

## TESTING THE $E_{\text{peak}}-E_{\text{iso}}$ RELATION FOR GRBs DETECTED BY *SWIFT* AND *SUZAKU*-WAM

H. A. KRIMM<sup>1,2</sup>, K. YAMAOKA<sup>3</sup>, S. SUGITA<sup>3,4</sup>, M. OHNO<sup>5</sup>, T. SAKAMOTO<sup>1,6</sup>, S. D. BARTHELMY<sup>7</sup>, N. GEHRELS<sup>7</sup>, R. HARA<sup>8</sup>,  
J. P. NORRIS<sup>9</sup>, N. OHMORI<sup>8</sup>, K. ONDA<sup>10</sup>, G. SATO<sup>5</sup>, H. TANAKA<sup>8</sup>, M. TASHIRO<sup>10</sup>, AND M. YAMAUCHI<sup>8</sup>

<sup>1</sup> CRESST and NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA

<sup>2</sup> Universities Space Research Association, 10211 Wincopin Circle, Suite 500, Columbia, MD 21044, USA

<sup>3</sup> Department of Physics and Mathematics, Aoyama Gakuin University, 5-10-1 Fuchinobe, Sagamihara, Kanagawa 229-8558, Japan

<sup>4</sup> Institute of Physical and Chemical Research (RIKEN), 2-1 Hirosawa, Wako, Saitama 351-0198, Japan

<sup>5</sup> Institute of Space and Astronautical Science/JAXA, 3-1-1 Yoshinodai, Sagamihara, Kanagawa 229-8510, Japan

<sup>6</sup> Joint Center for Astrophysics, University of Maryland, Baltimore County, 1000 Hilltop Circle, Baltimore, MD 21250, USA

<sup>7</sup> NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA

<sup>8</sup> Department of Applied Physics, University of Miyazaki, 1-1 Gakuen Kibanadai-nishi, Miyazaki-shi, Miyazaki 889-2192, Japan

<sup>9</sup> Department of Physics and Astronomy, University of Denver, 2112 East Wesley Ave. Room 211, Denver, CO 80208, USA

<sup>10</sup> Department of Physics, Saitama University, 255 Shimo-Okubo, Sakura-ku, Saitama-shi, Saitama 338-8570, Japan

Received 2009 April 30; accepted 2009 August 13; published 2009 October 2

### ABSTRACT

One of the most prominent, yet controversial associations derived from the ensemble of prompt-phase observations of gamma-ray bursts (GRBs) is the apparent correlation in the source frame between the peak energy ( $E_{\text{peak}}$ ) of the  $\nu F(\nu)$  spectrum and the isotropic radiated energy,  $E_{\text{iso}}$ . Since most GRBs have  $E_{\text{peak}}$  above the energy range (15–150 keV) of the Burst Alert Telescope (BAT) on *Swift*, determining accurate  $E_{\text{peak}}$  values for large numbers of *Swift* bursts has been difficult. However, by combining data from *Swift*/BAT and the *Suzaku* Wide-band All-Sky Monitor (WAM), which covers the energy range from 50 to 5000 keV, for bursts which are simultaneously detected, one can accurately fit  $E_{\text{peak}}$  and  $E_{\text{iso}}$  and test the relationship between them for the *Swift* sample. Between the launch of *Suzaku* in 2005 July and the end of 2009 April, there were 48 GRBs that triggered both *Swift*/BAT and WAM, and an additional 48 bursts that triggered *Swift* and were detected by WAM, but did not trigger. A BAT–WAM team has cross-calibrated the two instruments using GRBs, and we are now able to perform joint fits on these bursts to determine their spectral parameters. For those bursts with spectroscopic redshifts, we can also calculate the isotropic energy. Here, we present the results of joint *Swift*/BAT–*Suzaku*/WAM spectral fits for 91 of the bursts detected by the two instruments. We show that the distribution of spectral fit parameters is consistent with distributions from earlier missions and confirm that *Swift* bursts are consistent with earlier reported relationships between  $E_{\text{peak}}$  and isotropic energy. We show through time-resolved spectroscopy that individual burst pulses are also consistent with this relationship.

*Key words:* gamma rays: bursts

*Online-only material:* color figures

### 1. INTRODUCTION

The *Swift* gamma-ray burst explorer mission (Gehrels et al. 2004) has vastly increased the number of gamma-ray bursts (GRBs) for which X-ray and optical counterparts have been detected. This has led to a much larger sample of bursts for which a redshift is known or inferred. For the first 409 bursts that triggered *Swift*, 135 have a published redshift, compared with 42 redshifts before the advent of *Swift* (Jakobsson et al. 2006). This data set has allowed for the first time the use of GRBs as cosmological probes (e.g., Schaefer 2007). Once redshifts were known for a significant number of bursts, several authors derived relationships between various measured quantities of the prompt emission—most of these relationships involved relating the time-averaged  $\nu F\nu$  spectral peak energy ( $E_{\text{peak}}$ ) of the prompt emission to bolometric properties of the explosion. Testing such relationships for *Swift* bursts using *Swift* data alone is problematic because the narrow bandpass of the Burst Alert Telescope (BAT; 15–150 keV for a strong modulated response; Barthelmy et al. 2005a) is below  $E_{\text{peak}}$  for the majority of GRBs. Our results show that three-quarters of *Swift* bursts have  $E_{\text{peak}} > 170$  keV. However, when the *Swift* data are combined with data from another instrument with a higher energy response, such as the Wide-band All-Sky Monitor (WAM) on *Suzaku* (Yamaoka et al. 2006, 2009a), it is possible to accurately determine  $E_{\text{peak}}$  for

all bursts that are bright enough for their spectra to be reasonably fitted.

Due to the large fields of view (FOVs) of the BAT on *Swift* (Barthelmy et al. 2005a) and the WAM on *Suzaku*, it is not uncommon that GRBs will be observed by both instruments. Between 2005 August (the start of the *Suzaku* mission) and 2009 April, 48 bursts triggered both instruments. Of these bursts, 22 have redshifts. There are an additional 48 bursts untriggered in WAM (and two untriggered in BAT), 14 of which have redshifts. After rejecting seven bursts which could not be fitted, we were able to fit the spectra of 91 bursts. Of this set, 24 bursts were best fitted by a simple power-law model (see below for details on the models used); thus, we have 67 bursts (29 with redshifts) for which  $E_{\text{peak}}$  can be determined—about 1.5 per month and 18% of all *Swift* triggers (24% of triggers with redshifts) during the period of overlap between *Suzaku* and *Swift*. This compares with eight *Swift* bursts in the sample reported by Amati (2006, hereafter A06). The burst sample includes six bursts that were determined by the *Swift*/BAT team to be short bursts. All of the short bursts triggered both instruments, have known redshifts, and are fitted by a model for which  $E_{\text{peak}}$  can be determined.

The first paper in which an energy–fluence relationship was derived using accurately determined burst redshifts was that of Amati et al. (2002). In this paper, the authors analyzed 12 GRBs detected by BeppoSAX and derived a linear relationship

between  $\log(E_{\text{peak}})$  and  $\log(E_{\text{iso}})$ , where  $E_{\text{iso}}$  is the total bolometric energy (1–10,000 keV) of the burst. A06 extended and revised this work using a larger sample of 41 bursts, but found that short GRBs and the subenergetic event GRB 980425/SN1998bw do not fit the main relation. A number of authors have compared *Swift* bursts with these pre-*Swift* relations. Cabrera et al. (2007), Nava et al. (2008), and Ghirlanda et al. (2008) show that there is no significant difference between *Swift* and pre-*Swift* bursts in terms of  $E_{\text{peak}}$  relations, although Ghirlanda et al. (2008) caution that spectral analysis threshold effects could influence the correlation for *Swift* bursts.

Ghirlanda et al. (2004) found that a tighter correlation could be derived if one corrected the total burst energy for collimation using the jet opening angle, which was in turn derived from the panchromatic break time in the afterglow light curve using a geometric relationship (Sari et al. 1999). This is known as the  $E_{\text{peak}}-E_{\gamma}$  relation. It has been difficult to study  $E_{\text{peak}}-E_{\gamma}$  relations for *Swift* because *Swift* bursts show more complicated afterglow light curves than had been observed before, and a smaller fraction of bursts show clear late-time jet breaks (Panaitescu 2007). However, Ghirlanda et al. (2008) found that the relationship derived by Ghirlanda et al. (2004;  $E_{\text{peak}}-E_{\gamma}$ ) holds for the small sample of *Swift* bursts for which a jet break time was derivable. However, Campana et al. (2007) point out that the presence of significant outliers weakens the case for an  $E_{\text{peak}}-E_{\gamma}$  relationship. Since the sample of *Swift-Suzaku* bursts with confirmed jet breaks is very small, we do not attempt here to comment on the  $E_{\text{peak}}-E_{\gamma}$  relations.

A somewhat different relationship is derived by Yonetoku et al. (2004) showing a linear correlation between  $\log(E_{\text{peak}})$  and the log of the luminosity during the peak second of the burst. This relationship has been refined by adding the high-signal GRB time duration (Firmani et al. 2006) or a luminosity time (Tsutsui et al. 2009).

All of the relations discussed above have been criticized by various authors. In particular, Band & Preece (2005) and Nakar & Piran (2005) show that the majority of BATSE bursts are inconsistent with both the  $E_{\text{peak}}-E_{\text{iso}}$  and the  $E_{\text{peak}}-E_{\gamma}$  relations, and Butler et al. (2007) argue that the relations are mostly due to selection effects. We show in this paper that the  $E_{\text{peak}}-E_{\text{iso}}$  relation does hold for long *Swift* bursts and that the relation cannot result simply from selection effects.

The organization of the paper is as follows. In Section 2, we discuss the methodology and data selection and describe the spectral models used. In Section 3, we describe the distributions of spectral fit parameters. In Section 4, we cover the correlations between burst parameters and compare these results with previously published results. Finally, in Section 5 we provide general conclusions and interpretation.

## 2. METHODOLOGY

All of the bursts used in this study triggered either the BAT on *Swift* or the WAM on *Suzaku*, and in nearly half of the cases triggered both instruments. The spectra were fitted jointly to the BAT and the WAM data and fits include the time-integrated spectra and sets of time-resolved intervals as described below. Either one or two of the four WAM detectors were used in the fits, depending on which of the side detectors were hit. For all but one of the BAT bursts,<sup>11</sup> event data were used to derive first a light curve in the 15–200 keV band. From this light curve, we

used the standard *Swift*/BAT tool `batblocks` to determine the total time interval of the burst in the BAT energy range,  $T_{100}$ , and those subsidiary peaks of the prompt emission that were found by the tool to be statistically significant. The `batblocks` tool uses the Bayesian Block method of Scargle (1998) to determine significant time intervals in a light curve based on Bayesian analysis. The initial Bayesian blocks are determined from the BAT light curves, but we elected to combine blocks so that they represent significant variations in both BAT and WAM. The bin edges are then shifted to match the time quantization of the WAM spectral data (see below). The normal *Swift* response to a GRB consists of a spacecraft slew to the burst location commencing usually between 7 and 40 s after the trigger and lasting typically between 40 and 80 s. For 37 of the bursts in the sample, the prompt emission, which was intense enough to be analyzed in both BAT and WAM, lasted into the spacecraft slew and for 24 of these bursts, the prompt emission continued after the termination of the slew. Since the location of the burst in the BAT FOV changes during the slew, care must be taken when deriving the instrument's response for bursts containing slews (see below). For this reason, we have also divided burst intervals into, as appropriate, pre-slew, slew, and post-slew periods, and when Bayesian block edges fall within a few seconds of the start or end of a slew, we have shifted the bin edges to match these physical transitions.

For each significant time interval, we used the tool `batbinevt` to derive a BAT spectral file and `batdrgen` to derive a response file. When the spacecraft pointing was stable (pre-slew and post-slew), we could use a single response file since the burst was at a constant position in the FOV. For any intervals overlapping in whole or in part with the slew, we used a special procedure to average the response so that it correctly accounted for the changing location of the burst in the FOV. This procedure is described by Sakamoto et al. (2008a, hereafter S08). T. Sakamoto et al. (2009, in preparation) have shown that there is no systematic problem with analyzing the BAT spectral data during the slew using a weighted energy response. Tables 1 and 5 clearly indicate which bursts and burst intervals are so affected.

The temporal boundaries of the selected *Swift*/BAT intervals had to be further adjusted to match the WAM data. The WAM spectral data have a time quantization of 0.5 s for BST data covering the period from 8.0 s before to 56.0 s after a burst trigger, and 1.0 s for the TRN data outside these intervals and for untriggered bursts.<sup>12</sup> Thus, the boundaries of the time intervals must be adjusted to match the WAM time quantization. Times were also corrected for time-of-flight differences between the two spacecraft, but because both are in low-earth orbit, this correction is typically only a few milliseconds. The WAM data were inspected for each of the BAT-derived time intervals, and when WAM emission was intense enough for a spectrum to be derived, a WAM spectral file was produced. In a number of cases, it was necessary to combine multiple BAT time intervals into a single interval in order to get enough WAM counts for fitting. Since *Suzaku* only rarely slews during bursts,<sup>13</sup> a single response file for each WAM detector is used for a given burst. In several cases, even though two WAM detectors were hit, we decided to use only one WAM detector for analysis, either

<sup>11</sup> The one exception is GRB 060124, for which BAT triggered on a precursor. This event is discussed below.

<sup>12</sup> The current setting for WAM BST data was initiated on 2006 March 20. Before this date, all WAM spectral data have 1.0 s time resolution.

<sup>13</sup> The only GRB in our sample for which *Suzaku* was slewing during a burst was GRB 070721B. We were unable to fit a spectrum to this burst, so it is not included in our analysis.

