$, $\alpha_{X2}$, $\alpha_{X3}$, and $\beta_X$ taken as representatives of the prompt and afterglow emission of a subsample of 175 GRBs with canonical X-ray light curves, the results from the PCA show that the first two eigenvectors account for more than 60% of the variance in the sample. We can see directly that eigenvector 1 represents the luminosity, isotropic energy, or both of the GRB in the rest-frame 15–150 keV band (Figure 18). This is somewhat expected. What is interesting is that despite using different input parameters (see Section 3.4), Margutti et al. (2013) came to a similar conclusion. The question that remains is what actually determines the luminosity and energy release of a burst.

Are GRBs with spectroscopic redshifts, in particular those used in our PCA, representative of the whole sample? In other words, can the conclusions that we draw from the statistical analysis of this subsample of bursts, including the PCA, be applied to the rest of the sample that does not have redshift measurements? This is an important question because, as discussed above, the entire sample is driven by selection biases.

In order to test this, we need to look at the statistics between the GRB samples with and without spectroscopic measurements. We have already mentioned (Section 3.2) that *Swift* GRBs are affected by selection effects, primarily due to the BAT properties. As pointed out by Coward et al. (2013), selection biases become even more important when dealing with high-redshift bursts. In order to answer this question, we looked at the observed parameters of the samples for GRBs with and without spectroscopic redshift measurements and those used in the PCA. The mean, standard deviation, and median of each sample are listed in Table 7. All parameters like $T_{\text{break}}$ or $\alpha_{X2}$ have very similar means, standard deviations, and medians, suggesting that they are all drawn from the same underlying distribution. However, this is not true for the observed 15–150 keV fluence and the peak energy $E_{\text{peak}}$. Here the distributions seem to be different: GRBs with spectroscopic redshifts have, on average, a fluence twice as high when compared with GRBs with no redshift measurements.

We performed Kolmogorov–Smirnov tests on the samples of GRBs with and without spectroscopic redshift measurements and found that, indeed, the distributions of the fluence and $E_{\text{peak}}$ in these two samples are drawn from different populations. For the fluence, we found $D = 0.2166$ with a probability $P < 10^{-4}$ of a random result, and for $E_{\text{peak}}$, $D = 0.30$ with $P = 0.002$. Clearly, the bursts with redshift measurements are biased toward brighter GRBs. As shown in Table 8, this is really a selection effect between bursts with and without redshifts and not driven by different redshift intervals. What this means is that these GRBs are also more likely to have optical counterparts and, as a result, be observed preferentially by ground-based...
observers. This becomes apparent when looking at the UVOT detections in both samples: while two-thirds of all GRBs with spectroscopic redshift measurements have UVOT detections, this is only true for 17% of the GRBs without spectroscopic redshift measurements. Nevertheless, the fact that otherwise the observed parameters of the bursts are very similar suggests that they are drawn from the same population. If this is true, then the correlations found among the rest-frame parameters in bursts with redshifts also apply to those bursts without redshift measurements. In particular, the conclusion of our PCA that the energetics is the main driver in GRB properties does therefore apply to all GRBs.

4.3. What Is Driving the Prompt and Afterglow Properties?

As we have seen from the PCA, the properties of the prompt and afterglow phases seem to be driven primarily by energetics. This means the largest relative scatter in the multidimensional data cloud can be accounted for by luminosity. In other words, if we know the luminosity, we have accounted for a high percentage of the information otherwise obtainable. Moreover, the luminosity changes by five orders of magnitude, more than any other parameter. There are two viable mechanisms for extracting luminosity from a black hole–accretion disk system.

If the luminosity is extracted from the central engine by the Blandford–Znajek (Blandford & Znajek 1977) mechanism, this means $L \propto a^2 B^2 M^2$, where $a$ is the dimensionless spin parameter, $B$ is the magnetic field threading the central engine, and $M$ is its mass. In current models, the mass can have a spread of 1 order of magnitude and the rotational parameter is ideally around 0.5 for maximum efficiency, and it cannot introduce a large amount of variance. Thus, the magnetic field has to account to the bulk of the variance. If the jet is launched by neutrino emission from the disk, the luminosity scales as $L \propto M^{9/4} \rho^{3/4}$ (Zalamea & Beloborodov 2011). In this scenario, the large variance in luminosity can be accounted by a variation in the accretion rate by two orders of magnitude.

However, what is really behind all these properties, or, in other words, what determines the energetics of a burst? Part of the problem is that for all correlations mentioned here, we measured isotropic energies and luminosities. We know, however, that in a GRB the outflow is collimated. This may explain the anticorrelation we found between the luminosity and energy of the prompt emission with (rest frame) $T_{90}$ and break times before and after the plateau phase. Naively one would assume that the more energetic a burst, the longer its $T_{90}$ and the later the plateau phase start and end times. However, as we have shown, this seems not to be the case. We do, however, assume isotropic energies/luminosities for all of our correlations. What may be the case is that bursts with short $T_{90}$ and earlier break times before and after the plateau phase are those bursts that have highly collimated outflows. Correcting for collimation would make the total energy release of these bursts significantly lower than that in bursts that are less collimated. This means that, if calibrated, $T_{90}$ and break times can be used as a measure of the jet opening angle. This relation then would be somewhat similar to the relation between jet opening angle and break times found by Frail et al. (2001) for optical and radio afterglows. What this means is that bursts with large opening angles are those that are intrinsically less energetic and show shorter $T_{90}$ and break times. This is exactly what we see in the second eigenvector in our PCA. The second eigenvector thus might represent the jet opening angle.