**Table 1**  
General Properties of BAT/WAM Bursts

GRB	$T_{90}$ (s) <sup>a</sup>	$z^b$	BAT trigger	WAM trigger	WAM dets	Total interval	Segment interval	Segment
050904	174.2	6.2900 <sup>1</sup>	153514	untrig	12	16.63–216.63 (sl)	...	Total
050915B	40.9	...	155284	untrig	1	–7.51–72.49	...	Total
051006	34.8	...	158593	untrig	3	–5.79–25.21	...	Total
051008	16.0 <sup>2</sup>	...	158855	0061	03	–24.82–21.18	...	Total
051111	46.1	1.5500 <sup>3</sup>	163438	0086	23	–6.42–61.58	...	Total
051213	71.1	...	172516	untrig	0	–11.15–65.85	...	Total
051221A	1.4 (S)	0.5454 <sup>4</sup>	173780	0139	01	0.03–2.53	0.03–1.03	peak
060105	54.4	...	175942	0148	03 <sup>c</sup>	–20.77–66.23 (sl)	...	Total
060110	26.0	...	176702	untrig	2	–2.15–39.85	...	Total
060111A	13.2	...	176818	untrig	03	–0.50–15.50 (sl)	...	Total
060111B	58.8	...	176918	0156	3	–2.65–62.35 (sl)	...	Total
060117	16.9	...	177666	0160	01	–2.04–26.96	...	Total
060124	324.0 <sup>5</sup>	2.2970 <sup>5</sup>	178750	0169	23	–1.16–12.84	451.20–691.20	batdph <sup>d</sup>
060204B	139.4	...	180241	untrig	1	–23.52–171.48 (sl)	–23.52–24.48	seq1
060210	255.0	3.9100 <sup>6</sup>	180977	untrig	12	–227.29–205.71 (sl)	–96.29–14.71 (sl)	seq3-6
060211A	126.3	...	181126	untrig	3	47.51–190.51 (sl)	...	Total
060223A	11.3	4.4100 <sup>7</sup>	192059	untrig	1	–2.58–10.42	...	Total
060306	61.2	...	200638	0207	01	–1.42–66.58 (sl)	–2.42–46.58 (sl)	seq1-4
060322	221.5	...	202442	untrig	1	–22.15–202.85	...	Total
060413	147.7	...	205096	untrig	3	29.83–256.83 (sl)	...	Total
060421	12.2	...	206257	untrig	03	–3.71–11.29	...	Total
060501	21.9	...	208050	0272	03	–1.35–25.65	–1.35–10.65	seq1
060502A	28.4	1.5026 <sup>8</sup>	208169	0273	3	–7.65–40.85 (sl)	...	Total
060505	4.0 <sup>9</sup>	0.0894 <sup>10</sup>	208654	0276	03	–2.37–3.13	...	Total
060607B	31.1	...	213934	untrig	0	–1.04–36.96	...	Total
060729	115.3	0.5400 <sup>11</sup>	221755	untrig	1	–0.77–132.23 (sl)	...	Total
060801	0.5 (S)	1.1310 <sup>12</sup>	222154	0360	03	–0.21–0.79	...	Total
060813	16.1	...	224364	0374	03	–0.39–8.11	...	Total
060814	145.3	0.8400 <sup>13</sup>	224552	0376	01	–11.75–224.25 (sl)	...	Total
060825	8.0	...	226382	untrig	1	–3.53–7.47	...	Total
060904A	80.1	...	227996	0397	03	–24.16–108.84 (sl)	...	Total
060904B	171.5	0.7029 <sup>8</sup>	228006	untrig	1	–0.83–184.17 (sl)	–0.83–8.17	seq1
060908	19.3	2.4300 <sup>14</sup>	228581	0401	2	–13.36–15.64	...	Total
060912A	5.0	0.9360 <sup>15</sup>	229185	0405	2	–0.71–6.29	...	Total
061006	129.9 (S)	0.4377 <sup>16</sup>	232585	0429	23 <sup>c</sup>	–23.39–21.39	–23.39–21.89	seq1-3
061007	75.3	1.2600 <sup>17</sup>	232683	0430	23	–4.18–231.82 (sl)	...	Total
061110B	134.0	3.4344 <sup>8</sup>	238174	untrig	3	–17.29–103.71	–17.29–9.71	seq1
061202	91.2	...	241963	0479	01	–1.08–147.92 (sl)	71.42–107.92 (sl)	seq2-4
061210	85.3 (S)	0.4100 <sup>18</sup>	243690	0489	23	0.21–89.21	0.21–1.21	seq1
061222A	71.4	...	252588	0508	23 <sup>c</sup>	–2.71–118.29 (sl)	...	Total
070107	347.3	...	255029	0520	3	–20.61–104.89 (sl)	–20.61–42.39 (sl)	seq1-3
070318	74.6	0.8397 <sup>8</sup>	271019	0578	01	–1.14–103.36 (sl)	–1.14–23.86 (sl)	seq1-3
070328	75.3	...	272773	0585	1	–17.81–131.19 (sl)	...	Total
070419B	236.4	...	276212	untrig	01 <sup>f</sup>	–11.89–315.11 (sl)	–11.89–115.11 (sl)	seq1-4
070508	20.9	0.8200 <sup>19</sup>	278854	0638	12	–13.93–33.07 (sl)	...	Total
070520B	65.8	...	279898	untrig	0	–14.52–97.48 (sl)	–14.52–35.48	seq1
070529	109.2	2.4996 <sup>20</sup>	280706	untrig	3	–0.73–121.27 (sl)	–0.73–22.27	seq1
070531	44.5	...	280958	untrig	01	–1.91–45.09	–1.91–7.09	seq1
070612A	368.8	0.6170 <sup>21</sup>	282066	0670	01	–4.49–417.51	–4.49–36.01	seq1-2
070612B	13.5	...	282073	untrig	2	–15.29–9.71	...	Total
070616	402.4	...	282445	0674	0	–2.55–602.45 (sl)	–2.55–173.95 (sl)	seq1-4
070704	380.0 <sup>22</sup>	...	283791	0691	0	–57.58–48.42	–57.08–15.58	seq1-2
070714B	64.0 <sup>23</sup> (S)	0.9200 <sup>24</sup>	284856	0700	03	–0.88–2.12	...	Total
070808	32.0 <sup>25</sup>	...	287260	0725	12	–0.61–65.39 (sl)	–0.61–15.89	preslew
070911	162.0 <sup>26</sup>	...	290624	0755	23 <sup>g</sup>	–69.52–158.48 (sl)	–69.52–73.48	preslew
070913	3.2 <sup>27</sup>	...	290843	untrig	03 <sup>c</sup>	–1.46–1.54	...	Total
070917	7.3 <sup>28</sup>	...	291292	0759	23 <sup>g</sup>	0.01–11.01	...	Total
070923	0.1 <sup>29</sup>	...	292004	untrig	0	–0.03–0.47	...	Total
071003	150.0 <sup>30</sup>	1.1000 <sup>31</sup>	292934	0770	12 <sup>f</sup>	–7.23–167.77 (sl)	–7.23–40.77	preslew
071010B	35.7 <sup>32</sup>	0.9470 <sup>33</sup>	293795	0777	01	–36.01–23.99	...	Total
071112B	0.3 <sup>34</sup>	...	296503	untrig	03	–0.62–0.38	...	Total
071227	1.8 <sup>35</sup> (S)	0.3830 <sup>36</sup>	299787	0848	3	0.17–1.17	...	Total
080123	115.0 <sup>37</sup>	...	301578	0875	0	0.00–122.00	...	Total
080218A	27.6 <sup>38</sup>	...	303609	untrig	0	–12.52–19.48	...	Total
080303	67.0 <sup>39</sup>	...	304549	untrig	12	–0.19–72.81 (sl)	...	Total

**Table 1**  
(Continued)

GRB	$T_{90}$ (s) <sup>a</sup>	$z$ <sup>b</sup>	BAT trigger	WAM trigger	WAM dets	Total interval	Segment interval	Segment
080319C	34.0 <sup>40</sup>	1.9492 <sup>8</sup>	306778	0920	23	−0.54–51.46	...	Total
080328	90.6 <sup>41</sup>	...	307931	0927	23	−2.76–117.24 (sl)	−2.76–17.24	preslew
080409	20.2 <sup>42</sup>	...	308812	untrig	01 <sup>f</sup>	−12.91–10.09	...	Total
080413A	46.0 <sup>43</sup>	2.4330 <sup>8</sup>	309096	untrig	1	−0.66–50.34	−0.66–24.34 (sl)	seq1-2
080413B	8.0 <sup>44</sup>	1.1014 <sup>8</sup>	309111	untrig	01	−1.89–11.11	...	Total
080605	20.0 <sup>45</sup>	1.6403 <sup>8</sup>	313299	untrig	12 <sup>g</sup>	−5.31–30.19 (sl)	...	Total
080623	15.2 <sup>46</sup>	...	315080	untrig	2	−1.57–16.43	...	Total
080701	18.0 <sup>47</sup>	...	315615	untrig	03	−2.87–25.13	...	Total
080707	17.1 <sup>48</sup>	1.2322 <sup>8</sup>	316204	untrig	3	−2.00–37.00 (sl)	...	Total
080727C	79.7 <sup>49</sup>	...	318170	1026	3	−2.86–116.14 (sl)	...	Total
080805	78.0 <sup>50</sup>	1.5042 <sup>8</sup>	319036	untrig	2	−3.90–136.10 (sl)	...	Total
080905A	1.0 <sup>51</sup>	...	323870	1053	2	−0.40–1.10	...	Total
080916A	60.0 <sup>52</sup>	0.6887 <sup>8</sup>	324895	1059	23	−2.90–89.10 (sl)	−2.90–22.10 (sl)	seq1-2
081008	185.5 <sup>53</sup>	1.9685 <sup>54</sup>	331093	untrig	1	−65.69–201.31 (sl)	...	Total
081022	160.0 <sup>55</sup>	...	332399	untrig	0	−9.23–207.77	...	Total
081025	23.0 <sup>56</sup>	...	untrig	1087	3	54.71–79.71 (sl) <sup>h</sup>	...	Total
081109A	190.0 <sup>57</sup>	...	334112	untrig	0	−15.27–29.73 (sl)	−15.27–29.73 (sl)	seq2
090113	9.1 <sup>58</sup>	...	339852	untrig	3	−1.28–9.72	...	Total
090123	131.0 <sup>59</sup>	...	340895	untrig	3	−50.07–117.93 (sl)	...	Total
090301A	41.0 <sup>60</sup>	...	344582	1182	03	−17.28–60.72	...	Total
090305	0.4 <sup>61</sup>	...	345127	untrig	2	−0.21–0.79	...	Total
090401A	112.0 <sup>62</sup>	...	348128	untrig	03	90.13–131.13	...	Total
090401B	183.0 <sup>63</sup>	...	348152	1205	0	0.13–39.13 (sl)	...	Total
090410	165.0 <sup>64</sup>	...	348929	1215	01	−49.48–139.52	...	Total
090418B	65.0 <sup>65</sup>	...	untrig	untrig	23	5.96–112.96 (sl) <sup>h</sup>	...	Total
090424	48.0 <sup>66</sup>	0.5440 <sup>67</sup>	350311	1229	12	−0.62–15.88 (sl)	...	Total

**Notes.**  $T_{90}$ : Unless otherwise noted, all  $T_{90}$  values are from S08. A letter “(S)” in this column indicates a short burst. *WAM dets*: the identifier of the WAM detector or a pair of detectors in which the burst was detected; cases where only one of a pair was used in the fits are noted. *Total interval and Segment interval*: times are with respect to the *Swift*/BAT trigger time. A symbol “(sl)” in this column indicates that the time interval included all or part of a spacecraft slew maneuver. *Segment*: this column indicates the portion of the burst used for the time-integrated spectral fit.

<sup>a</sup> Values of  $T_{90}$  are from S08 unless otherwise indicated with a superscript and listed below.

<sup>b</sup> References for this column are given as superscripts and listed below.

<sup>c</sup> Only WAM side 0 used for fits.

<sup>d</sup> BAT triggered on a precursor to the main burst. Analysis was done using BAT survey (“dph”) data.

<sup>e</sup> Only WAM side 3 used for fits.

<sup>f</sup> Only WAM side 1 used for fits.

<sup>g</sup> Only WAM side 2 used for fits.

<sup>h</sup> This burst did not trigger BAT, but was discovered as part of the BAT slew survey. For this burst,  $T_0$  is the start of the spacecraft slew.

**References.** (1) Cusumano et al. 2007; (2) Barthelmy et al. 2005b; (3) Guidorzi et al. 2007; (4) Soderberg et al. 2006; (5) Romano et al. 2006; (6) Curran et al. 2007; (7) Berger et al. 2006; (8) Fynbo et al. 2009; (9) Hullinger et al. 2006; (10) Ofek et al. 2007; (11) Grupe et al. 2007; (12) Cucchiara et al. 2006; (13) Thoene et al. 2007; (14) Rol et al. 2006; (15) Levan et al. 2007; (16) Berger et al. 2007c; (17) Schady et al. 2007a; (18) Cenko et al. 2006; (19) Jakobsson et al. 2007; (20) Berger et al. 2007a; (21) Cenko et al. 2007; (22) Sakamoto et al. 2007; (23) Racusin et al. 2007; (24) Graham et al. 2007; (25) Fenimore et al. 2007; (26) Krimm et al. 2007; (27) Markwardt et al. 2007a; (28) Cummings et al. 2007b; (29) Cummings et al. 2007a; (30) Schady et al. 2007b; (31) Perley et al. 2008; (32) Markwardt et al. 2007b; (33) Stern et al. 2007; (34) Perri et al. 2007; (35) Sato et al. 2007; (36) Berger et al. 2007b; (37) Ukwatta et al. 2008a; (38) Ziaepour et al. 2008a; (39) Sakamoto et al. 2008b; (40) Pagani et al. 2008; (41) Perri et al. 2008; (42) Holland et al. 2008; (43) Marshall et al. 2008; (44) Barthelmy et al. 2008; (45) Sbarufatti et al. 2008; (46) Ukwatta et al. 2008b; (47) Fenimore et al. 2008a; (48) Schady et al. 2008; (49) Fenimore et al. 2008b; (50) Pagani et al. 2008a; (51) Pagani et al. 2008b; (52) Ziaepour et al. 2008b; (53) Racusin et al. 2008; (54) D’Avanzo et al. 2008; (55) Stratta et al. 2008; (56) Mao et al. 2008; (57) Immler et al. 2008; (58) Krimm et al. 2009a; (59) Grupe et al. 2009a; (60) Vetere et al. 2009; (61) Krimm et al. 2009b; (62) Schady et al. 2009a; (63) Schady et al. 2009b; (64) Grupe et al. 2009b; (65) Copete et al. 2009; (66) Cannizzo et al. 2009; (67) Chornock et al. 2009.

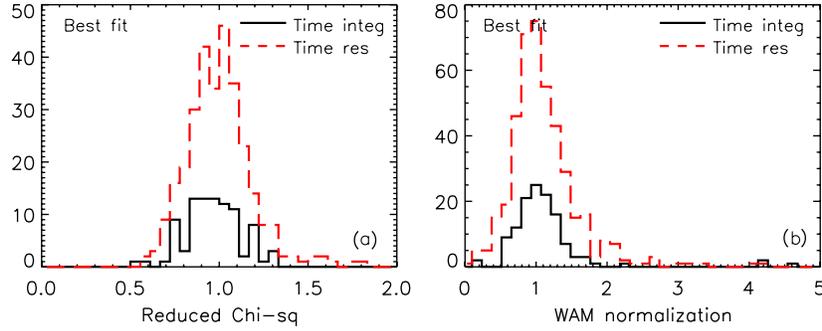
because the incident angle was bad (passing through too much passive material) or because the count rate was too low in one of the detectors to allow a proper spectrum to be accumulated. Such cases are noted in Table 1.

The *Suzaku* WAM data analysis was performed using the standard FTOOLS in the HEADAS version 6.6 package. In accordance with *Swift*/BAT time intervals, the spectra were accumulated and dead time corrected. The WAM instrumental background is significantly variable with time, so we fitted the WAM light curve for each channel before and after the time intervals with a fourth-order polynomial function, then interpolated the best-fit model into the source-extracted regions. The

energy response was calculated based on incident angles using the response generator, *wamresp* v. 1.9. The energy range was limited to be above 120 keV in the fitting. The uncertainty of the flux using the current response is estimated at about 30% above 120 keV (Yamaoka et al. 2009a).

For each time interval, joint fits were made to the BAT and WAM data. Data were fit using *xspec* 11.3<sup>14</sup> to a simple power-law (PL) model, a power-law model with an exponential cutoff (CPL), and the two-component (Band) model (Band et al. 1993).

<sup>14</sup> <http://heasarc.gsfc.nasa.gov/xanadu/xspec/xspec11/index.html>



**Figure 1.** Left panel: distribution of  $\chi_{\text{red}}^2$  for the fits used in this work. The median values are 0.96 for the time-integrated and 1.00 for the time-resolved sets. Right panel: distribution of the WAM normalization for the fits used in this work. The median values are 1.06 for the time-integrated and 1.06 for the time-resolved sets.

The functional forms of these models are, respectively:

$$N_{PL}(E) = C \cdot A \left( \frac{E}{E_{\text{norm}}} \right)^\alpha, \quad (1)$$

$$N_{CPL}(E) = C \cdot A \left( \frac{E}{E_{\text{norm}}} \right)^\alpha \exp \left[ -\frac{E(2 + \alpha)}{E_{\text{peak}}} \right], \quad (2)$$

$$N_{\text{Band}}(E) = \begin{cases} C \cdot A \left( \frac{E}{E_{\text{norm}}} \right)^\alpha \exp \left[ -\frac{E(2 + \alpha)}{E_{\text{peak}}} \right] & E < E_c, \\ C \cdot A' \left( \frac{E}{E_{\text{norm}}} \right)^\beta & E \geq E_c. \end{cases} \quad (3)$$

In each of the above equations,  $A$  is the normalization in photons  $\text{s}^{-1} \text{cm}^{-2} \text{keV}^{-1}$ ,  $E$  is the energy measured in keV,  $E_{\text{norm}}$  is the normalization energy, which is fixed at 100 keV for this analysis,  $\alpha$  is a photon spectral index, and  $C$  is a dimensionless constant. In the Band model,  $\beta$  is a second photon spectral index,  $E_c \equiv (\alpha - \beta)(E_{\text{peak}}/2 + \alpha)$ , and the normalization parameter  $A'$  is defined as

$$A' \equiv A \left[ \frac{(\alpha - \beta)E_{\text{peak}}}{E_{\text{norm}}(2 + \alpha)} \right]^{(\alpha - \beta)} \exp(\beta - \alpha). \quad (4)$$

In the fits, the constant  $C$  was fixed to a value of 1.0 for the BAT and was allowed to vary as a free parameter for the WAM. The fits for each interval and each model were inspected and a time interval/model was rejected if either (1) the lower-energy power-law index,  $\alpha$ , was not constrained, (2) the reduced chi-squared,  $\chi_{\text{red}}^2 > 2$ , or (3) the WAM constant  $C$  was not consistent with unity (with a few exceptions listed below). For the CPL and Band models, we added the criteria that (4)  $E_{\text{peak}}$  be constrained. We did not require the higher energy index  $\beta$  to be constrained. If the original “total” time interval did not yield an acceptable fit, then a shorter time interval that was better matched to the extent of the WAM emission was chosen for the time-integrated interval. Such cases are clearly noted in Table 1. In the subsequent discussion, the term “total burst interval” will designate the longest continuous time interval over which an acceptable model fit can be made to either the CPL or the Band model. In a companion work, T. Sakamoto et al. (2009, in preparation), the cross-correlation between BAT and WAM (and also *Konus-WIND*) is studied in detail. They find that the normalizations between the instruments are consistent to within 20%. A detailed study of GRB 050904 has also been carried out (Sugita et al. 2009) and the results are consistent with this work.

For each time interval (time integrated and time resolved), the “best” spectral model was determined. The default for each case was a simple power-law model. If, however, the difference in  $\chi^2$  between the PL fit and the CPL fit or between the CPL fit and

the Band fit was  $\Delta\chi_{(a,b)}^2 > 6.0$ , where  $\Delta\chi_a^2 \equiv \Delta\chi_{PL}^2 - \Delta\chi_{CPL}^2$  or  $\Delta\chi_b^2 \equiv \Delta\chi_{CPL}^2 - \Delta\chi_{\text{Band}}^2$ , then the more complicated model was deemed to be the “best” model. Of course, this more complicated model fit also had to meet the acceptability criteria listed in the preceding paragraph. With this selection method, for the full burst intervals, 26 bursts were found to be best fit by the simple PL model, 51 by the CPL model, and 14 with the Band model.<sup>15</sup> However, for all of the bursts for which the CPL model was the best fit, the Band model was also an acceptable fit. In each case, the values of  $E_{\text{peak}}$  for the two models were identical to within statistics.

In all cases in which either the CPL or the Band model is the best fit and for which a redshift is known, we then transformed  $E_{\text{peak}}$  to the source frame by multiplying  $E_{\text{peak}}^{\text{obs}}$  by a factor  $(1 + z)$ . The next step was to determine, for each burst, the isotropic energy,  $E_{\text{iso}}$ , integrated over the total burst interval and over each time-resolved burst interval. To make sure that we were comparing equivalent quantities for each burst, we used only the Band model to calculate the integrated flux, including those cases for which the Band model gives an acceptable fit, but is not the “best” fit model. This choice is justified in Section 3.4. We also include in our sample bursts for which the high-energy power-law index  $\beta$  is not constrained, allowing the uncertainty in this parameter to contribute to the overall error in the flux. To find  $E_{\text{iso}}$ , we used the definition of Amati et al. (2002) to derive  $E_{\text{iso}}$  from the integrated flux:  $E_{\text{iso}} = 1/(1 + z) \int_1^{10000} [EN(E)dE \times 4\pi * dL^2]$ . To allow a direct comparison, we used the same cosmological parameters as the earlier authors:  $H_0 = 65 \text{ km s}^{-1}$ ,  $\Omega_m = 0.3$ , and  $\Omega_\Lambda = 0.7$ .

It is also important to check the results for the overall quality of fits. In Figure 1, we show two plots that verify the overall validity of our results. In Figure 1(a), we show the distribution of reduced  $\chi^2$  for the time-integrated and time-resolved fits. We see that both histograms peak at  $\chi_{\text{red}}^2 = 1$  with an appropriate distribution of values. In Figure 1(b), we show a histogram of the WAM normalization factor for those bursts and sequences that otherwise meet the quality standards outlined above. We see that the distribution has a peak at unity as expected and a tail at high values of the normalization constant. Two of the tail points in the time-integrated histogram at just above 4.0 are due to GRB 060124, which is a unique burst in the sample in that BAT triggered on a precursor  $\approx 450$  s before the main emission and the WAM trigger. The BAT event data extended to only

<sup>15</sup> In two cases, GRBs 050915B and 081109A, neither  $\Delta\chi_a^2$  nor  $\Delta\chi_b^2$  were  $> 6.0$ , but  $\Delta\chi^2 = \Delta\chi_{PL}^2 - \Delta\chi_{\text{Band}}^2 > 6.0$ , so these bursts are included in our data set and  $E_{\text{peak}}$  values used in the analysis.

$T_0 + 302$  s, where  $T_0$  here and henceforth refers to the *Swift*/BAT trigger time. Therefore, we used the BAT survey data with a time resolution of 250 s instead of the usual 100  $\mu$ s resolution. The WAM data covered only the 33 s of actual emission. This difference in data duration is responsible for an increased WAM normalization factor. Since the energy resolution for survey data is as good as for the event data and the analysis looks robust, we include the burst in our sample. The other high tail point is due to GRB 080218A, which has a very low  $E_{\text{peak}} = 32 \pm 9$  keV, and for which  $E_{\text{peak}}$  is fitted well with the BAT data alone. Inclusion of the WAM data does not significantly affect the result, so given the high-normalization factor, we have decided to report the result of the BAT fit for this burst. Tail points for individual sequences were from weak sequences and were excluded from the data tables and plots.

### 3. RESULTS OF SPECTRAL FITS

The results of this analysis for individual bursts are given in four tables. Table 1 gives a list of all jointly detected bursts and includes BAT and WAM trigger numbers, the WAM detector sides used in the analysis, the burst redshift when available, BAT  $T_{90}$ , and the temporal extent of each total burst interval (see the note added in proof at the end of this paper). In Tables 2–4, the fit parameters for the total burst intervals are given. Bursts for which either the CPL or the Band model is an acceptable fit are listed in Table 2, while those bursts for which only a PL model is acceptable are listed separately in Table 3. Table 4 lists the fluence values from a Band model fit for each burst in Table 2. In Table 5, we list the fit parameters for each time-resolved burst segment for which we could find an acceptable fit to either the CPL or the Band model. We do not include burst segments for which only a simple PL is an acceptable fit.

The histograms of the fit parameters for the time-integrated and time-resolved spectra are shown in the following figures: the low-energy power-law index  $\alpha$  in Figure 2, the high-energy power-law index  $\beta$  in Figure 3, and  $E_{\text{peak}}$  in Figure 4. For a given parameter, a pair of plots (time integrated and time resolved) is given for each model that contains that parameter. In other words, the  $\alpha$  parameter is plotted for all three models, the  $\beta$  parameter only for the Band model, and the  $E_{\text{peak}}$  parameter for the CPL and the Band models. The dashed histograms in Figures 2(a) and (b) are created by assigning each burst to a histogram based on which model is the best fit for that burst (see Column 9 in Table 2). The solid black histograms are the accumulations of the dashed line histograms. In Figures 2(c), 3(a), and 4(c), we also show for the time-integrated spectra the histograms of the parameter distributions for short bursts in blue or light gray.<sup>16</sup> The median values and the dispersions (quartile) for each histogram are given in Table 6. We also show a pair of scatter plots in Figure 5. We plot  $\alpha$  with respect to fluence in the 15–150 keV band and with respect to  $E_{\text{peak}}$ . These plots are discussed in the text below.

We see in Figure 2(a) that the harder the burst (less negative  $\alpha$ ) the more likely we are able to fit a model with a larger number of parameters. This bias is also seen for the time-resolved spectra in Figure 2(b). Furthermore, in examining Figures 2(c), 3, and 4(c) and the relevant individual histograms, one can see a few differences in the distributions of  $\alpha$ ,  $\beta$ , and  $E_{\text{peak}}$  between the time-integrated and time-resolved fits. One can see in Figure 2(c) that the median  $\alpha$  for the time-resolved spectra is softer than

that for the time-integrated spectra. The time-resolved spectra are more likely to be from later and hence softer segments of the bursts.

Although there are far fewer short bursts than long bursts, one can see some differences between spectral fit parameters for these two classes of bursts. In Figure 2(c), we note that although the distributions overlap, short bursts are clustered toward the hard side of the  $\alpha$  distribution, with a median value,  $-0.72$ , different from the overall median,  $-1.23$ . Figure 4(c) gives a similar picture—one cannot distinguish short from long bursts by their  $E_{\text{peak}}$  values, but short bursts are much more likely to have a high value of  $E_{\text{peak}}$  than long bursts.

#### 3.1. Power-law Spectral Fits

First, we examine the bursts for which the PL model is the best fit. One can see clearly in Figure 5(a) (black points) that these are not intrinsically faint bursts, even though we are likely “losing” a significant fraction of the flux below 15 keV. However, due to their soft spectra (low  $\alpha$  values), these bursts tend to be very weak in the WAM band and/or have an  $E_{\text{peak}}$  value below the WAM energy threshold and a weak “lever arm” in the BAT energy range, so that it is not possible to fit a spectral break using the joint BAT/WAM data. The basic conclusion of this is that if the low-energy index  $\alpha \lesssim -1.5$ , it is very difficult to constrain  $E_{\text{peak}}$  with the BAT–WAM data unless the burst is particularly bright ( $F > 7 \times 10^{-6}$  erg cm<sup>-2</sup>). As the work of Sakamoto et al. (2009, hereafter S09) shows, bursts in this range tend to have low values of  $E_{\text{peak}} \lesssim 100$  keV. Figure 5(a) shows that there is no apparent correlation between the burst fluence and the form of the most acceptable spectral model.

The results of S09 allow us to verify that  $E_{\text{peak}}$  for the PL-only bursts is indeed likely to be within the BAT energy range, but below the WAM energy range. In Table 3, we include estimates of  $E_{\text{peak}}$  derived from the formulas given in S09, which relate  $E_{\text{peak}}$  to the power-law index derived from a power-law model fit,  $\alpha$  (called  $\Gamma$  in S09). Two of the bursts (GRBs 060211A and 060322) were bright enough to be fitted with the BAT data and we have used  $E_{\text{peak}}$  from S08. Another two bursts have  $\alpha$  outside the range for which the S09 formulas are considered valid and we report no  $E_{\text{peak}}$  values. For 19 of the 22 bursts with  $E_{\text{peak}}$  values, we see that our best-fit estimates of  $E_{\text{peak}}$  are within the BAT energy range, but below the WAM energy range. All of the remaining three have  $E_{\text{peak}}$  values at the lower end of the WAM range and PL indices near the lower edge of the validity of the S09 relation, so  $E_{\text{peak}}$  values derived from S09 may be in question. GRB 080303 and GRB 090305 are weak bursts which were not triggered in WAM. The other, GRB 080123, did trigger WAM, but we were unable to constrain  $E_{\text{peak}}$  with either the BAT–WAM data or the BAT-only data. However, with a few possible exceptions, all PL-only bursts in our sample have estimated  $E_{\text{peak}}$  values in the BAT energy range which puts them at the low end of the BAT–WAM energy range.

In conclusion, for this set of bursts we are fitting mostly to the part of the Band spectrum above the break energy. Therefore, what we derive as  $\alpha$  in a PL fit is actually  $\beta$  in the intrinsic spectrum, hardened somewhat by an inclusion of part of the spectrum below the break. This explains why the PL index values are so soft:  $\alpha \approx -1.6$ , which is intermediate between  $\alpha$  and  $\beta$  measured for GRBs fit with the Band function.

#### 3.2. Cutoff Power-law Spectral Fits

Next, we examine those bursts for which the CPL model is the best fit. In those cases for which  $E_{\text{peak}}$  is determined, one

<sup>16</sup> Note that the solid black histograms are cumulative, including both long and short bursts.