A connection between the X-ray spectral slope and the decay slopes in the light curve is expected from, e.g., the closure relations (Racusin et al. 2009; Zhang & Meszaros 2004; Zhang et al. 2006). The big question remaining is whether we can predict the behavior of the X-ray afterglow, assuming a canonical behavior, based on properties measured from the prompt emission. If this is possible, then it gives us a handle on how to plan future observations of the X-ray afterglows. We have already seen that $T_{90}$ and the break times before and after the plateau in the X-ray afterglow light curves are strongly correlated. So, one prediction we can make is that bursts with a short $T_{90}$ will show early breaks in their X-ray light curves. Although this correlation is statistically very strong ($P < 10^{-8}$), the scatter in the relation is large, making it impossible to derive a precise prediction of the break times based on $T_{90}$. We have also found that the photon spectrum measured in the prompt emission in the BAT 15–150 keV band is strongly anticorrelated with the X-ray afterglow decay slopes. So if, for example, the 15–150 keV hard X-ray photon index $\Gamma$ is flat, the X-ray photon...
afterglow light curve decay slopes are likely to be steep, and vice versa. Again, this seems to be linked to the energetics of the burst. More luminous/energetic bursts have flatter hard X-ray spectra (see Figure 40 in Appendix D). Nevertheless, we do not find a clear correlation between the luminosity/energy and the decay slopes in the X-ray light curves. The correlation between $E_{90}$ and the decay slope in the plateau phase, $\alpha_{2}$, is mild ($r_s = 0.240$, $P = 5 \times 10^{-4}$), and that with the “normal” decay slope $\alpha_{3}$ has $r_s = 0.306$ and $P = 3.1 \times 10^{-3}$ (see Table 3). So, the X-ray afterglows of more energetic bursts decay faster than those of less energetic bursts. This is somewhat the opposite of what one would normally expect. The reason here again may be the opening angle of the burst. Because we obtained all our correlations based on $E_{90}$, however, we do not know what the opening angle is and what the real energy release is.

The question is, do the properties of the prompt emission of a burst determine the fate of the afterglow emission (assuming that the afterglow follows a canonical light curve)? Or, in other words, can we use the properties measured from the prompt emission to make predictions of the behavior of the X-ray afterglow? How will the light curve evolve?

One of the strongest correlations found is that between the 15–150 keV $T_{90}$ and the break times at the beginning and end of the plateau phase in the X-ray light curve. This correlation gives us a rough estimate of when these breaks happen based on $T_{90}$. A burst with a short $T_{90}$ will have breaks in the X-ray light curve earlier than a burst with long $T_{90}$. We also found an anticorrelation between the 15–150 keV spectral slope $\Gamma$ and the decay slopes in the X-ray light curve: a burst with a soft 15–150 keV spectrum will show flatter decay slopes than a burst with a harder 15–150 keV spectrum. Last but not least, there are strong correlations between the fluence in the 15–150 keV BAT energy band and the decay slopes in the X-ray light curves. These results in GRBs with high fluence decaying faster in X-rays than GRBs with lower fluence.

**4.4. Swift BAT Short- and Long-duration GRBs**

The distribution of $T_{90}$ shown in Figure 2 from BAT-discovered GRBs suggests a bimodal distribution, such has been found from BATSE bursts (Kouveliotou et al. 1993). However, because of the lower energy window of the Swift BAT, the detection rate for short GRBs is significantly lower, and the dividing line between short- and long-duration GRBs appears to be at shorter times, compared with BATSE bursts. As pointed out by Bromberg et al. (2013), the division between collapsars (long GRBs) and noncollapsars (short GRBs) is driven by the different physical processes involved in these types. Bromberg et al. (2013) suggested that a division between short and long bursts at about 0.8 s is more suitable for Swift-detected bursts. The observed $T_{90}$ distribution (Figure 2) seem to support this value. As already found from BATSE bursts, short GRBs tend to exhibit harder spectra than long GRBs, allowing another parameter to distinguish between the two classes. As shown in the distributions of the 15–150 keV photon indices $\Gamma$ for long and short GRBs in Figure 31 of Appendix C, we see the same effect in Swift-detected short and long GRBs as well. Figure 10 displays the relations between the observed $T_{90}$ and $\Gamma$, suggesting that there are two distinct groups. As pointed out by Margutti et al. (2013), short GRBs appear to be less energetic compared with long GRBs. The consequence is that the fluence of short GRBs is significantly lower than that of long GRBs (Figure 32 in Appendix C).

To determine whether a burst belongs to one class or the other, one method that has been suggested is spectral lag analysis (e.g., Ukwatta et al. 2012; Gehrels et al. 2006; Norris et al. 2000). Another option is to apply statistical tools to the $n$-dimensional data set and classify a GRB as short- or long-duration by using cluster analysis (e.g., Everitt et al. 2011). We use the observed $T_{90}$, 15–150 keV fluence, and $\gamma$ (all normalized) to span a three-dimensional space. We then run a hierarchical cluster analysis with centroid linkage on this data set. Besides the outliers, which consist of GRB 060202B, which has an extremely soft 15–150 keV X-ray spectrum (Aharonian et al. 2009), and GRB 060218, which is the low-luminosity burst associated with supernova SN 2006aj (Soderberg et al. 2006), we see two main groups: group 1, with 685 members, and group 2, consisting of 55 members—all short GRBs. There is a small third group that consists of GRBs 050416A, 050819, 050824, 060428B, 061218, 080520, and 130608A. All these bursts are X-ray flashes (XRFs; e.g., Sakamoto et al. 2008). This group has previously been suggested to be an intermediate-duration GRB group by, e.g., Mukherjee et al. (1998) and Veres et al. (2010). Figure 29 displays where these GRB groups appear in $T_{90}$–$\Gamma$, $T_{90}$–fluence, and $\Gamma$–fluence diagrams. These suggest that there is still some overlap between the groups, although the XRFs (group 3) are clearly distinct in the $T_{90}$–$\Gamma$ and $\Gamma$–fluence diagrams. However, these diagrams are merely two-dimensional projections of the three-dimensional space spanned by $T_{90}$, $\Gamma$, and the 15–150 keV fluence. To really see if the three groups are disjoint, we need to perform an axis transformation in the same way as was done for the PCA. Therefore, we performed a PCA in the three-parameter space and calculated the first two eigenvectors for each burst. This is shown in Figure 30.
Clearly, short and long GRBs and XRFs occupy different areas in this diagram: short GRBs have low eigenvector 1 and high eigenvector 2. XRFs, on the other hand, have very high values of eigenvector 2. We can use this diagram to determine whether a burst with a borderline $T_{90}$ is a short- or a long-duration GRB. In Appendix F, we give the equations to determine where on the eigenvector 1–eigenvector 2 diagram (Figure 30) a burst lies based on its observed BAT properties.