**Table 2**  
Time-integrated Spectral Parameters of BAT/WAM Bursts

GRB	$\alpha$	$\beta$	$E_{\text{peak}}$ (keV)	$E_{\text{iso}}$ ( $10^{52}$ erg)	WAM A norm	WAM B norm	$\chi^2/\text{dof}$	Model
050904	$-1.36 \pm 0.06$	...	...	...	$1.06 \pm 0.30$	$1.05^{+0.21}_{-0.17}$	117.50/89	PL
	$-1.13 \pm 0.12$	...	$324^{+312}_{-109}$	...	$1.54 \pm 0.43$	$1.38^{+0.30}_{-0.26}$	91.73/88	CPL*
	$-1.11 \pm 0.20$	$-1.99^{+0.32}_{-5.23}$	$284^{+270}_{-139}$	$109.26 \pm 25.41$	$1.57^{+0.56}_{-0.48}$	$1.40^{+0.38}_{-0.27}$	89.04/87	Band
050915B	$-1.91 \pm 0.07$	...	...	...	$0.52 \pm 0.16$	...	79.04/73	PL*
	$-1.51 \pm 0.33$	...	$59^{+47}_{-9}$	...	$0.81^{+0.35}_{-0.31}$	...	74.53/72	CPL
	$-1.21 \pm 0.57$	$-2.20^{+0.21}_{-0.53}$	$49 \pm 11$	...	$0.69^{+0.33}_{-0.28}$	...	68.98/1	Band
051008	$-1.04 \pm 0.05$	...	$815^{+91}_{-78}$	...	$1.08 \pm 0.07$	$1.01 \pm 0.07$	129.77/108	CPL*
	$-1.01 \pm 0.06$	$-2.37^{+0.26}_{-0.71}$	$719^{+105}_{-88}$	...	$1.07 \pm 0.07$	$1.01 \pm 0.07$	125.05/107	Band
051111	$-1.37 \pm 0.04$	...	...	...	$0.65 \pm 0.13$	$0.58^{+0.08}_{-0.07}$	116.79/87	PL
	$-1.23 \pm 0.07$	...	$521^{+273}_{-149}$	...	$0.85 \pm 0.16$	$0.71^{+0.10}_{-0.09}$	83.17/86	CPL*
	$-1.22 \pm 0.15$	$-2.10^{+0.43}_{-7.90}$	$447^{+329}_{-280}$	$13.14 \pm 3.29$	$0.87^{+0.26}_{-0.21}$	$0.73^{+0.20}_{-0.11}$	82.97/85	Band
051221A	$-1.38 \pm 0.05$	...	...	...	$0.42 \pm 0.13$	$0.50^{+0.09}_{-0.07}$	201.01/89	PL
	$-1.07 \pm 0.09$	...	$381^{+157}_{-93}$	...	$0.60 \pm 0.16$	$0.68^{+0.11}_{-0.10}$	103.91/88	CPL
	$-0.96 \pm 0.15$	$-2.03^{+0.18}_{-0.55}$	$243^{+123}_{-77}$	$0.38 \pm 0.09$	$0.66 \pm 0.20$	$0.77^{+0.15}_{-0.12}$	94.76/87	Band*
060105	$-1.14 \pm 0.03$	...	...	...	$0.29 \pm 0.06$	...	137.23/73	PL
	$-1.02 \pm 0.06$	...	$665^{+380}_{-219}$	...	$0.86 \pm 0.19$	...	62.32/72	CPL*
	$-0.97 \pm 0.08$	$-2.13^{+0.31}_{-1.09}$	$476^{+278}_{-164}$	...	$0.94 \pm 0.20$	...	58.98/71	Band
060111A	$-1.68 \pm 0.06$	...	...	...	$0.74 \pm 0.18$	$0.59^{+0.13}_{-0.12}$	116.38/87	PL
	$-1.35 \pm 0.19$	...	$109^{+56}_{-25}$	...	$1.14^{+0.39}_{-0.34}$	$0.97^{+0.31}_{-0.23}$	92.21/86	CPL
	$-0.63 \pm 0.47$	$-2.29^{+0.24}_{-0.32}$	$62 \pm 11$	...	$1.36^{+0.48}_{-0.42}$	$1.12^{+0.37}_{-0.28}$	75.39/85	Band*
060111B	$-1.39 \pm 0.11$	...	...	...	$1.50^{+0.45}_{-0.39}$	...	112.68/72	PL
	$-0.90 \pm 0.21$	...	$503^{+232}_{-124}$	...	$1.21^{+0.31}_{-0.28}$	...	85.74/71	CPL*
	$-0.88 \pm 0.16$	$-2.35^{+0.59}_{-7.65}$	$475^{+228}_{-130}$	...	$1.21^{+0.32}_{-0.28}$	...	85.30/70	Band
060117	$-1.67 \pm 0.03$	...	$92 \pm 5$	...	$0.99 \pm 0.05$	$0.87 \pm 0.04$	170.50/108	CPL
	$-1.52 \pm 0.06$	$-2.53 \pm 0.07$	$71^{+6}_{-4}$	...	$1.13 \pm 0.07$	$1.00 \pm 0.05$	125.64/107	Band*
060124	$-1.74 \pm 0.04$	...	...	...	$3.91 \pm 0.51$	$3.96^{+0.48}_{-0.40}$	104.82/43	PL
	$-1.52 \pm 0.07$	...	$265^{+91}_{-56}$	...	$4.20 \pm 0.51$	$4.29 \pm 0.47$	43.94/42	CPL*
	$-1.52 \pm 0.07$	$-2.76^{+0.56}_{-7.24}$	$253^{+92}_{-61}$	$35.99 \pm 4.57$	$4.21 \pm 0.52$	$4.31^{+0.50}_{-0.40}$	43.35/41	Band
060204B	$-1.39 \pm 0.06$	...	...	...	$0.69 \pm 0.13$	...	97.36/72	PL
	$-1.22 \pm 0.14$	...	$321^{+390}_{-137}$	...	$0.95^{+0.26}_{-0.22}$	...	84.04/71	CPL
	$-0.44 \pm 0.93$	$-1.80 \pm 0.29$	$83^{+40}_{-29}$	...	$1.15 \pm 0.33$	...	66.79/70	Band*
060210	$-1.44 \pm 0.07$	...	...	...	$0.55 \pm 0.24$	...	96.10/87	PL
	$-1.16 \pm 0.19$	...	$191^{+150}_{-58}$	...	$1.34^{+0.70}_{-0.61}$	...	76.57/86	CPL*
	$-1.18 \pm 0.18$	...	$207^{+106}_{-75}$	$44.17 \pm 12.92$	$1.30 \pm 0.42$	...	76.66/85	Band
060306	$-1.82 \pm 0.09$	...	...	...	$1.79^{+0.52}_{-0.47}$	$1.63^{+0.39}_{-0.31}$	78.67/87	PL
	$-1.60 \pm 0.14$	...	$144^{+102}_{-44}$	...	$2.27^{+0.67}_{-0.61}$	$1.87^{+0.46}_{-0.37}$	64.00/86	CPL*
	$-0.87 \pm 0.98$	$-2.23^{+0.22}_{-0.28}$	$56 \pm 15$	...	$2.92^{+1.17}_{-1.00}$	$2.44^{+0.82}_{-0.59}$	59.55/85	Band
060421	$-1.62 \pm 0.07$	...	...	...	$0.73 \pm 0.14$	$0.56^{+0.13}_{-0.11}$	99.85/88	PL
	$-1.34 \pm 0.14$	...	$165^{+82}_{-41}$	...	$0.96 \pm 0.19$	$0.80^{+0.21}_{-0.17}$	73.12/87	CPL*
	$-1.15 \pm 0.32$	$-2.23^{+0.26}_{-7.77}$	$109^{+113}_{-30}$	...	$1.07 \pm 0.25$	$0.91^{+0.26}_{-0.22}$	71.97/86	Band
060501	$-1.48 \pm 0.10$	...	...	...	$0.76^{+0.22}_{-0.20}$	$0.67^{+0.18}_{-0.14}$	112.99/87	PL
	$-1.04 \pm 0.18$	...	$246^{+110}_{-62}$	...	$0.87^{+0.23}_{-0.21}$	$0.76^{+0.19}_{-0.15}$	79.10/86	CPL*
	$-0.92 \pm 0.35$	$-2.21^{+0.32}_{-7.79}$	$184^{+134}_{-74}$	...	$0.96^{+0.37}_{-0.31}$	$0.84^{+0.30}_{-0.20}$	77.41/85	Band
060502A	$-1.46 \pm 0.07$	...	...	...	$0.66 \pm 0.16$	...	87.76/72	PL
	$-1.29 \pm 0.16$	...	$282^{+447}_{-124}$	...	$0.89^{+0.29}_{-0.25}$	...	77.68/71	CPL*
	$-1.19 \pm 0.41$	...	$302^{+431}_{-143}$	$4.82 \pm 2.78$	$1.00^{+0.19}_{-0.26}$	...	77.84/70	Band
060505	$-1.72 \pm 0.13$	...	...	...	$1.56^{+0.61}_{-0.50}$	$1.60^{+0.82}_{-0.53}$	92.81/90	PL
	$-1.23 \pm 0.33$	...	$443^{+482}_{-154}$	...	$0.99^{+0.44}_{-0.36}$	$1.05^{+0.55}_{-0.35}$	82.66/89	CPL*
	$-1.19 \pm 0.37$	$-2.39^{+0.58}_{-7.61}$	$397^{+485}_{-185}$	$0.006 \pm 0.003$	$0.97^{+0.43}_{-0.35}$	$1.02^{+0.54}_{-0.34}$	82.42/88	Band
060801	$-1.09 \pm 0.17$	...	...	...	$0.83^{+0.34}_{-0.58}$	$1.21^{+0.74}_{-0.45}$	125.85/87	PL
	$-0.44 \pm 0.32$	...	$657^{+406}_{-211}$	...	$0.77^{+0.47}_{-0.39}$	$0.88^{+0.41}_{-0.28}$	104.18/86	CPL*
	$-0.44 \pm 0.31$	$-2.87^{+1.41}_{-7.13}$	$642^{+9309}_{-355}$	$0.33 \pm 0.22$	$0.77^{+0.47}_{-0.39}$	$0.88^{+0.35}_{-0.28}$	104.18/85	Band
060813	$-0.96 \pm 0.04$	...	$259 \pm 13$	...	$1.09 \pm 0.05$	$0.97 \pm 0.05$	114.64/109	CPL
	$-0.94 \pm 0.04$	$-2.73^{+0.22}_{-0.38}$	$245 \pm 15$	...	$1.11 \pm 0.05$	$0.99 \pm 0.05$	103.06/108	Band*
060814	$-1.60 \pm 0.03$	...	...	...	$0.96 \pm 0.13$	$0.94^{+0.07}_{-0.06}$	92.87/89	PL
	$-1.51 \pm 0.05$	...	$595^{+482}_{-196}$	...	$1.06 \pm 0.15$	$1.01 \pm 0.08$	66.65/86	CPL*
	$-1.45 \pm 0.18$	$-1.85 \pm 0.11$	$290^{+366}_{-169}$	$13.39 \pm 2.04$	$1.14^{+0.24}_{-0.18}$	$1.08^{+0.16}_{-0.05}$	64.09/87	Band
060825	$-1.73 \pm 0.07$	...	...	...	$0.45 \pm 0.15$	...	83.18/72	PL
	$-1.19 \pm 0.35$	...	$72^{+47}_{-11}$	...	$1.02^{+0.72}_{-0.58}$	...	76.30/71	CPL
	$-0.63 \pm 0.88$	$-2.02^{+0.17}_{-0.29}$	$50^{+20}_{-10}$	...	$0.65^{+0.31}_{-0.26}$	...	67.25/70	Band*
060904A	$-1.62 \pm 0.04$	...	...	...	$0.72 \pm 0.14$	$0.74^{+0.07}_{-0.07}$	87.49/89	PL
	$-1.55 \pm 0.06$	...	$565^{+932}_{-250}$	...	$0.81 \pm 0.17$	$0.81^{+0.10}_{-0.09}$	74.11/88	CPL*
	$-1.44 \pm 0.15$	$-1.89^{+0.13}_{-0.47}$	$207^{+376}_{-85}$	...	$0.96^{+0.18}_{-0.22}$	$0.95^{+0.09}_{-0.18}$	70.05/87	Band
060904B	$-1.36 \pm 0.08$	...	...	...	$0.56^{+0.19}_{-0.17}$	...	74.45/73	PL
	$-1.16 \pm 0.16$	...	$331^{+527}_{-142}$	...	$0.92^{+0.34}_{-0.30}$	...	62.62/72	CPL*

**Table 2**  
(Continued)

GRB	$\alpha$	$\beta$	$E_{\text{peak}}$ (keV)	$E_{\text{iso}}$ ( $10^{52}$ erg)	WAM A norm	WAM B norm	$\chi^2/\text{dof}$	Model
060908	$-0.61 \pm 0.67$	$-1.78^{+0.25}_{-0.37}$	$103^{+94}_{-42}$	$0.72 \pm 0.43$	$1.08^{+0.48}_{-0.42}$	...	57.24/71	Band
	$-1.39 \pm 0.06$	...	...	...	$0.32 \pm 0.09$	...	73.11/72	PL
	$-1.05 \pm 0.22$	...	$163^{+146}_{-47}$	...	$0.71^{+0.32}_{-0.27}$	...	54.62/71	CPL*
061006	$-0.89 \pm 0.32$	$-2.24^{+0.55}_{-7.76}$	$124^{+77}_{-38}$	$10.70 \pm 5.94$	$0.77 \pm 0.32$	...	52.00/70	Band
	$-1.10 \pm 0.06$	...	...	...	$1.02 \pm 0.16$	...	63.22/68	PL
	$-0.97 \pm 0.10$	...	$1037^{+1184}_{-361}$	...	$1.11 \pm 0.16$	...	51.42/67	CPL*
061007	$-0.95 \pm 0.07$	$-8.96^{+4.62}_{-1.04}$	$888^{+374}_{-207}$	$0.23 \pm 0.06$	$1.13 \pm 0.15$	...	52.13/70	Band
	$-0.94 \pm 0.03$	...	$503 \pm 34$	...	$1.28 \pm 0.07$	$1.25 \pm 0.06$	72.64/109	CPL
	$-0.93 \pm 0.03$	$-2.59^{+0.21}_{-0.36}$	$471 \pm 36$	$104.65 \pm 6.94$	$1.30 \pm 0.07$	$1.27 \pm 0.06$	59.35/108	Band*
061110B	$-1.14 \pm 0.11$	...	...	...	$1.12^{+0.41}_{-0.35}$	...	137.38/72	PL
	$-0.46 \pm 0.21$	...	$428^{+142}_{-92}$	...	$1.10^{+0.29}_{-0.26}$	...	76.32/71	CPL*
	$-0.46 \pm 0.21$	$-4.24^{+2.35}_{-5.76}$	$428 \pm 120$	$9.56 \pm 2.98$	$1.10^{+0.30}_{-0.25}$	...	76.30/70	Band
061202	$-1.55 \pm 0.04$	...	...	...	$0.82 \pm 0.22$	$0.85^{+0.10}_{-0.09}$	120.88/87	PL
	$-1.39 \pm 0.07$	...	$303^{+147}_{-79}$	...	$1.15^{+0.31}_{-0.23}$	$1.04^{+0.14}_{-0.13}$	84.38/86	CPL*
	$-1.39 \pm 0.06$	$-7.27^{+5.40}_{-2.73}$	$193^{+212}_{-81}$	...	$1.14^{+0.61}_{-0.41}$	$1.04^{+0.41}_{-0.10}$	84.38/85	Band
061210	$-1.24 \pm 0.12$	...	...	...	$1.90^{+0.89}_{-0.73}$	$1.81^{+0.89}_{-0.57}$	107.98/87	PL
	$-0.72 \pm 0.20$	...	$718^{+320}_{-203}$	...	$1.51^{+0.52}_{-0.46}$	$1.43^{+0.53}_{-0.40}$	72.21/86	CPL*
	$-0.48 \pm 0.60$	$-1.71^{+0.20}_{-1.16}$	$306^{+439}_{-185}$	$0.15 \pm 0.08$	$1.93^{+1.18}_{-0.92}$	$1.85^{+1.18}_{-0.66}$	69.17/85	Band
061222A	$-1.44 \pm 0.03$	...	...	...	$1.05 \pm 0.15$	...	113.70/74	PL
	$-1.33 \pm 0.05$	...	$691^{+418}_{-249}$	...	$1.37 \pm 0.18$	...	59.66/73	CPL*
	$-1.33 \pm 0.05$	$-9.21^{+19.21}_{-0.79}$	$688^{+305}_{-240}$	...	$1.37 \pm 0.18$	...	59.66/72	Band
070107	$-1.38 \pm 0.05$	...	...	...	$1.11^{+0.15}_{-0.13}$	...	132.95/72	PL
	$-1.12 \pm 0.08$	...	$719^{+215}_{-143}$	...	$1.06 \pm 0.12$	...	71.66/71	CPL*
	$-1.12 \pm 0.08$	$-9.29^{+7.28}_{-0.71}$	$719^{+216}_{-143}$	...	$1.05 \pm 0.12$	...	71.66/70	Band
070318	$-1.56 \pm 0.05$	...	...	...	$1.16 \pm 0.19$	$1.13^{+0.19}_{-0.16}$	96.89/87	PL
	$-1.37 \pm 0.08$	...	$462^{+235}_{-132}$	...	$1.21 \pm 0.18$	$1.21^{+0.19}_{-0.16}$	61.09/86	CPL*
	$-1.34 \pm 0.27$	$-2.15^{+0.36}_{-7.85}$	$365 \pm 284$	$1.45 \pm 0.38$	$1.25^{+0.38}_{-0.29}$	$1.24 \pm 0.18$	60.57/85	Band
070328	$-1.23 \pm 0.04$	...	$1564^{+304}_{-253}$	...	$1.02 \pm 0.07$	...	69.97/82	CPL*
	$-1.20 \pm 0.03$	...	$1627^{+262}_{-322}$	...	$0.99^{+0.09}_{-0.05}$	...	71.35/81	Band
	$-1.62 \pm 0.04$	...	...	...	$0.83 \pm 0.11$	...	116.14/73	PL
070419B	$-1.46 \pm 0.07$	...	$264^{+113}_{-67}$	...	$1.08 \pm 0.15$	...	69.19/72	CPL*
	$-1.46 \pm 0.07$	$-9.31^{+6.64}_{-0.69}$	$264^{+114}_{-66}$	...	$1.08 \pm 0.15$	...	69.19/71	Band
	$-1.17 \pm 0.04$	...	$238 \pm 11$	...	$0.93 \pm 0.03$	$1.27 \pm 0.07$	78.25/86	CPL*
070508	$-1.17 \pm 0.04$	$-3.49^{+0.58}_{-6.51}$	$235 \pm 12$	$9.96 \pm 0.59$	$0.93 \pm 0.03$	$1.27 \pm 0.07$	77.67/85	Band
	$-1.33 \pm 0.15$	...	...	...	$1.18^{+0.62}_{-0.51}$	...	90.58/73	PL
	$-0.92 \pm 0.30$	...	$748^{+1264}_{-433}$	...	$0.92^{+0.46}_{-0.38}$	...	78.97/72	CPL*
070529	$-0.72 \pm 0.87$	$-1.78^{+0.35}_{-8.22}$	$333^{+9538}_{-241}$	...	$1.07^{+0.79}_{-0.59}$	...	78.15/71	Band
	$-1.41 \pm 0.16$	...	...	...	$0.77^{+0.38}_{-0.32}$	...	75.98/72	PL
	$-0.95 \pm 0.31$	...	$290^{+298}_{-108}$	...	$0.85^{+0.36}_{-0.31}$	...	63.21/71	CPL*
070531	$-0.86 \pm 0.64$	$-2.14^{+0.48}_{-7.86}$	$222^{+304}_{-135}$	$6.22 \pm 3.47$	$0.91^{+0.56}_{-0.43}$	...	62.57/70	Band
	$-1.25 \pm 0.16$	...	...	...	$0.56^{+0.34}_{-0.28}$	$0.50^{+0.28}_{-0.19}$	115.22/87	PL
	$-0.23 \pm 0.34$	...	$141^{+57}_{-30}$	...	$1.16^{+0.61}_{-0.51}$	$1.00^{+0.51}_{-0.35}$	87.47/86	CPL*
070612A	$-0.23 \pm 0.73$	$-3.87^{+1.78}_{-6.13}$	$141^{+59}_{-47}$	...	$1.14^{+0.77}_{-0.59}$	$1.00^{+0.64}_{-0.35}$	87.41/85	Band
	$-1.56 \pm 0.07$	...	...	...	$1.24^{+0.30}_{-0.25}$	$1.08^{+0.28}_{-0.20}$	214.19/89	PL
	$-0.70 \pm 0.18$	...	$214^{+42}_{-32}$	...	$1.07 \pm 0.19$	$0.93^{+0.20}_{-0.17}$	91.18/88	CPL*
070616	$-0.62 \pm 0.31$	$-2.55^{+0.40}_{-7.45}$	$189 \pm 59$	$1.14 \pm 0.32$	$1.12^{+0.34}_{-0.28}$	$0.99^{+0.32}_{-0.21}$	89.34/87	Band
	$-1.48 \pm 0.05$	...	...	...	$0.56 \pm 0.11$	...	94.73/72	PL
	$-1.11 \pm 0.14$	...	$140^{+46}_{-25}$	...	$1.12 \pm 0.26$	...	56.71/71	CPL*
070704	$-1.12 \pm 0.14$	$-9.35^{+19.35}_{-0.65}$	$143^{+43}_{-28}$	...	$1.10^{+0.28}_{-0.25}$	...	56.72/70	Band
	$-1.50 \pm 0.04$	...	...	...	$0.85 \pm 0.12$	...	94.63/72	PL
	$-1.43 \pm 0.07$	...	$583^{+1163}_{-267}$	...	$0.99 \pm 0.17$	...	87.24/71	CPL
070714B	$-0.68 \pm 0.47$	$-1.78^{+0.12}_{-0.17}$	$82^{+34}_{-22}$	...	$1.20^{+0.26}_{-0.23}$	...	64.73/70	Band*
	$-1.29 \pm 0.05$	...	...	...	$1.10^{+0.23}_{-0.20}$	$1.19^{+0.24}_{-0.19}$	130.49/89	PL
	$-1.00 \pm 0.09$	...	$1285^{+514}_{-358}$	...	$0.89 \pm 0.16$	...	71.87/88	CPL*
070808	$-0.97 \pm 0.06$	$-2.12^{+0.42}_{-7.88}$	$1044^{+683}_{-342}$	$1.33 \pm 0.34$	$0.91 \pm 0.15$	$1.01^{+0.18}_{-0.12}$	71.31/87	Band
	$-1.46 \pm 0.11$	...	...	...	$0.91 \pm 0.41$	$0.63^{+0.33}_{-0.26}$	99.24/87	PL
	$-1.22 \pm 0.25$	...	$224^{+449}_{-102}$	...	$1.27^{+0.63}_{-0.56}$	$1.03^{+0.65}_{-0.44}$	90.31/86	CPL*
070911	$-0.76 \pm 0.79$	$-2.08^{+0.41}_{-0.61}$	$90^{+172}_{-42}$	...	$1.60^{+0.88}_{-0.78}$	$1.28^{+0.83}_{-0.57}$	88.77/85	Band
	$-1.68 \pm 0.04$	...	...	...	$0.80 \pm 0.11$	...	71.75/73	PL
	$-1.57 \pm 0.10$	...	$242^{+432}_{-100}$	...	$0.98^{+0.21}_{-0.19}$	...	64.47/72	CPL*
070917	$-1.39 \pm 0.34$	$-1.88^{+0.15}_{-0.52}$	$117^{+186}_{-57}$	...	$0.99^{+0.24}_{-0.21}$	...	60.76/71	Band
	$-1.56 \pm 0.05$	...	...	...	$0.87 \pm 0.16$	...	72.26/72	PL
	$-1.47 \pm 0.09$	...	$372^{+605}_{-163}$	...	$1.14 \pm 0.27$	...	63.23/71	CPL*
070923	$-1.31 \pm 0.20$	$-1.95^{+0.25}_{-8.05}$	$161^{+395}_{-64}$	...	$1.31 \pm 0.34$	...	61.19/70	Band
	$-1.52 \pm 0.32$	...	...	...	$1.26^{+1.71}_{-1.23}$	...	78.38/74	PL

**Table 2**  
(Continued)

GRB	$\alpha$	$\beta$	$E_{\text{peak}}$ (keV)	$E_{\text{iso}}$ ( $10^{52}$ erg)	WAM A norm	WAM B norm	$\chi^2/\text{dof}$	Model
	$-0.84 \pm 0.68$	...	$224^{+519}_{-117}$	...	$1.19^{+1.23}_{-0.92}$	...	71.74/73	CPL*
	$-0.86 \pm 0.59$	$-9.26^{+19.26}_{-0.74}$	$229^{+157}_{-131}$	...	$1.18^{+1.02}_{-0.83}$	...	71.74/72	Band
071003	$-1.38 \pm 0.04$	...	...	...	$1.30 \pm 0.16$	...	129.31/73	PL
	$-1.21 \pm 0.05$	...	$1222^{+435}_{-295}$	...	$1.34 \pm 0.14$	...	60.14/72	CPL*
	$-1.22 \pm 0.04$	$-9.27^{+7.14}_{-0.73}$	$1307 \pm 381$	$18.77 \pm 3.29$	$1.33^{+0.16}_{-0.12}$	...	60.76/71	Band
071010B	$-2.02 \pm 0.04$	...	...	...	$0.77 \pm 0.16$	$0.73 \pm 0.15$	76.95/87	PL
	$-1.76 \pm 0.19$	...	$47 \pm 9$	...	$1.13^{+0.44}_{-0.35}$	$1.06^{+0.39}_{-0.24}$	65.75/86	CPL
	$-1.34 \pm 0.47$	$-2.34^{+0.16}_{-0.26}$	$45^{+4}_{-7}$	$2.55 \pm 0.41$	$1.08^{+0.33}_{-0.29}$	$1.01^{+0.31}_{-0.24}$	50.46/85	Band*
071112B	$-1.29 \pm 0.21$	...	...	...	$0.96^{+1.03}_{-0.79}$	$1.26^{+1.03}_{-0.58}$	121.30/91	PL
	$-0.57 \pm 0.50$	...	$690^{+1060}_{-368}$	...	$0.58^{+0.58}_{-0.46}$	$0.74^{+0.54}_{-0.31}$	109.89/90	CPL*
	$-0.57 \pm 0.47$	$-9.37^{+19.37}_{-0.63}$	$688^{+1075}_{-397}$	...	$0.58 \pm 0.36$	$0.74^{+0.54}_{-0.30}$	109.89/89	Band
071227	$-1.29 \pm 0.08$	...	...	...	$2.10^{+0.62}_{-0.54}$	...	109.59/84	PL
	$-0.71 \pm 0.22$	...	$1630^{+738}_{-482}$	...	$1.12^{+0.39}_{-0.34}$	...	79.88/83	CPL*
	$-0.86 \pm 0.13$	...	$1743^{+1119}_{-743}$	$0.12 \pm 0.05$	$1.33^{+0.05}_{-0.24}$	...	82.71/82	Band
080218A <sup>a</sup>	$-2.38 \pm 0.35$	...	...	...	$0.93^{+1.20}_{-0.92}$	...	74.83/74	PL
	$-0.48 \pm 0.82$	...	$32^{+10}_{-8}$	...	$4.69^{+14.74}_{-9.05}$	...	67.46/73	CPL*
	$-0.62 \pm 1.63$	$-8.33^{+18.30}_{-1.67}$	$31^{+10}_{-8}$	...	$4.37^{+9.41}_{-6.14}$	...	67.53/72	Band
080319C	$-1.54 \pm 0.05$	...	...	...	$1.65 \pm 0.27$	$1.43^{+0.18}_{-0.15}$	132.82/89	PL
	$-1.34 \pm 0.07$	...	$1349^{+606}_{-384}$	...	$1.43 \pm 0.23$	$1.20^{+0.15}_{-0.14}$	94.11/88	CPL*
	$-1.33 \pm 0.05$	...	$1332^{+766}_{-353}$	$22.55 \pm 3.35$	$1.23^{+0.37}_{-0.19}$	$1.18^{+0.17}_{-0.08}$	97.87/87	Band
080328	$-1.27 \pm 0.05$	...	...	...	$0.92 \pm 0.14$	$0.54^{+0.13}_{-0.11}$	144.55/88	PL
	$-1.05 \pm 0.09$	...	$411^{+184}_{-109}$	...	$1.36 \pm 0.20$	$0.84^{+0.21}_{-0.18}$	83.73/87	CPL*
	$-1.00 \pm 0.12$	$-2.10^{+0.31}_{-0.71}$	$325^{+136}_{-105}$	...	$1.41 \pm 0.21$	$0.90^{+0.23}_{-0.19}$	79.61/86	Band
080413A	$-1.54 \pm 0.05$	...	...	...	$0.54 \pm 0.09$	...	103.93/73	PL
	$-1.29 \pm 0.12$	...	$179^{+102}_{-45}$	...	$0.89 \pm 0.20$	...	80.40/72	CPL*
	$-1.15 \pm 0.29$	$-2.12^{+0.33}_{-7.88}$	$126^{+131}_{-42}$	$11.95 \pm 3.10$	$0.95 \pm 0.23$	...	78.25/71	Band
080413B	$-1.92 \pm 0.06$	...	...	...	$0.87 \pm 0.13$	$0.72^{+0.11}_{-0.09}$	143.54/87	PL
	$-1.51 \pm 0.12$	...	$83^{+14}_{-11}$	...	$1.30 \pm 0.22$	$1.05^{+0.18}_{-0.16}$	76.08/86	CPL
	$-1.24 \pm 0.26$	$-2.77^{+0.22}_{-0.27}$	$67^{+13}_{-8}$	$2.09 \pm 0.28$	$1.59 \pm 0.33$	$1.28^{+0.28}_{-0.24}$	64.12/85	Band*
080605	$-1.55 \pm 0.03$	...	...	...	$0.74^{+0.08}_{-0.08}$	...	229.97/83	PL
	$-1.31 \pm 0.05$	...	$313^{+72}_{-51}$	...	$1.07 \pm 0.11$	...	60.76/82	CPL*
	$-1.30 \pm 0.06$	$-2.59^{+0.39}_{-7.41}$	$291 \pm 75$	$26.87 \pm 3.37$	$1.09^{+0.14}_{-0.12}$	...	58.59/81	Band
080623	$-1.51 \pm 0.14$	...	...	...	$1.05^{+0.53}_{-0.45}$	...	89.48/72	PL
	$-1.22 \pm 0.24$	...	$227^{+273}_{-90}$	...	$1.55^{+0.79}_{-0.66}$	...	78.50/71	CPL*
	$-1.22 \pm 0.22$	$-9.35^{+7.36}_{-0.65}$	$227^{+282}_{-46}$	...	$1.55^{+0.81}_{-0.67}$	...	78.50/70	Band
080727C	$-1.28 \pm 0.04$	...	...	...	$0.46 \pm 0.06$	...	168.71/73	PL
	$-1.08 \pm 0.08$	...	$302^{+157}_{-83}$	...	$0.72 \pm 0.13$	...	111.30/72	CPL
	$-0.71 \pm 0.23$	$-1.82 \pm 0.20$	$121^{+37}_{-30}$	...	$0.90 \pm 0.17$	...	94.16/71	Band*
080916A	$-1.47 \pm 0.04$	...	...	...	$0.71 \pm 0.14$	$0.57 \pm 0.11$	145.61/89	PL
	$-1.15 \pm 0.13$	...	$169^{+64}_{-34}$	...	$1.20 \pm 0.23$	$0.88^{+0.19}_{-0.17}$	95.22/88	CPL*
	$-0.95 \pm 0.26$	$-2.15^{+0.27}_{-7.85}$	$121^{+80}_{-25}$	$1.21 \pm 0.46$	$1.27 \pm 0.25$	$0.94^{+0.20}_{-0.18}$	93.48/87	Band
081025	$-1.23 \pm 0.06$	...	...	...	$0.58^{+0.12}_{-0.11}$	...	144.91/72	PL
	$-0.92 \pm 0.10$	...	$342^{+117}_{-77}$	...	$0.88 \pm 0.16$	...	69.27/71	CPL*
	$-0.92 \pm 0.08$	$-9.37^{+19.37}_{-0.63}$	$343^{+117}_{-85}$	...	$0.88 \pm 0.16$	...	69.27/70	Band
081109A	$-1.65 \pm 0.06$	...	...	...	$1.02 \pm 0.27$	...	83.86/72	PL*
	$-1.38 \pm 0.25$	...	$120^{+364}_{-34}$	...	$1.80^{+1.00}_{-0.80}$	...	78.69/71	CPL
	$-1.27 \pm 0.34$	$-2.19^{+0.42}_{-0.95}$	$99^{+73}_{-40}$	...	$1.76^{+0.94}_{-0.79}$	...	74.72/70	Band
090301A	$-1.14 \pm 0.02$	...	$637 \pm 47$	...	$1.26 \pm 0.07$	$1.13 \pm 0.07$	127.99/108	CPL
	$-1.13 \pm 0.02$	$-2.53^{+0.15}_{-0.22}$	$574 \pm 46$	...	$1.31 \pm 0.07$	$1.18 \pm 0.07$	100.08/107	Band*
090401A	$-1.76 \pm 0.04$	...	...	...	$0.95 \pm 0.10$	$1.00^{+0.14}_{-0.12}$	126.00/107	PL
	$-1.66 \pm 0.05$	...	$359^{+164}_{-91}$	...	$1.11 \pm 0.13$	$1.21^{+0.17}_{-0.16}$	99.10/108	CPL
	$-1.43 \pm 0.16$	$-2.11 \pm 0.10$	$117^{+61}_{-25}$	...	$1.42 \pm 0.20$	$1.52^{+0.25}_{-0.22}$	76.37/105	Band*
090401B	$-0.99 \pm 0.08$	...	$259^{+66}_{-44}$	...	$1.57 \pm 0.22$	...	62.96/72	CPL
	$-0.89 \pm 0.11$	$-2.32^{+0.21}_{-0.39}$	$205^{+55}_{-37}$	...	$1.73 \pm 0.25$	...	52.82/71	Band*
090410	$-1.42 \pm 0.04$	...	...	...	$1.14^{+0.16}_{-0.14}$	$0.99^{+0.16}_{-0.12}$	259.82/89	PL
	$-1.02 \pm 0.08$	...	$342^{+88}_{-61}$	...	$1.27 \pm 0.16$	$1.16^{+0.16}_{-0.14}$	95.71/88	CPL*
	$-0.98 \pm 0.10$	$-2.23^{+0.25}_{-0.54}$	$290 \pm 80$	...	$1.34^{+0.23}_{-0.20}$	$1.22^{+0.20}_{-0.16}$	89.72/87	Band
090418B	$-1.77 \pm 0.03$	...	...	...	$0.56 \pm 0.07$	$0.98^{+0.13}_{-0.12}$	125.38/89	PL
	$-1.58 \pm 0.07$	...	$153^{+52}_{-29}$	...	$0.75 \pm 0.11$	$1.40^{+0.22}_{-0.19}$	77.68/88	CPL*
	$-1.49 \pm 0.15$	$-2.38^{+0.21}_{-7.62}$	$116^{+85}_{-22}$	...	$0.83 \pm 0.15$	$1.52^{+0.27}_{-0.31}$	77.12/87	Band
090424	$-1.34 \pm 0.05$	...	$204^{+27}_{-22}$	...	$0.59 \pm 0.07$	$0.57 \pm 0.07$	113.00/108	CPL*
	$-1.06 \pm 0.24$	$-2.50^{+0.11}_{-1.13}$	$116^{+94}_{-15}$	$4.19 \pm 0.34$	$0.78^{+0.13}_{-0.17}$	$0.76^{+0.12}_{-0.22}$	108.56/107	Band