What this analysis also shows is that GRB 050724 and GRB 051221A, previously considered to be short bursts (e.g., Grupe et al. 2006 and Burrows et al. 2006), respectively) are long GRBs. Other GRBs that were considered short bursts in our previous analysis using the 2 s cutoff line are GRBs 070809, 071227, 080426, 080905, 081024, 090426, 100724A, 120403A, and 121226A. These bursts, however, need to be classified as long GRBs. On the other hand, our analysis also found two short GRBs with observed $T_{90}$’s of 2.6 and 5.2 s, GRB 081016B and GRB 110726A, respectively, although these are significantly longer than the 0.8 s suggested from our analysis and consistent with the results of Bromberg et al. (2013). These can be classified as short bursts because of their low fluences, of order $10^{-7}$ erg cm$^{-2}$, and hard X-ray spectra, with $\Gamma = 0.79$ and $\Gamma = 0.64$, respectively.

### 4.5. Luminosity Functions

We noticed a steepening of the slope for the higher luminosity part of the luminosity function with increasing redshift. However, one must be very careful in drawing conclusions from this findings. The redshift distribution of GRBs is strongly biased against high-redshift bursts as a result of selection effects. As mentioned above, bursts without redshift measurements are drawn from a fainter population than bursts with redshift measurements. As also pointed out by Salvaterra et al. (2012), the Swift redshift sample is far from being complete. To obtain a complete sample, they proposed using only bursts with high peak photon flux in the BAT band. This is not the case for all Swift bursts with redshift measurements. Because we do have a bias against GRBs with low fluence, the sample of bursts with redshift measurements is biased against high-redshift bursts because of their typically lower fluence.

While the selection effect of GRBs with redshift measurements can explain the steep decay in the GRB rate at higher redshifts shown in Figure 22, it does not explain the lower rate of bright GRBs in the low-redshift universe. The smaller comoving volume for the universe with $z < 1$ may explain part of this effect, but not the whole picture. The comoving volume of the universe with $z < 1$ is 153 Gpc$^3$; it is 453 Gpc$^3$ in the redshift interval between $z = 1$ and $z = 2$, and about 250 Gpc$^3$ in the intervals from $z = 2$ to $z = 4$ in $z = 0.5$ bins. Another effect may be that of metallicity and the evolution of the star formation rate. As shown by Grieco et al. (2012), the star formation rate in spiral galaxies peaks at a redshift of about 3, which is consistent with the GRB rate shown in Figure 22. The conclusion here is that in the local universe, only a small number of very massive stars is formed that will end up as GRBs, while at earlier epochs the rate of very massive stars was been higher.

### 4.6. Redshift Predictions for Swift-detected GRBs

Last but not least, we raise the question whether we can make rough predictions of X-ray light curve behavior based on prompt emission properties. Can we use any relation between observed burst properties and redshift to make predictions about the possible redshift of a burst? We initially did this with the relation we found for excess absorption in the X-ray afterglow spectrum (Grupe et al. 2007): GRBs with high excess absorption column density above the Galactic value are low-redshift bursts. We found similar relations between the BAT photon index $\Gamma_{BAT}$ and the observed 15–150 keV fluence and redshift: GRBs with steep $\Gamma_{BAT}$ (>$2.0$) and high fluence (>10$^{-5}$ erg s$^{-1}$ cm$^{-2}$) are only seen in bursts with redshifts $z < 4$. Again, we can only discriminate low-redshift GRBs by their observed properties. One step further is the method described at the end of Section 3.6, where we used a PCA to determine an eigenvector 1 for a burst (see also Appendix E) based on the observed BAT parameters $T_{90}$, fluence, and $\Gamma$. There is still strong scatter in this relation, which still needs independent redshift discriminators.

As shown in Section 4.1, the relations between the energy/luminosity of a GRB’s prompt emission and the decay slopes in the X-ray afterglow light curves are most promising. This, however, requires that a burst be observed until the decay slopes can be measured, which typically means at least several hours after the burst for the plateau phase at a minimum. So far, no secure discriminator has been found for high-redshift bursts. Our plan is to apply machine learning techniques to the data set in order to obtain better redshift predictions based on observed GRB properties measured from Swift data, similar to what has been done by Morgan et al. (2012). What is really needed is a relation between a redshift-independent parameter such as $\Gamma$ and redshift-dependent parameters such as energy and luminosity.

### 5. CONCLUSIONS

The main result of our statistical study of Swift-discovered GRBs is new evidence that the GRB prompt and afterglow emissions are linked. This is supported by the following findings:

1. The BAT $T_{90}$ and the break times in the X-ray light curve before and after the plateau phase are strongly correlated (Section 3.3). Bursts with longer $T_{90}$ tend to show later breaks in their X-ray afterglow light curves. This is a statistically highly significant result, suggesting a physical
relationship between the high-energy prompt and soft X-ray afterglow emission. These correlations appear to be strong in the observed frame as well as the rest frame.

2. The hard X-ray photon index $\Gamma$ of the prompt emission is strongly anticorrelated with the decay slopes in the X-ray afterglow light curves. The observed fluence in the 15–150 keV BAT energy range anticorrelates with the decay slopes in X-rays. Together with the $T_{90}-T_{\text{break}}$ correlation, these relations can be used to predict the behavior of the X-ray afterglow with a canonical light curve based on prompt emission parameter measurements.

3. A PCA shows that the prompt and afterglow emissions are driven primarily by the burst luminosity, isotropic energy release, or both (Sections 3.4 and 4.3).

4. A cluster analysis of the observed BAT parameters shows that short and long GRBs can be well separated and that the dividing line between short- and long-duration GRBs detected by BAT is less than 1 s. We also identified a third group in the cluster analysis: XRFs.

5. The large number of Swift-detected bursts with redshift measurements allows GRB cosmology (Sections 3.5 and 4.5). Analysis of the GRB luminosity function at different redshift intervals shows that the slope of the high-luminosity end of the luminosity function becomes steeper with increasing redshift. The density of high-luminosity ($L > 10^{52}$ erg s$^{-1}$) GRBs peaks at about $z = 3$, and the results suggest a “cosmic downsizing” of GRBs at lower redshifts, similar to what has been observed for quasars. The peak of the GRB density agrees with the peak of the cosmic quasar density and the star formation rate history, suggesting a close connection between GRBs and star formation and quasar evolution.

6. The detection of a GRB strongly depends on the BAT detector characteristics (Section 3.2). This is due primarily to a combination of burst length and fluence. We cannot detect very long bursts with low fluence.

7. Observed BAT parameters can be used to obtain a rough estimate of a burst’s redshift.

The statistical analysis presented in this paper can only be the beginning of data-mining the rich Swift GRB data set. In the future, we need to look into analysis of the data sets including survival statistics to take upper and lower limits, e.g., for the break times in the X-ray light curves, into account. Another important task for the future will be to develop a support vector machine analysis that will allow predictions to be made about the X-ray afterglow light curve and its behavior based on prompt emission properties. Last but not least, we need to examine the possibility of predicting estimated redshifts, similar to what has been done by Morgan et al. (2012). Ultimately it is important that ground-based observers increase the number of afterglows for which spectroscopic data are obtained, to measure redshifts. Only with redshifts and therefore distance measurements will we be able to derive the intrinsic physical properties of the bursts.

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### APPENDIX A

### GRB CATALOG

Here we present the catalog of our sample of 754 Swift BAT onboard-detected GRBs. The ASCII file of the catalog is available as a machine-readable file on the Astrophysical Journal Supplement Web site linked to this paper. A summary explanation of the ASCII file is given in Table 9. A more detailed explanation of all parameters used in this paper is given in Appendix B.

### Table 9

| GRB Name | BAT trigger number | Redshift of the GRB | Observed BAT 15–150 keV $T_{90}$ | $T_{\text{break}}$ uncertainty | Fluence in the 15–150 keV BAT band | Uncertainty in the 15–150 keV BAT fluence | BAT 15–150 keV photon index $\Gamma$ | Uncertainty of the BAT 15–150 keV photon index $\Gamma$ | Peak break energy in keV at high energies, $E_{\text{peak}}$ | Uncertainty in $E_{\text{peak}}$ |
|----------|--------------------|---------------------|---------------------------------|-------------------------------|-----------------------------------|---------------------------------|----------------------------------|---------------------------------|----------------------------------|-----------------|
| Notes.   | $k$-corrected energy in the 15–150 keV BAT band$^a$ given in units of erg $k$-corrected luminosity in the 15–150 keV BAT band$^b$ given in units of erg s$^{-1}$ Galactic absorption column density (Kalberla et al. 2005) Free fit absorption column density$^b$ Negative uncertainty in the free fit Positive uncertainty in the free fit Absorption column density at the redshift of the burst Negative uncertainty in absorption column density at the redshift of the burst Positive uncertainty in absorption column density at the redshift of the burst 0.3–10 keV energy spectral index, $\beta_X$ Negative uncertainty in $\beta_X$ Positive uncertainty in $\beta_X$ X-ray light curve break time before the plateau phase, $T_{\text{break}1}$ Uncertainty in $T_{\text{break}1}$ X-ray light curve break time after the plateau phase, $T_{\text{break}2}$ Uncertainty in $T_{\text{break}2}$ X-ray light curve decay slope during the plateau phase, $\alpha_{X3}$ Uncertainty in $\alpha_{X3}$ X-ray light curve decay slope during the plateau phase, $\alpha_{X3}$ Uncertainty in $\alpha_{X3}$ |

$^a$ The $k$-corrected energy and luminosity are based on the $k$-corrected fluence following the standard $k$-correction by Oke & Sandage (1968): $\text{Fluence}_{\text{cor}} = \frac{\text{Fluence}_{\text{obs}}}{{1 + z}^{-1}}$.

$^b$ The excess absorption above the Galactic value is then given by $N_{\text{H}} = N_{\text{H,fit}} - N_{\text{H,gal}}$.

(This table is available in its entirety in a machine-readable form in the online journal. A portion is shown here for guidance regarding its form and content.)
Figure 31. Distributions of the 15–150 keV BAT photon index (top) and the 0.3–10 keV XRT energy spectral slope $\beta_X$ (bottom). As in Figure 2, the histogram, box plot, and Q–Q plot are shown. In the box plots, short bursts are displayed on top, long bursts in the middle, and all bursts on the bottom.

(A color version of this figure is available in the online journal.)

APPENDIX B
EXPLANATION OF PARAMETERS

In this Appendix, we explain the parameters used in this paper and how they were derived. For this purpose, we follow the order in the GRB catalog, Table 9.

Redshift $z$ The redshifts prior to 2012 were taken primarily from the GRB redshift catalogs by Fynbo et al. (2009), Jakobsson et al. (2012), and Krühler et al. (2012). All other redshift measurements were taken from GCN Circulars.

$T_{90}$ The time in which 90% of the energy is released in the prompt emission. The $T_{90}$ used in this paper is the time measured in the observed 15–150 keV band in the Swift BAT.

$T_{90,z}$ Rest-frame $T_{90}$, i.e., $T_{90,z} = T_{90}/(1 + z)$.

Fluence The fluence in the observed 15–150 keV BAT band.

Fluence$_k$ The $k$-corrected fluence, $\text{Fluence}_k = \text{Fluence}_{\text{obs}} \times (1 + z)^2 \Gamma$.

$\Gamma$ Photon index of the hard X-ray spectrum in the observed 15–150 keV band.

$E_{\text{peak}}$ Peak energy of the hard energy spectrum derived from a Band function (Band et al. 1993). We took $E_{\text{peak}}$ from GCN Circulars. Before the launch of Fermi, $E_{\text{peak}}$ was primarily measured by the Konus instrument on Wind. After the Fermi launch, we primarily relied on measurements from its GBM instrument.

$E_{\text{peak},z}$ Rest-frame peak energy, $E_{\text{peak},z} = E_{\text{peak}} \times (1 + z)$.

$E_{15–150\text{keV}}$ The $k$-corrected energy in the 15–150 keV BAT band, assuming an isotropic energy release.

$L_{15–150\text{keV}}$ The $k$-corrected luminosity in the 15–150 keV BAT band assuming isotropic energy release, $L_{15–150\text{keV}} = E_{15–150\text{keV}} / T_{90,z}$.

$N_{\text{H,gal}}$ Galactic absorption column density derived from the H1 maps by Kalberla et al. (2005). Throughout the paper, the Galactic $N_{\text{H}}$ is given in units of $10^{20} \text{cm}^{-2}$.

$N_{\text{H,fit}}$ Free-fit absorption column density. This was derived when the 0.3–10 keV X-ray spectrum could not be fitted with just the Galactic value.