**Notes.** The fit parameters  $\alpha$ ,  $\beta$ ,  $E_{\text{peak}}$ , and  $E_{\text{iso}}$  are defined in Section 2. WAM A/B norm: these are the constants  $C$  defined in Section 2 for the WAM data. Model: the best-fit model (by the  $\Delta\chi^2$  test) is indicated with an asterisk. <sup>a</sup> Since the WAM normalization is anomalously large, we quote fit parameters derived from the BAT data alone for this burst.

**Table 3**

Spectral Parameters for BAT/WAM Bursts Fitted Only by a Power-law Model

GRB	$\alpha$	$E_{\text{peak}}$ (keV)	WAM A norm	WAM B norm	$\chi^2/\text{dof}$
051006	$-1.49 \pm 0.11$	$104^{+411}_{-62}$	$0.94^{+0.29}_{-0.25}$	...	94.11/73
051213	$-1.66 \pm 0.19$	$75^{+205}_{-28}$	$1.38^{+0.76}_{-0.63}$	...	84.52/72
060110	$-1.67 \pm 0.08$	$74^{+194}_{-32}$	$0.94 \pm 0.31$	...	62.85/72
060211A	$-1.76 \pm 0.11$	$58^{+18}_{-8}$ a	$1.11 \pm 0.36$	...	96.03/73
060223A	$-1.76 \pm 0.12$	$62^{+129}_{-12}$	$0.68^{+0.27}_{-0.24}$	...	91.92/73
060322	$-1.60 \pm 0.07$	$96^{+90}_{-16}$ a	$0.63 \pm 0.15$	...	80.49/72
060413	$-1.67 \pm 0.07$	$74^{+194}_{-22}$	$1.50 \pm 0.29$	...	78.19/72
060607B	$-1.64 \pm 0.11$	$79^{+230}_{-28}$	$0.89^{+0.27}_{-0.24}$	...	78.29/72
060729	$-1.72 \pm 0.12$	$68^{+160}_{-16}$	$1.04 \pm 0.37$	...	61.66/73
060912A	$-1.73 \pm 0.07$	$66^{+151}_{-15}$	$0.68 \pm 0.16$	...	69.30/69
070612B	$-1.62 \pm 0.12$	$81^{+244}_{-30}$	$0.16 \pm 0.10$	...	54.03/72
070913	$-1.50 \pm 0.25$	$103^{+402}_{-60}$	$0.96^{+0.84}_{-0.66}$	...	73.38/73
080123	$-1.34 \pm 0.14$	$141^{+651}_{-98}$	$1.25^{+0.57}_{-0.46}$	...	77.19/74
080303	$-1.30 \pm 0.23$	$150^{+692}_{-100}$	$0.99^{+0.63}_{-0.53}$	...	69.12/74
080409	$-2.12 \pm 0.20$	$31^{+34}_{-2}$	$0.57^{+0.49}_{-0.44}$	...	64.39/74
080701	$-2.22 \pm 0.15$	$26^{+28}_{-2}$	$1.72^{+1.05}_{-0.90}$	$1.15^{+1.16}_{-0.97}$	78.17/87
080707	$-1.78 \pm 0.17$	$61^{+123}_{-11}$	$1.21^{+0.72}_{-0.62}$	...	86.92/72
080805	$-0.55 \pm 0.21$	...	$0.16^{+0.16}_{-0.12}$	...	84.26/69
080905A	$-1.12 \pm 0.19$	...	$1.32^{+0.96}_{-0.76}$	...	69.54/72
081008	$-1.63 \pm 0.07$	$81^{+239}_{-29}$	$1.03 \pm 0.22$	...	68.36/72
081022	$-1.67 \pm 0.10$	$74^{+194}_{-22}$	$1.17 \pm 0.40$	...	68.17/72
090113	$-1.61 \pm 0.09$	$83^{+257}_{-33}$	$0.75 \pm 0.31$	...	65.69/72
090123	$-1.64 \pm 0.12$	$78^{+222}_{-26}$	$1.02^{+0.32}_{-0.28}$	...	63.54/72
090305	$-1.35 \pm 0.30$	$137^{+628}_{-96}$	$1.36^{+1.70}_{-1.27}$	...	75.12/73

**Notes.** For all bursts except those noted,  $E_{\text{peak}}$  values are estimated from the S09  $\alpha - E_{\text{peak}}$  relation (see text). WAM A/B norms are as explained in the caption to Table 2.

<sup>a</sup> This burst has a fit  $E_{\text{peak}}$  from S08.

can see an interesting trend in Figures 4(a) and 5(b). Bursts for which the Band model is statistically favored tend to have a hard  $\alpha \sim -1.0$ , but a low  $E_{\text{peak}} \sim 80$  keV (the dashed histogram in Figure 4(a) and blue points in Figure 5(b)). Beyond this set, we find a large sample of bursts (the solid histogram in Figure 4(a)) for which the Band model is an acceptable fit, but not statistically favored over the CPL model. For these bursts, one finds a much broader distribution of  $E_{\text{peak}}$  values with a higher average,  $E_{\text{peak}} \sim 300$  keV. This tells us that for most bursts with a moderate  $E_{\text{peak}} : \sim 100 \text{ keV} < E_{\text{peak}} < 1000 \text{ keV}$ , both the Band and the CPL models produce acceptable fits, but only those bursts with a particularly low  $E_{\text{peak}}$  have a sufficient flux above the spectral break for the Band model to be favored by more than  $\Delta\chi^2 > 6.0$ . We can see from the fourth column of Table 6 that most of the bursts which are “Band-acceptable/CPL-favored” (BACF) have a distribution of the high-energy Band parameter  $\beta$  quite similar to the “Band-best” bursts. For these bursts, we are fitting mostly to the part of the Band spectrum below the break energy, where a cutoff power law dominates. An inclusion of part of the spectrum above the break softens the apparent  $\alpha$ . Some of the bursts in the BACF set do have  $\beta$  values outside the main distribution ( $\beta \lesssim -7$ ), suggesting that we are only deriving an upper limit for  $\beta$  values for these bursts.

### 3.3. Band Spectral Fits

Even with the extended energy range of BAT and WAM, we have a minority of bursts for which the Band model is unambiguously the best fit. Earlier studies of burst spectra have shown that the form of the fit model that yields the lowest

**Table 4**

Fluence Values for BAT/WAM Bursts

GRB	Fluence ( $10^{-6} \text{ erg cm}^{-2}$ )		
	15–150 keV	15–2000 keV	1–10000 keV
050904	$4.7 \pm 0.19$	$16.4 \pm 4.89$	$24.2^{+17.07}_{-11.31}$
050915B	$3.3 \pm 0.15$	$6.3^{+1.28}_{-1.81}$	$8.4^{+2.28}_{-2.39}$
051008	$5.8 \pm 0.15$	$32.6^{+1.79}_{-2.53}$	$44.1 \pm 5.84$
051111	$4.1 \pm 0.13$	$14.4^{+4.09}_{-2.30}$	$19.7^{+15.29}_{-6.40}$
051221A	$0.9^{+0.04}_{-0.02}$	$3.0^{+0.74}_{-0.39}$	$3.5^{+3.01}_{-3.50}$
060105	$18.0 \pm 0.30$	$65.0^{+6.33}_{-4.11}$	$74.8^{+138.38}_{-8.22}$
060111A	$1.1^{+0.05}_{-0.04}$	$2.2^{+0.47}_{-0.54}$	$2.8^{+0.54}_{-0.93}$
060111B	$1.6 \pm 0.14$	$7.8^{+2.11}_{-2.35}$	$10.5^{+6.77}_{-4.91}$
060117	$20.4 \pm 0.21$	$28.1^{+9.63}_{-0.08}$	$43.3^{+5.14}_{-0.66}$
060124	$8.9 \pm 0.25$	$20.5 \pm 2.40$	$26.2^{+5.21}_{-4.09}$
060204B	$2.3 \pm 0.10$	$7.8^{+2.80}_{-2.40}$	$14.4^{+9.12}_{-6.96}$
060306	$1.7 \pm 0.11$	$3.2^{+0.81}_{-0.63}$	$4.6^{+1.31}_{-1.46}$
060421	$1.2 \pm 0.06$	$2.4^{+0.59}_{-0.45}$	$2.9^{+1.71}_{-0.54}$
060501	$1.1 \pm 0.08$	$2.8^{+0.93}_{-0.61}$	$3.6^{+2.20}_{-1.26}$
060502A	$2.2^{+0.13}_{-0.11}$	$5.8^{+3.29}_{-1.92}$	$7.9^{+10.57}_{-3.50}$
060505	$0.7 \pm 0.13$	$2.3^{+1.08}_{-0.66}$	$2.8^{+1.95}_{-0.84}$
060801	$0.09 \pm 0.01$	$0.9^{+0.08}_{-0.10}$	$1.3^{+1.68}_{-0.83}$
060813	$4.7 \pm 0.09$	$13.5^{+0.27}_{-1.77}$	$15.4^{+0.64}_{-2.22}$
060814	$13.9 \pm 0.28$	$42.5^{+5.14}_{-4.11}$	$66.7^{+25.98}_{-7.70}$
060825	$1.0 \pm 0.04$	$2.2^{+0.45}_{-0.60}$	$3.5^{+0.55}_{-1.16}$
060904A	$7.5 \pm 0.17$	$19.9^{+5.24}_{-1.67}$	$28.5^{+22.04}_{-3.23}$
060904B	$1.0^{+0.06}_{-0.05}$	$3.7^{+1.24}_{-1.43}$	$6.6^{+4.60}_{-3.59}$
060908	$2.7 \pm 0.12$	$6.8^{+3.81}_{-2.49}$	$8.8^{+10.93}_{-4.00}$
061006	$0.5 \pm 0.02$	$1.6 \pm 0.03$	$2.5^{+4.26}_{-0.08}$
061007	$43.7 \pm 0.52$	$232.8^{+1.56}_{-73.73}$	$289.7^{+4.83}_{-105.62}$
061110B	$0.7 \pm 0.04$	$3.5^{+1.42}_{-0.77}$	$5.4 \pm 3.01$
061202	$2.8^{+0.07}_{-0.11}$	$6.9^{+0.21}_{-0.16}$	$13.6^{+3.71}_{-7.02}$
061210	$0.3 \pm 0.03$	$2.6^{+0.47}_{-1.59}$	$4.2^{+1.85}_{-2.20}$
061222A	$8.1 \pm 0.16$	$28.1^{+4.98}_{-3.49}$	$32.5^{+5.65}_{-4.63}$
070107	$4.1 \pm 0.15$	$20.0^{+3.23}_{-2.57}$	$26.3^{+9.33}_{-7.30}$
070318	$1.7 \pm 0.06$	$5.2^{+0.87}_{-0.78}$	$8.2^{+2.51}_{-1.90}$
070328	$9.0^{+0.16}_{-0.25}$	$61.1^{+4.06}_{-8.33}$	$79.9^{+14.02}_{-1.90}$
070419B	$6.2 \pm 0.14$	$13.8^{+2.73}_{-1.65}$	$16.6^{+2.68}_{-2.31}$
070508	$19.3 \pm 0.25$	$42.5^{+2.26}_{-0.70}$	$46.3^{+6.53}_{-0.76}$
070520B	$0.7 \pm 0.10$	$3.7^{+3.03}_{-1.71}$	$6.9^{+7.30}_{-4.52}$
070529	$1.1 \pm 0.14$	$3.4^{+1.99}_{-1.32}$	$4.4^{+5.88}_{-2.21}$
070531	$0.5^{+0.06}_{-0.06}$	$1.0^{+0.59}_{-0.30}$	$0.9^{+0.98}_{-0.23}$
070612A	$3.5 \pm 0.22$	$9.0 \pm 1.86$	$9.5^{+4.44}_{-2.75}$
070616	$5.3 \pm 0.18$	$9.2^{+1.67}_{-1.28}$	$10.0^{+2.38}_{-1.90}$
070704	$3.2 \pm 0.09$	$10.4^{+2.20}_{-1.91}$	$17.1^{+7.60}_{-4.65}$
070714B	$0.5^{+0.01}_{-0.02}$	$3.9^{+0.54}_{-0.87}$	$6.4^{+0.98}_{-2.47}$
070808	$0.9 \pm 0.07$	$2.2^{+1.34}_{-0.75}$	$3.0^{+3.81}_{-1.36}$
070911	$8.3^{+0.21}_{-0.18}$	$21.0^{+6.48}_{-4.67}$	$34.4^{+15.65}_{-12.23}$
070917	$2.0^{+0.05}_{-0.06}$	$6.1^{+1.28}_{-2.08}$	$8.8^{+4.45}_{-3.31}$
070923	$0.04 \pm 0.01$	$0.1^{+0.12}_{-0.05}$	$0.1^{+0.32}_{-0.06}$
071003	$7.2 \pm 0.17$	$40.3^{+1.52}_{-9.33}$	$46.6^{+1.61}_{-11.35}$
071010B	$4.2 \pm 0.12$	$7.0^{+0.75}_{-1.06}$	$10.0^{+1.35}_{-1.95}$
071112B	$0.06^{+0.01}_{-0.01}$	$0.5^{+0.60}_{-0.08}$	$0.6^{+0.91}_{-0.40}$
071227	$0.1 \pm 0.02$	$1.1^{+2.92}_{-0.18}$	$1.1^{+0.15}_{-0.06}$
080218A	$0.6 \pm 0.12$	$0.6^{+0.12}_{-0.10}$	$0.9^{+0.67}_{-0.29}$
080319C	$3.6^{+0.18}_{-0.11}$	$20.1 \pm 1.04$	$25.3^{+5.16}_{-3.42}$
080328	$4.5^{+0.13}_{-0.12}$	$16.7^{+3.66}_{-2.81}$	$24.0^{+10.78}_{-9.22}$
080413A	$2.8^{+0.12}_{-0.08}$	$8.5^{+1.43}_{-1.19}$	$16.4^{+3.51}_{-11.37}$
080413B	$3.1 \pm 0.12$	$4.4^{+0.47}_{-0.41}$	$5.7^{+0.80}_{-0.71}$
080605	$11.2 \pm 0.20$	$32.1^{+1.66}_{-6.40}$	$38.3^{+5.05}_{-8.44}$
080623	$1.0 \pm 0.09$	$2.2^{+1.11}_{-0.81}$	$2.0^{+4.81}_{-0.43}$
080727C	$5.1 \pm 0.15$	$16.6^{+4.82}_{-3.25}$	$28.4^{+14.90}_{-9.57}$
080916A	$2.9 \pm 0.09$	$8.3^{+1.00}_{-3.70}$	$9.1^{+4.96}_{-0.51}$
081025	$1.8^{+0.04}_{-0.07}$	$6.7^{+2.09}_{-1.24}$	$6.9^{+0.42}_{-1.25}$
081109A	$2.5^{+0.10}_{-0.05}$	$4.6^{+3.31}_{-1.07}$	$7.5^{+6.48}_{-3.24}$
090301A	$23.1^{+0.26}_{-0.20}$	$93.9^{+12.14}_{-1.12}$	$117.1^{+20.22}_{-2.40}$
090401A	$8.3^{+0.21}_{-0.17}$	$17.3^{+2.82}_{-2.77}$	$25.0^{+5.52}_{-2.77}$
090401B	$8.7 \pm 0.15$	$25.6^{+1.97}_{-5.24}$	$32.1^{+4.95}_{-8.31}$