$\Delta N_{\text{H}}$ Excess absorption density as explained in Grupe et al. (2007), with $\Delta N_{\text{H}} = N_{\text{H,fit}} - N_{\text{H,gal}}$.

$N_{\text{H,b}}$ Absorption column density at the redshift of the burst. These column densities were derived with a power-law fit to the 0.3–10 keV X-ray spectrum plus an absorption parameter fixed to the Galactic value.

$\beta_X$ X-ray energy spectral index in the observed 0.3–10 keV band, with $\nu F_\nu \propto \nu^{-\beta}$.

$T_{\text{break1}}$ Observed break time in the X-ray afterglow light curve before the plateau phase.
Figure 32. Same as Figure 31, but for the observed (top) and k-corrected (bottom) 15–150 keV fluence in the BAT band in units of erg cm$^{-2}$.

(A color version of this figure is available in the online journal.)

$T_{\text{break2}}$ Observed break time in the X-ray afterglow light curve after the plateau phase.

$T_{\text{break1}, z}$ Break time in the rest frame in the X-ray afterglow light curve before the plateau phase, $T_{\text{break1}, z} = T_{\text{break1}}/(1 + z)$.

$T_{\text{break2}, z}$ Break time in the rest frame in the X-ray afterglow light curve after the plateau phase, $T_{\text{break2}, z} = T_{\text{break2}}/(1 + z)$.

$\alpha_{X2}$ Decay slope of the plateau phase of the X-ray afterglow light curve in the 0.3–10 keV band, with $\nu F_\nu \propto \nu^{-\alpha_2}$.

$\alpha_{X3}$ Decay slope of the normal decay phase of the X-ray afterglow light curve in the 0.3–10 keV band, with $\nu F_\nu \propto \nu^{-\alpha_3}$.

$Fluence_{0.3-10\text{keV}}$ Fluence in the observed 0.3–10 keV band during the plateau phase. This was determined by integrating over the afterglow 0.3–10 keV flux light curve from the beginning of the plateau phase, $T_{\text{break1}}$, to the end, $T_{\text{break2}}$.

APPENDIX C
ADDITIONAL DISTRIBUTIONS

In this Appendix, we present additional distributions of GRB parameters observed by Swift that were not shown in Section 3.1. As mentioned there, we applied statistical visualization tools to the data sets that are common in data mining.

1. The left panels display histograms with the kernel density estimator (solid curves) of the distributions. The bottom of these plots shows the distribution of the real values of the relevant property.

2. The middle plots show box diagrams for each property for short, long, and all GRBs (top to bottom). The boxes are centered on the mean and indicate the median and quartiles; the “whiskers” extend to the minimum and maximum values of the distribution or 1.5 times the interquartile range (between the first and third quartile, so basically the 95% confidence level), whichever comes first. Values beyond the “whiskers” are outliers and are displayed as circles.

3. The right panels display quartile–quartile (Q–Q) plots. These make it easy to identify how well (or poorly) a distribution agrees with a Gaussian distribution, shown as solid lines in these plots. The dashed lines mark the region of 95% confidence.

More information about these tools can be found in, e.g., Feigelson & Babu (2012), Torgo (2011), and Crawley (2007).
in the 15–150 keV range of $\Gamma = 0.94$, while long GRBs have median $\Gamma = 1.56$. Note that although $T_{90}$ and 15–150 keV fluence measurements exist for all the bursts, three early bursts (GRBs 041219A, B, and C) did not have any spectral data available. In addition, GRB 120401 came into the BAT field of view during a slew, and therefore $T_{90}$ and the fluence could not be measured (Palmer et al. 2012). In the 0.3–10 keV X-ray band, however, the spectral slopes of the X-ray afterglows of short and long GRBs are similar, with median values of $\beta_X = 0.82$ and $\beta_X = 0.99$, respectively. As noted by O’Brien et al. (2006) from a sample of 40 early Swift bursts, the spectral slope of the afterglow data appears to be softer as compared with the 15–150 keV slope during the prompt emission.

Figure 32 shows the distributions of the observed and $k$-corrected 15–150 keV fluences; the objects with the lowest flux are short-duration bursts. As we discussed in Section 3.2, this is the result of a selection effect: we cannot detect long bursts with low fluence, because their signals will be dominated by detector background. Bursts with low fluence therefore must emit their energy in a short amount of time to be detected. Similar to these distributions are the distributions of the rest-frame 15–150 keV $k$-corrected luminosity and the isotropic energy, shown in Figure 33.

The distributions of the peak energies $E_{\text{peak}}$ in the observed and rest frames are shown in Figure 34. As expected from the $E_{\text{peak}}-\Gamma$ anticorrelation found by Sakamoto et al. (2009), short GRBs, which have flatter hard X-ray spectra than long-duration GRBs, tend to have very high peak energies. In fact, the burst with the highest $E_{\text{peak}, z}$ in our sample is the short GRB 090510, which was also detected in the Fermi Large Area Telescope (e.g., Abdo et al. 2009; De Pasquale et al. 2010; Racusin et al. 2011). Note, however, that there are only six short bursts with redshifts and $E_{\text{peak}}$ measurements.

APPENDIX D
ADDITIONAL CORRELATION ANALYSIS

In this Appendix, we describe those correlations that were not discussed in Section 3.3. We also list Kendall and Pearson correlation coefficients in addition to the Spearman rank order analysis discussed in Section 3.3. The numbers of correlation parameter pairs are the same as listed for the Spearman rank order correlations in Table 2 for the entire sample and in Table 3 for the sample GRBs with spectroscopic redshifts. These tables, Kendall’s $\tau$ and probability are listed above the diagonal, and the Pearson correlation coefficient and probability are listed below. Table 10 lists the Kendall $\tau$ values and Pearson correlation coefficients for all GRBs, and Table 11 is for those GRBs with spectroscopic redshift measurements.

Somewhat expected are correlations among afterglow parameters. As can be seen from Table 2, we find clear correlations between the break times before and after the plateau phase ($P < 10^{-3}$) and between the decay slopes $\alpha_{X2}$ and $\alpha_{X3}$ during the plateau and the normal afterglow decay phase ($P < 10^{-3}$). These two relations are displayed in Figures 35 and 36, respectively. The $T_{\text{break}, 1}-T_{\text{break}, 2}$ relation is shown for the
Table 10
Kendall’s τ and Pearson Correlation Coefficients and Probabilities for the Observed Parameters of All GRBs

|                  | $\Gamma_{\text{BAT}}$ | $\beta_X$ | $\alpha_{X2}$ | $\alpha_{X3}$ | $T_{90}$ | $T_{\text{break}1}$ | $T_{\text{break}2}$ | 15–150 keV Fluence |
|------------------|------------------------|-----------|---------------|---------------|----------|---------------------|---------------------|-------------------|
| $\Gamma_{\text{BAT}}$ | ⋯                      | 0.123, $4.76 \times 10^{-6}$ | $-0.176, <10^{-8}$ | $-0.215, <10^{-8}$ | $+0.054, 0.0271$ | $+0.048, 0.1676$ | $+0.083, 0.0117$ | $-0.1025, 2.89 \times 10^{-5}$ |
| $\beta_X$        | $+0.254, <10^{-8}$     | ⋯         | $-0.103, 4.17 \times 10^{-4}$ | $-0.116, 1.88 \times 10^{-4}$ | $+0.021, 0.4317$ | $-0.049, 0.1504$ | $+0.1106, 7.95 \times 10^{-4}$ | $+0.006, 0.817$ |
| $\alpha_{X2}$    | $-0.228, 8.31 \times 10^{-8}$ | $-0.161, 1.70 \times 10^{-4}$ | ⋯ | $+0.279, <10^{-8}$ | $+0.144, 6.49 \times 10^{-7}$ | $-0.023, 0.5057$ | $+0.1725, 1.79 \times 10^{-7}$ | $+0.1831, <10^{-8}$ |
| $\alpha_{X3}$    | $-0.229, 4.62 \times 10^{-7}$ | $-0.128, 0.0052$ | $+0.234, 1.48 \times 10^{-6}$ | ⋯ | $+0.1841, <10^{-8}$ | $+0.086, 0.0339$ | $+0.163, 8.46 \times 10^{-7}$ | $+0.1547, 5.18 \times 10^{-7}$ |
| $T_{90}$         | $+0.162, 8.16 \times 10^{-6}$ | $-0.005, 0.905$ | $+0.212, 7.33 \times 10^{-7}$ | $-0.045, 0.325$ | ⋯ | $+0.223, <10^{-8}$ | $+0.348, <10^{-8}$ | $+0.481, <10^{-8}$ |
| $T_{\text{break}1}$ | $+0.033, 0.5218$ | $-0.059, 0.2451$ | $+0.010, 0.852$ | $+0.075, 0.2143$ | $+0.296, <10^{-8}$ | ⋯ | $+0.360, <10^{-8}$ | $-0.042, 0.2169$ |
| $T_{\text{break}2}$ | $+0.088, 0.0744$ | $+0.166, 6.91 \times 10^{-4}$ | $+0.272, 272 \times 10^{-8}$ | $+0.055, 0.2595$ | $+0.526, <10^{-8}$ | $+0.531, <10^{-8}$ | ⋯ | $+0.126, 1.25 \times 10^{-3}$ |
| 15–150 keV fluence | $-0.1007, 0.0058$ | $-0.055, 0.165$ | $+0.261, <10^{-8}$ | $-0.019, 0.6741$ | $+0.715, <10^{-8}$ | $-0.016, 0.7498$ | $+0.235, 1.20 \times 10^{-6}$ | ⋯ |

Notes. Kendall’s τ and Pearson correlation coefficients and probabilities are listed above and below the diagonal, respectively. The numbers of parameter pairs are given in Table 2.
Table 11
Kendall’s $\tau$ and Pearson Correlation Coefficients and Probabilities for GRBs with Spectroscopic Redshifts

| $t_{\text{BAT}}$ | $\beta_\text{X}$ | $\phi_\text{X}$ | $\phi_{\text{X}3}$ | $T_{0,\alpha}$ | $T_{\text{break1,}x}$ | $T_{\text{break2,}x}$ | $L_{15-190 \text{ keV}}$ | $E_{\text{iso}}$ | $E_{\text{peak,}x}$ |
|----------------|---------------|----------------|-----------------|-------------|------------------|------------------|-----------------|-------------|----------------|
| $t_{\text{BAT}}$ | 0.140, 1.10 $\times 10^{-3}$ | -0.186, 7.53 $\times 10^{-3}$ | -0.189, 1.35 $\times 10^{-3}$ | 0.069, 0.117 | 0.032, 0.2054 | 0.107, 0.0306 | 0.2655, $\times 10^{-8}$ | -0.266, $\times 10^{-8}$ | -0.301, 6.31 $\times 10^{-6}$ |
| $\beta_\text{X}$ | +0.228, 8.82 $\times 10^{-4}$ | -0.122, 0.0189 | -10.1809, 2.58 $\times 10^{-4}$ | 0.050, 0.257 | 0.074, 0.1915 | 0.182, 3.88 $\times 10^{-4}$ | -0.090, 0.0443 | -0.060, 0.0604 | -0.089, 0.1878 |
| $\phi_\text{X}$ | -0.248, 2.99 $\times 10^{-5}$ | -0.224, 0.0012 | -0.2189, 2.07 $\times 10^{-5}$ | 0.1235, 0.0084 | -0.0546, 0.4311 | 0.0633, 0.2149 | 0.0887, 0.0592 | 0.1627, 5.31 $\times 10^{-4}$ | 0.2267, 1.04 $\times 10^{-3}$ |
| $\phi_{\text{X}3}$ | -0.157, 0.1556 | -0.244, 7.34 $\times 10^{-4}$ | +0.202, 0.0074 | 0.1272, 0.0098 | -0.075, 0.2361 | 0.043, 0.4033 | -0.1180, 0.0256 | 0.2057, 2.97 $\times 10^{-3}$ | 0.1904, 0.0093 |
| $T_{\text{break1,}x}$ | +0.143, 0.0298 | +0.029, 0.6643 | +0.198, 0.0401 | +0.086, 0.2392 | ... | 0.251, 8.46 $\times 10^{-6}$ | 0.305, $\times 10^{-8}$ | -0.206, 3.09 $\times 10^{-6}$ | 0.130, 3.30 $\times 10^{-3}$ |
| $T_{\text{break2,}x}$ | +0.050, 0.5524 | +0.079, 0.3449 | -0.023, 0.7824 | -0.101, 0.2836 | +0.362, 8.01 $\times 10^{-6}$ | 0.432, $\times 10^{-8}$ | -0.409, 1.31 $\times 10^{-8}$ | -0.337, 0.2923 | -0.089, 0.2923 |
| $L_{15-190 \text{ keV}}$ | +0.160, 0.03398 | +0.355, 7.67 $\times 10^{-6}$ | +0.103, 0.175 | +0.070, 0.3535 | +0.450, $\times 10^{-8}$ | +0.615, $\times 10^{-8}$ | -0.285, 2.05 $\times 10^{-8}$ | -0.151, 0.0100 | -0.106, 0.1599 |
| $E_{\text{iso}}$ | -0.343, 9.01 $\times 10^{-8}$ | -0.129, 0.0512 | +0.110, 0.1154 | +0.058, 0.4289 | -0.238, 2.65 $\times 10^{-4}$ | -0.574, $\times 10^{-8}$ | -0.439, $\times 10^{-8}$ | 0.664, $\times 10^{-8}$ | 0.293, 1.19 $\times 10^{-3}$ |
| $E_{\text{peak,}x}$ | -0.256, 8.34 $\times 10^{-5}$ | -0.113, 0.0886 | +0.222, 1.3 $\times 10^{-3}$ | +0.110, 0.133 | +0.323, 5.33 $\times 10^{-7}$ | -0.415, 2.45 $\times 10^{-7}$ | -0.207, 0.0060 | +0.843, $\times 10^{-8}$ | ... |