**Table 4**  
(Continued)

GRB	Fluence ( $10^{-6}$ erg $\text{cm}^{-2}$ )		
	15–150 keV	15–2000 keV	1–10000 keV
090410	$5.5 \pm 0.16$	$18.5^{+2.81}_{-2.50}$	$24.7^{+6.59}_{-5.75}$
090418B	$15.9^{+0.37}_{-0.30}$	$28.6^{+5.44}_{-2.05}$	$37.4^{+12.66}_{-2.65}$
090424	$19.4 \pm 0.39$	$32.7^{+11.53}_{-0.68}$	$39.4^{+13.77}_{-1.08}$

$\chi^2$  depends where  $E_{\text{peak}}$  falls with respect to the high- and low-energy bounds of the detector. In particular, Band et al. (1993) show through simulations that even when the Band model is the intrinsic spectrum of a burst, increasing the lower energy bound in the fit biases fits toward simpler models. They also show that, on average, fits to bursts with low signal-to-noise ratios (S/N) yield the correct fit parameters, but that the dispersion in the fit parameters increases with decreasing S/N. Later work by S09 shows that it is difficult to fit bursts with low  $E_{\text{peak}}$  with a CPL or Band model because there is not sufficient data on *both* sides of  $E_{\text{peak}}$  to adequately constrain a model with a break. In short, the results of Band et al. (1993) and S09 tell us that while all bursts are probably representable by the Band model, simpler models are often found to be acceptable or even statistically favored. The distribution of fit parameters and the nature of the best-fit models found in our work are consistent with these conclusions.

### 3.4. Possible Biases in the $E_{\text{peak}}$ Distributions

In Section 2, we noted that we will use parameters derived from the Band model for the correlations to be examined in Section 4. Thus, it is important to verify that the  $E_{\text{peak}}$  values derived from the Band fit for the BACF bursts are acceptable to use. We conclude that this is the case for several reasons. First of all, as discussed above, spectral studies and simulations show that the Band model is likely to be able to represent all long GRB spectra. Secondly, all bursts for which a CPL model was the best fit could also be acceptably fitted with a Band model. Thirdly, in Figure 4(a), we see that the distributions of  $E_{\text{peak}}$  values derived from the CPL model and from the Band model are nearly identical and have median values that agree to within error (see Table 6). Finally, we find in Figure 6 that the correspondence between the two  $E_{\text{peak}}$  values (CPL and Band) is good. We do see a clear trend for the CPL model to find a higher  $E_{\text{peak}}$  than the Band model for a given burst. This makes sense if we assume that the Band model represents the intrinsic spectrum: fitting such a spectrum to a model without a separate high-energy component requires a higher cutoff energy to adequately fit the high-energy data. This is to be expected, based on an examination of the functional forms of the two models (Equations (2) and (3)) we see that the models are the same for  $E < E_c$ , differing only in their behavior when  $E > E_c$ . And using the median values for  $\alpha$  and  $\beta$ , we get  $E_c \approx 1.3E_{\text{peak}}$ . As we will see in Section 3.5 (Figure 8), the BAT/WAM  $E_{\text{peak}}$  distribution matches the BATSE distribution in the center. These correlations indicate that it is acceptable to use the Band model-derived  $E_{\text{peak}}$  values (and  $E_{\text{iso}}$  derived from a Band model) for bursts where the Band model is acceptable, though not necessarily favored by the  $\chi^2$  test. We only include bursts for which we have a good fit, not just an estimate of  $E_{\text{peak}}$ —therefore, we do not include in our  $E_{\text{peak}}-E_{\text{iso}}$  plots, bursts for which estimated  $E_{\text{peak}}$  values are listed in Table 3. It turns out that neither of the two bursts in Table 3 with fit, rather than calculated,  $E_{\text{peak}}$  values have measured redshifts.

In order to study any possible overall bias in our data, we have compared our  $E_{\text{peak}}$  values with those independently derived from bursts that also triggered the *WIND/Konus* instrument (Aptekar et al. 1995). The results of the 21 bursts that triggered both BAT/WAM and Konus are plotted in Figure 7. For 12 of these bursts (shown as diamonds in Figure 7), T. Sakamoto et al. (2009, in preparation) matched exactly the time interval quoted by Konus in the literature to a corresponding time interval in the BAT and WAM light curves, and so were able to calculate  $E_{\text{peak}}$  values that could be directly compared with the Konus values. For these bursts we use the values from T. Sakamoto et al. (2009, in preparation) in the plot and the fits. For the other nine bursts (triangles in Figure 7), we do not have the precise relative timing information with Konus, so we show  $E_{\text{peak}}$  values from this work as close in time as possible to the Konus times. These bursts are shown on the plot for comparison, but are not included in the fits.

Fitting a straight line to the data (dashed line in Figure 7) gives  $E_{\text{peak}}^{\text{Konus}} = (19.5 \pm 8.1) + (0.89 \pm 0.05) * E_{\text{peak}}^{\text{BAT-WAM}}$ ,  $\chi^2 = 7.8$  for 10 degrees of freedom (dof). This is formally  $2.5\sigma$  away from the line  $E_{\text{peak}}^{\text{Konus}} = E_{\text{peak}}^{\text{BAT-WAM}}$  (solid line in Figure 7). A weighted mean of the ratio  $E_{\text{peak}}^{\text{BAT-WAM}}/E_{\text{peak}}^{\text{Konus}}$  (dominated by GRB 060117, the point at the lower left with very small errors) is  $0.9 \pm 0.24$ , and without weighting the mean is  $1.1 \pm 0.24$ . The straight-line fit suggests a small ( $\sim 10\%$ ) bias toward larger  $E_{\text{peak}}$  values for BAT/WAM compared with Konus, and both calculations of the mean of the ratios are consistent with unity and inconclusive as to a systematic bias toward higher or lower  $E_{\text{peak}}^{\text{BAT-WAM}}$ . T. Sakamoto et al. (2009, in preparation) find a 20% systematic bias in  $E_{\text{peak}}^{\text{BAT-WAM}}$  with respect to  $E_{\text{peak}}^{\text{Konus}}$  (BAT-WAM higher), which they attribute to the smaller energy ranges of BAT and WAM compared with Konus. But even a 20% bias is relatively small and as shown below does not significantly impact our results. T. Sakamoto et al. (2009, in preparation) have also found a 10%–20% systematic bias in the BAT normalization with respect to *WIND/Konus*. However, if we increase  $E_{\text{iso}}$  and decrease  $E_{\text{peak}}$  values by random percentages within this range, we do not see a significant change in  $E_{\text{peak}}-E_{\text{iso}}$  fit parameters.

### 3.5. Distributions of Model Fit Parameters

The distributions of the model fit parameters  $\alpha$  and  $E_{\text{peak}}$  can be seen in the scatter plots of Figure 5 and the solid black histograms of Figures 2(a) and 4(c). We first compare the distribution of  $\alpha$  with the limits on the photon index determined for the emission process in which  $\gamma$  rays are produced by synchrotron emission by relativistic electrons in intense magnetic fields. At the low end, the photon index cannot be less than  $-3/2$ , which is the limit derived from the synchrotron power-law emission formula (Rybicki & Lightman 1979) for a cooling distribution of particles characterized by a power index of  $-2$  (Preece et al. 1998). The examination of Figure 2(a) shows that for GRBs fit to the CPL or Band models, only about 13% have  $\alpha < -3/2$ , and the error bars for all of these extend above the limit. Bursts with a PL fit do extend well below the limit, but as discussed in Section 3.1, the  $\alpha$  parameter in a PL fit is not the true low-energy index of the Band model, but rather a slope intermediate between the Band model  $\alpha$  and  $\beta$ . Thus, like other authors (Preece et al. 1998; Ghirlanda et al. 2003) have found, our sample does not violate this lower limit. At the high end, the theory of optically thin synchrotron emission predicts (Katz 1994) that  $\alpha$  cannot exceed  $-2/3$ . However, a number of authors (e.g., Preece et al. 1998; Ghirlanda et al. 2003) have found a significant number of bursts

**Table 5**  
Time-resolved Spectral Parameters of BAT/WAM Bursts

GRB	Sequence	Interval	$\alpha$	$\beta$	$E_{\text{peak}}$ (keV)	$E_{\text{iso}}$ ( $10^{52}$ erg s)	$\chi^2/\text{dof}$	Model
050904	slew	73.63–148.63 (sl)	$-1.31 \pm 0.07$	...	...	...	102.93/89	PL
			$-1.03 \pm 0.19$	...	$266^{+458}_{-102}$	...	84.31/88	CPL
			$-0.73 \pm 0.51$	$-1.82^{+0.28}_{-0.39}$	$131^{+127}_{-62}$	$45.70 \pm 13.70$	78.15/87	Band*
	seq3	100.63–148.63 (sl)	$-1.25 \pm 0.07$	...	...	...	105.51/89	PL
			$-0.90 \pm 0.17$	...	$247^{+177}_{-76}$	...	74.50/88	CPL*
			$-0.74 \pm 0.35$	$-1.93^{+0.31}_{-8.07}$	$168^{+195}_{-61}$	$35.10 \pm 10.10$	72.38/87	Band
postslew	148.63–216.63	$-1.33 \pm 0.09$	...	...	...	100.93/89	PL	
		$-1.05 \pm 0.18$	...	$276^{+303}_{-100}$	...	83.22/88	CPL*	
		$-1.05 \pm 0.18$	$-2.88^{+1.10}_{-7.12}$	$278^{+293}_{-104}$	$27.30 \pm 10.48$	83.08/87	Band	
050915B	seq1	148.63–216.63	$-1.89 \pm 0.06$	...	...	...	79.29/73	PL
			$-1.52 \pm 0.24$	...	$65^{+28}_{-10}$	...	69.31/72	CPL*
			$-1.36 \pm 0.39$	$-2.35^{+0.31}_{-1.27}$	$59 \pm 14$	...	65.83/71	Band
051008	seq2	–9.82–4.18	$-1.06 \pm 0.07$	...	$788^{+124}_{-99}$	...	150.00/108	CPL
			$-1.00 \pm 0.08$	$-2.18^{+0.20}_{-0.36}$	$652^{+114}_{-96}$	...	140.26/107	Band*
	seq3	4.18–11.18	$-0.92 \pm 0.07$	...	$738 \pm 70$	...	85.30/108	CPL
051111	seq1	–24.82–21.18	$-0.88 \pm 0.08$	$-2.48^{+0.30}_{-0.71}$	$669 \pm 85$	...	78.83/107	Band*
			$-1.36 \pm 0.04$	...	...	...	134.93/87	PL
			$-1.21 \pm 0.06$	...	$512^{+186}_{-118}$	...	77.19/86	CPL*
060105	preslew	–20.77–14.23	$-1.21 \pm 0.07$	$-3.21^{+9.77}_{-6.79}$	$509 \pm 196$	$10.48 \pm 2.79$	77.19/85	Band
			$-1.06 \pm 0.04$	...	...	...	189.35/73	PL
			$-0.92 \pm 0.06$	...	$826^{+290}_{-217}$	...	67.24/72	CPL*
060111A	slew	14.23–66.23 (sl)	$-0.91 \pm 0.07$	$-2.77^{+0.77}_{-7.23}$	$743^{+824}_{-277}$	...	67.11/71	Band
			$-1.21 \pm 0.04$	...	...	...	86.17/73	PL
			$-1.00 \pm 0.13$	...	$302^{+320}_{-92}$	...	67.83/72	CPL*
060111B	seq1	–6.42–61.58	$-1.00 \pm 0.13$	$-2.15^{+0.48}_{-7.85}$	$301^{+267}_{-95}$	...	66.11/71	Band
			$-1.58 \pm 0.06$	...	...	...	138.24/87	PL
			$-1.14 \pm 0.21$	...	$113^{+44}_{-23}$	...	102.28/86	CPL
060111B	seq1	–2.65–3.35	$-0.41 \pm 0.44$	$-2.33^{+0.27}_{-0.33}$	$68^{+12}_{-10}$	...	85.01/85	Band*
			$-1.36 \pm 0.10$	...	...	...	129.60/72	PL
			$-0.65 \pm 0.23$	...	$474^{+148}_{-95}$	...	85.31/71	CPL*
060111B	preslew	–2.65–13.35	$-0.62 \pm 0.24$	$-2.35^{+0.54}_{-7.65}$	$443^{+143}_{-105}$	...	84.24/70	Band
			$-1.39 \pm 0.10$	...	...	...	134.56/72	PL
			$-0.61 \pm 0.23$	...	$457^{+117}_{-79}$	...	81.31/71	CPL*
060111B	seq1-3	–2.65–25.35 (sl)	$-0.60 \pm 0.23$	$-2.70^{+0.69}_{-7.30}$	$450^{+110}_{-80}$	...	80.57/70	Band
			$-1.47 \pm 0.08$	...	...	...	158.62/72	PL
			$-0.69 \pm 0.19$	...	$435^{+92}_{-67}$	...	87.25/71	CPL*
060111B	seq2	3.35–13.35	$-0.68 \pm 0.20$	$-2.86^{+0.75}_{-7.14}$	$425^{+99}_{-70}$	...	87.07/70	Band
			$-1.49 \pm 0.17$	...	...	...	86.09/72	PL
			$-0.64 \pm 0.43$	...	$428^{+198}_{-107}$	...	67.65/71	CPL*
060111B	seq3	13.35–25.35 (sl)	$-0.63 \pm 0.43$	$-3.21^{+1.27}_{-6.79}$	$428^{+193}_{-107}$	...	67.58/70	Band
			$-1.58 \pm 0.16$	...	...	...	81.38/72	PL
			$-0.74 \pm 0.39$	...	$390^{+177}_{-100}$	...	60.61/71	CPL*
060117	seq1	–2.04–0.04	$-0.69 \pm 0.42$	...	$364^{+209}_{-132}$	...	60.74/70	Band
			$-1.89 \pm 0.08$	...	...	...	127.37/109	PL
			$-1.68 \pm 0.13$	...	$141^{+101}_{-46}$	...	111.46/108	CPL*
060117	seq2	–0.04–5.96	$-1.65 \pm 0.23$	$-2.54^{+0.39}_{-7.46}$	$120^{+139}_{-51}$	...	112.02/107	Band
			$-1.86 \pm 0.03$	...	...	...	306.01/109	PL
			$-1.63 \pm 0.05$	...	$136^{+20}_{-16}$	...	142.62/108	CPL
060117	seq3	5.96–8.96	$-1.49 \pm 0.11$	$-2.39^{+0.10}_{-0.16}$	$93^{+24}_{-15}$	...	128.63/107	Band*
			$-2.31 \pm 0.08$	...	...	...	110.22/109	PL
			$-1.92 \pm 0.11$	...	$9^{+2}_{-1}$	...	108.01/108	CPL
060117	seq4	8.96–10.96	$-1.70 \pm 0.28$	$-2.79^{+0.29}_{-0.49}$	$19^{+9}_{-12}$	...	99.25/107	Band*
			$-1.98 \pm 0.03$	...	...	...	214.21/109	PL
			$-1.77 \pm 0.06$	...	$91^{+18}_{-14}$	...	119.25/108	CPL*
060117	seq5	10.96–11.96	$-1.72 \pm 0.15$	$-2.62^{+0.25}_{-0.78}$	$82^{+18}_{-22}$	...	116.07/107	Band
			$-1.18 \pm 0.05$	...	$113 \pm 6$	...	131.64/108	CPL
			$-1.08 \pm 0.09$	$-3.18^{+0.20}_{-0.34}$	$101 \pm 8$	...	119.78/107	Band*
060117	seq6	11.96–12.96	$-1.48 \pm 0.06$	...	$146^{+16}_{-14}$	...	115.05/108	CPL*
			$-1.47 \pm 0.06$	$-3.38^{+0.64}_{-6.62}$	$144 \pm 16$	...	114.17/107	Band
			$-2.20 \pm 0.05$	...	...	...	147.19/109	PL
060117	seq7	12.96–13.96	$-1.91 \pm 0.16$	...	$14^{+3}_{-2}$	...	109.91/108	CPL
			$-1.33 \pm 0.35$	$-2.86^{+0.25}_{-0.34}$	$33^{+5}_{-5}$	...	97.94/107	Band*
			$-1.94 \pm 0.05$	...	...	...	173.31/109	PL
060117	seq8	13.96–15.96	$-1.68 \pm 0.09$	...	$77^{+16}_{-12}$	...	123.83/108	CPL*
			$-1.55 \pm 0.16$	$-2.64^{+0.21}_{-0.40}$	$65^{+15}_{-9}$	...	118.63/107	Band