Notes. Kendall’s $\tau$ and Pearson correlation coefficients and probabilities are listed above and below the diagonal, respectively. The numbers of parameter pairs are given in Table 3.
observed as well as the rest-frame times. For the observed break times, we found $r_s = 0.517$ and $T_b = 10.020$ (277 GRBs), and $r_s = 0.620$ and $T_b = 8.463$ (117 GRBs) for the rest-frame times. In both cases, the probability of a random result is $P < 10^{-8}$. Significant correlations exist between the decay slope during the plateau phase $\alpha_{X2}$ and the observed break time before the plateau phase, $T_{\text{break,2}}$, with $r_s = +0.254$, $T_b = +5.320$, and $P = 1.75 \times 10^{-7}$ (414 GRBs), and between the decay slope of the “normal” decay slope $\alpha_{X3}$ and the observed break time before the plateau phase, with $r_s = +0.231$, $T_b = +4.825$, and $P = 2.0 \times 10^{-6}$ (414 GRBs). Note that these correlations disappear in the rest frame (Table 3).

As shown by Sakamoto et al. (2009), there is a clear anticorrelation between the photon index in the BAT spectrum and the peak energy in the spectrum $E_{\text{peak}}$, with a relation $\log E_{\text{peak}} = 3.258 - 0.829 \times \Gamma$. Especially since the launch
of Fermi with its all-sky monitor GBM, the number of GRBs with $E_{\text{peak}}$ measurements has significantly increased. While the pre-Fermi sample in Sakamoto et al. (2009) contained 55 bursts with $E_{\text{peak}}$ measurements, our sample has measurements of 201 such bursts (including those presented in Sakamoto et al. (2009)), of which 188 are long GRBs. This relation is displayed in the left panel of Figure 37. Of these bursts, 103 have spectroscopic redshift measurements. We obtained a regression fit for the long GRBs and found the following relations for the observed and rest-frame $E_{\text{peak}}$ values with $\Gamma$, respectively: $\log E_{\text{peak}} = (2.91 \pm 0.12) - (0.49 \pm 0.08) \times \Gamma$ and $\log E_{\text{peak}, z} = (3.32 \pm 0.16) - (0.43 \pm 0.11) \times \Gamma$. The rest-frame is shown in the right panel of Figure 37. In both cases, there is a clear anticorrelation between the two properties, with $r_s = -0.462$, $T_z = -7.455$, $P < 10^{-8}$ and $r_s = -0.416$, $T_s = -4.625$, $P = 1.10 \times 10^{-5}$ for the observed and rest-frame $E_{\text{peak}}$, respectively (206 and 104 GRBs respectively). The solid lines in these plots display the relations between $E_{\text{peak}}$ and $\Gamma$ that we found for our Swift GRB sample, and the dotted lines show the relation found by Sakamoto et al. (2009).

The best-known relationships for the peak energy $E_{\text{peak}}$ are those between the isotropically radiated energy $E_{\text{iso}}$ and the collimation-corrected energy $E_x$: the Amati and Ghirlanda relations, respectively (Amati et al. 2002; Ghirlanda et al. 2004). Similar to these is the $E_{\text{peak}}$–$L_{\text{iso}}$ relation found by Yonetoku et al. (2004) from BATSE-detected bursts. Schaefer (2007) previously found this relation for pre-Swift bursts; however, it has also been found in Swift-detected bursts, as reported by (Nava et al. 2012), who used 58 bursts with photon peak fluxes in the 15–150 keV BAT energy window with a photon peak flux of at least 2.6 photons cm$^{-2}$ s$^{-1}$. We found a similar correlation between the rest-frame $E_{\text{peak}}$, and the prompt emission luminosity and isotropic energy $E_{\text{iso}}$, as displayed in Figure 38. These correlations (103 long GRBs) are quite tight, with $r_s = 0.426$, $T_z = 4.735$, and $P = 7.0 \times 10^{-6}$ for the luminosity and $r_s = 0.459$, $T_z = 5.187$ with $P = 1.07 \times 10^{-6}$ for $E_{\text{iso}}$.

The question now is whether $E_{\text{peak}, z}$ also correlates with other burst properties. What we found is that among the long bursts, there is a correlation between $E_{\text{peak}, z}$ and the decay slope during the plateau phase, $\alpha_{x2}$, with $r_s = 0.344$, $T_z = 3.470$, and $P = 7.94 \times 10^{-4}$ (92 GRBs), as shown in Figure 39. This again demonstrates a clear connection between prompt and afterglow emission properties: bursts with steeper decay slopes during the plateau phase exhibit higher peak energies in the rest frame, $E_{\text{peak}, z}$, than bursts with flatter decay slopes. All other properties, such as $\beta_X$ and $\alpha_{X3}$, fail to show any significant correlation with $E_{\text{peak}}$. The relations between the $k$-corrected 15–150 keV luminosity and the spectral slope in the BAT band $\Gamma_{\text{BAT}}$ and the X-ray spectral slope of the afterglow emission are displayed in Figure 40 (top). While there is no correlation with $\beta_X$, there is a strong correlation with the photon index $\Gamma_{\text{BAT}}$. Here we find an anticorrelation for the long bursts, with $r_s = -0.457$, $T_z = -7.519$, and a probability $P < 10^{-8}$ (216 GRBs). In other words, bursts with steep BAT photon indices tend to be less luminous than bursts with flatter $\Gamma_{\text{BAT}}$. Note that short-duration GRBs do not follow this anticorrelation. Table 3 lists the correlations for all bursts, including short bursts. The anticorrelation between $\Gamma$ and $E_{\text{peak}}$ becomes slightly weaker when all GRBs are considered. Although this anticorrelation is a relation between a redshift-dependent parameter ($\Gamma$) and a redshift-independent property ($E_{\text{peak}}$), it is a useful tool for understanding the correlation between the prompt and afterglow emission properties of GRBs.

![Figure 36](image-url) Correlation between decay slopes during the plateau phase, $\alpha_{x2}$, and during the “normal” decay phase, $\alpha_{x3}$. The error bars at upper left show the median uncertainty of each property. (A color version of this figure is available in the online journal.)

![Figure 37](image-url) Correlations between the BAT 15–150 keV $\Gamma$ and the peak energy $E_{\text{peak}}$ in the observed (left) and rest (right) frames. The dotted lines display the relation found by Sakamoto et al. (2009), and the thick solid lines show the relation found by us (see Appendix D). (A color version of this figure is available in the online journal.)
parameter \((L_{15-150\text{ keV}})\), GRBs still cannot be used as standard candles. Not only is the scatter in the relation quite large, but \(L_{15-150\text{ keV}}\) is not independent of \(\Gamma\), because we used \(\Gamma\) as an input parameter in the \(k\)-correction.

We next see how \(\Gamma\) and \(\beta_X\) depend on the 15–150 keV energy release. These relations are displayed in the middle panels of Figure 40, where \(\Gamma\) anticorrelates strongly with the isotropic energy in the 15–150 keV band \(E_{15-150\text{ keV}}\) \((r_s = -0.492, T_s = -8.268, P < 10^{-8})\) for the 216 long GRBs. Again, as listed in Table 2, the relation becomes weaker for all GRBs. As for the 0.3–10 keV spectral slope \(\beta_X\), there is only a weak trend, with \(r_s = -0.177, T_s = -2.634,\) and \(P = 0.0090\) for the long GRBs (215).

Figure 41 displays the relation between the rest-frame \(T_{90,z}\) and the luminosity in the 15–150 keV band. For the whole GRB sample, we found \(r_s = -0.290\) and \(T_s = -4.580\) with
a probability $P = 8.41 \times 10^{-6}$ (231 GRBs). However, if we look only at the long GRBs in the sample with spectroscopic redshifts (216 GRBs), this correlation becomes even stronger, with $r_s = -0.420$, $T_s = -6.777$, and $P < 10^{-8}$. This relation suggests a strong anticorrelation, with high-luminosity bursts having shorter $T_{90}$. However, it should be kept in mind that the luminosity and $T_{90}$ are not independent parameters. The luminosity was calculated as $L = E/T_{90}$, so bursts with longer $T_{90}$ will have lower luminosities if we assume that their isotropic energies are somewhat similar. Although the $T_{90}$–luminosity relation looks like a significant correlation, it may not be a physical relation. If more energetic bursts really have shorter $T_{90}$, then we should expect such a relation between the isotropic energy in the 15–150 keV band and $T_{90}$. This is, however, a weak correlation, with $r_s = +0.197$, $T_s = 3.044$, and probability $P = 2.60 \times 10^{-3}$ of being a random distribution. This relation, moreover, is driven by the short bursts. When considering only long bursts, the correlation disappears completely.
APPENDIX E

REDSHIFT ESTIMATE BASED ON BAT PARAMETERS

In Section 3.6, we showed that it may be possible to determine the 15–150 keV $E_{iso}$ based on the observed Swift BAT parameters. The relations from the PCA described in Section 3.6 are shown in the diagram of eigenvector 1 versus $E_{iso}$, Figure 28. In order to place a new GRB onto this diagram, we provide the equations for the normalized BAT parameters $T_{90}$, $\Gamma$, and fluence:

$$\log T_{90,\text{norm}} = (\log T_{90} - 1.636871)/0.557497, \quad (E1)$$

$$\Gamma_{\text{norm}} = (\Gamma - 1.643410)/0.4071438, \quad (E2)$$

$$\log \text{Fluence}_{\text{norm}} = (\log \text{Fluence} + 5.650423)/0.5962325. \quad (E3)$$

Now we can calculate eigenvector 1 based on the PCA performed on the long GRBs with spectroscopic redshift measurements:

$$\text{eigenvector 1} = -0.558370 \times T_{90,\text{norm}} + 0.455017 \times \Gamma_{\text{norm}} - 0.693674 \times \text{Fluence}_{\text{norm}}. \quad (E4)$$

APPENDIX F

SEPARATING SHORT- AND LONG-DURATION GRBs

In this Appendix we give the equations that will allow the reader to place a new GRB in the eigenvector 1–eigenvector 2 diagram, Figure 30. As described in Section 4.4, we first list the equation for the normalized $T_{90}$, $\Gamma$, and fluence:

$$\log T_{90,\text{norm}} = (\log T_{90} - 1.43508)/0.798325, \quad (F1)$$

$$\Gamma_{\text{norm}} = (\Gamma - 1.614035)/0.4201068, \quad (F2)$$

$$\log \text{Fluence}_{\text{norm}} = (\log \text{Fluence} + 5.919272)/0.6762907. \quad (F3)$$

Now we can calculate the eigenvectors:

$$\text{eigenvector 1} = 0.714278 \times T_{90,\text{norm}} + 0.06593 \times \Gamma_{\text{norm}} + 0.696829 \times \text{Fluence}_{\text{norm}}, \quad (F4)$$

$$\text{eigenvector 2} = 0.120528 \times T_{90,\text{norm}} + 0.969348 \times \Gamma_{\text{norm}} - 0.214095 \times \text{Fluence}_{\text{norm}}. \quad (F5)$$

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