Table 5  
(Continued)

GRB	Sequence	Interval	$\alpha$	$\beta$	$E_{\text{peak}}$ (keV)	$E_{\text{iso}}$ ( $10^{52}$ erg s)	$\chi^2/\text{dof}$	Model
060210	seq9	15.96–17.96	$-2.14 \pm 0.05$	...	...	...	190.75/109	PL
			$-1.52 \pm 0.16$	...	$36 \pm 4$	...	104.90/108	CPL
			$-1.23 \pm 0.23$	$-3.34 \pm 0.37$	$38 \pm 3$	...	93.12/107	Band*
	seq3	–96.29–50.29	$-1.39 \pm 0.20$	...	...	...	98.58/87	PL
			$-0.82 \pm 0.47$	...	$164^{+154}_{-58}$	...	83.75/86	CPL*
			$-0.82 \pm 0.45$	$-9.37^{+19.37}_{-0.63}$	$164^{+75}_{-41}$	$9.75 \pm 3.84$	83.75/85	Band
	seq4	–50.29–22.29 (sl)	$-1.42 \pm 0.10$	...	...	...	90.66/87	PL
			$-1.13 \pm 0.19$	...	$236^{+208}_{-80}$	...	73.27/86	CPL*
	seq5	–22.29–2.29	$-1.12 \pm 0.28$	$-2.80^{+0.90}_{-7.20}$	$228^{+200}_{-112}$	$19.32 \pm 6.30$	72.98/85	Band
			$-1.74 \pm 0.13$	...	...	...	93.09/87	PL*
	seq5-6	–22.29–14.71	$-1.20 \pm 0.53$	...	$74^{+129}_{-16}$	...	88.68/86	CPL
			$-1.20 \pm 0.47$	$-9.37^{+19.37}_{-0.63}$	$74^{+45}_{-16}$	$5.53 \pm 2.73$	88.68/85	Band
$-1.62 \pm 0.09$			...	...	...	97.01/87	PL	
seq6	–2.29–14.71	$-1.30 \pm 0.26$	...	$125^{+126}_{-37}$	...	84.01/86	CPL*	
		$-1.37 \pm 0.27$	$-9.32^{+6.97}_{-0.68}$	$143^{+86}_{-55}$	$13.46 \pm 2.07$	84.23/85	Band	
		$-1.50 \pm 0.12$	...	...	...	93.08/87	PL	
060306	seq1-2	–2.42–6.58	$-1.25 \pm 0.24$	...	$223^{+300}_{-95}$	...	81.90/86	CPL*
			$-1.25 \pm 0.19$	$-9.24^{+19.23}_{-0.76}$	$223^{+300}_{-102}$	$8.61 \pm 3.56$	81.90/85	Band
			$-1.82 \pm 0.08$	...	...	...	96.32/87	PL
	preslew	–1.42–14.58	$-1.55 \pm 0.16$	...	$116^{+64}_{-30}$	...	76.81/86	CPL*
			$-1.11 \pm 0.45$	$-2.44^{+0.28}_{-0.35}$	$67^{+24}_{-14}$	...	71.62/85	Band
			$-1.78 \pm 0.10$	...	...	...	85.90/87	PL
	seq2	–0.42–6.58	$-1.61 \pm 0.17$	...	$159^{+180}_{-63}$	...	79.57/86	CPL*
			$-1.42 \pm 0.59$	$-2.26^{+0.37}_{-7.74}$	$89^{+226}_{-46}$	...	78.26/85	Band
			$-1.84 \pm 0.09$	...	...	...	89.35/87	PL
	seq3	25.58–33.58 (sl)	$-1.58 \pm 0.17$	...	$108^{+69}_{-30}$	...	73.67/86	CPL*
			$-1.18 \pm 0.50$	$-2.46^{+0.32}_{-0.38}$	$66^{+31}_{-17}$	...	70.24/85	Band
			$-1.86 \pm 0.17$	...	...	...	65.70/87	PL
seq4	41.58–46.58 (sl)	$-0.44 \pm 0.71$	...	$46^{+16}_{-7}$	...	57.79/86	CPL*	
		$0.23 \pm 1.45$	$-2.67^{+0.50}_{-2.71}$	$48^{+5}_{-15}$	...	57.53/85	Band	
		$-1.65 \pm 0.13$	...	...	...	100.06/87	PL	
060322	seq1-3	–22.15–34.85	$-1.47 \pm 0.19$	...	$252^{+495}_{-113}$	...	93.27/86	CPL*
			$-1.47 \pm 0.18$	...	$249^{+520}_{-111}$	...	93.36/85	Band
			$-1.37 \pm 0.08$	...	...	...	55.90/72	PL*
seq3	13.85–34.85	$-1.17 \pm 0.21$	...	$272^{+936}_{-121}$	...	50.05/71	CPL	
		$-0.59 \pm 1.14$	$-1.88^{+0.45}_{-0.55}$	$155^{+157}_{-107}$	...	46.05/70	Band	
		$-1.34 \pm 0.12$	...	...	...	70.97/72	PL	
seq5	177.85–202.85	$-1.00 \pm 0.31$	...	$188^{+393}_{-73}$	...	64.09/71	CPL*	
		$1.49 \pm 1.76$	$-1.62^{+0.18}_{-0.26}$	$47^{+56}_{-11}$	...	62.47/70	Band	
		$-1.65 \pm 0.06$	...	...	...	96.26/72	PL	
060421	seq1	–22.29–14.71	$-1.03 \pm 0.28$	...	$82^{+23}_{-11}$	...	71.87/71	CPL
			$-0.76 \pm 0.47$	$-2.36^{+0.38}_{-0.78}$	$71 \pm 15$	...	65.74/70	Band*
			$-1.49 \pm 0.07$	...	...	...	121.06/88	PL
060502A	seq1	–2.29–14.71	$-1.05 \pm 0.16$	...	$154^{+49}_{-30}$	...	69.56/87	CPL*
			$-0.90 \pm 0.31$	$-2.44^{+0.35}_{-7.56}$	$121^{+70}_{-31}$	...	68.42/86	Band
			$-1.36 \pm 0.06$	...	...	...	119.44/72	PL
060813	seq2	–1.42–66.58 (sl)	$-1.03 \pm 0.16$	...	$210^{+123}_{-59}$	...	84.81/71	CPL*
			$-0.89 \pm 0.27$	$-2.31^{+0.38}_{-7.69}$	$155^{+62}_{-42}$	$3.31 \pm 1.20$	83.24/70	Band
			$-1.85 \pm 0.11$	...	...	...	112.53/90	PL
060814	seq1	–11.75–10.75	$-1.39 \pm 0.37$	...	$67^{+46}_{-16}$	...	101.96/89	CPL
			$-0.46 \pm 0.92$	$-2.55^{+0.45}_{-0.60}$	$46 \pm 12$	...	92.84/88	Band*
			$-1.52 \pm 0.04$	...	...	...	215.30/90	PL
060904A	seq2	10.75–30.75 (sl)	$-1.22 \pm 0.07$	...	$372^{+103}_{-70}$	...	81.18/86	CPL*
			$-1.21 \pm 0.07$	$-2.46^{+0.43}_{-7.54}$	$365^{+119}_{-95}$	$2.45 \pm 0.52$	83.18/88	Band
			$-1.64 \pm 0.03$	...	...	...	243.85/110	PL
060904A	slew	10.75–60.25 (sl)	$-1.40 \pm 0.05$	...	$389^{+97}_{-65}$	...	70.54/86	CPL*
			$-1.38 \pm 0.06$	$-2.16^{+0.19}_{-1.08}$	$350^{+136}_{-100}$	$4.17 \pm 0.49$	96.46/108	Band
			$-1.61 \pm 0.03$	...	...	...	127.02/110	PL
060904A	slew	13.84–54.34 (sl)	$-1.48 \pm 0.05$	...	$458^{+280}_{-127}$	...	57.08/86	CPL*
			$-1.45 \pm 0.17$	$-1.93^{+0.16}_{-0.65}$	$352^{+345}_{-225}$	$5.31 \pm 0.76$	85.76/108	Band
			$-1.65 \pm 0.05$	...	...	...	81.89/89	PL*
060904A	postslew	54.34–108.84	$-1.59 \pm 0.08$	...	$475^{+2735}_{-244}$	...	76.85/88	CPL
			$-1.45 \pm 0.30$	$-1.89^{+0.19}_{-1.05}$	$160^{+830}_{-94}$	...	73.98/87	Band
			$-1.59 \pm 0.04$	...	...	...	95.64/89	PL
			$-1.46 \pm 0.07$	...	$397^{+287}_{-126}$	...	67.03/88	CPL*

**Table 5**  
(Continued)

GRB	Sequence	Interval	$\alpha$	$\beta$	$E_{\text{peak}}$ (keV)	$E_{\text{iso}}$ ( $10^{52}$ erg s)	$\chi^2/\text{dof}$	Model
060908	seq1-3	-13.36-3.14	$-1.46 \pm 0.09$	$-2.37^{+0.48}_{-7.64}$	$376^{+245}_{-189}$	...	68.06/87	Band
			$-1.31 \pm 0.06$	...	...	...	101.47/72	PL
	seq2	-8.36-0.14	$-0.85 \pm 0.22$	...	$143^{+69}_{-31}$	...	69.99/71	CPL*
			$-0.70 \pm 0.27$	$-2.46^{+0.58}_{-7.54}$	$120^{+49}_{-24}$	$7.44 \pm 3.31$	67.93/70	Band
061006	seq2	-22.89-22.39	$-1.27 \pm 0.06$	...	...	...	77.05/72	PL
			$-0.86 \pm 0.20$	...	$169^{+90}_{-42}$	...	48.48/71	CPL*
	seq2-3	-22.89-21.39	$-0.80 \pm 0.27$	$-2.65^{+0.69}_{-7.35}$	$151^{+106}_{-39}$	$5.32 \pm 2.22$	48.35/70	Band
			$-0.34 \pm 0.09$	...	$742 \pm 67$	...	225.61/111	CPL
061007	seq2	-22.89-21.39	$-0.62 \pm 0.10$	...	$619^{+136}_{-49}$	$0.15 \pm 0.05$	91.25/85	Band*
			$-1.05 \pm 0.06$	...	...	...	68.79/68	PL
	seq3	-22.39-21.89	$-0.88 \pm 0.10$	...	$951^{+706}_{-281}$	...	50.47/67	CPL*
			$-0.89 \pm 0.10$	...	$989^{+230}_{-309}$	$0.22 \pm 0.04$	51.51/70	Band
061007	seq1	-4.18-3.32	$-1.57 \pm 0.13$	...	...	...	75.88/73	PL
			$-1.35 \pm 0.20$	...	$367^{+863}_{-189}$	...	67.15/72	CPL*
	preslew	-4.18-12.32	$-1.35 \pm 0.16$	$-8.67^{+7.01}_{-1.33}$	$366^{+582}_{-188}$	$0.02 \pm 0.01$	67.14/70	Band
			$-0.89 \pm 0.09$	...	$484^{+49}_{-41}$	...	111.83/110	CPL*
	seq2	3.32-12.32	$-0.87 \pm 0.10$	$-3.01^{+0.51}_{-6.99}$	$467^{+55}_{-47}$	$5.04 \pm 0.64$	110.74/109	Band
			$-0.90 \pm 0.06$	...	$389 \pm 26$	...	114.62/110	CPL
	seq4	24.32-34.32	$-0.88 \pm 0.07$	$-2.70^{+0.24}_{-0.43}$	$369 \pm 28$	$11.48 \pm 0.95$	103.68/109	Band*
			$-0.88 \pm 0.08$	...	$321 \pm 23$	...	127.35/110	CPL
	seq5	34.32-42.32	$-0.86 \pm 0.08$	$-2.79^{+0.32}_{-0.71}$	$310 \pm 27$	$6.07 \pm 0.62$	120.39/109	Band*
			$-0.85 \pm 0.03$	...	$490 \pm 13$	...	194.86/110	CPL
seq6	42.32-50.32	$-0.83 \pm 0.03$	$-3.00^{+0.16}_{-0.23}$	$474 \pm 14$	$84.89 \pm 2.74$	160.03/109	Band*	
		$-0.72 \pm 0.04$	...	$555 \pm 16$	...	240.83/110	CPL	
seq7	50.32-56.82	$-0.68 \pm 0.04$	$-2.86^{+0.14}_{-0.18}$	$524 \pm 17$	$25.40 \pm 1.09$	191.37/109	Band*	
		$-0.81 \pm 0.03$	...	$573 \pm 17$	...	252.24/110	CPL	
seq8	56.82-69.82	$-0.79 \pm 0.03$	$-2.99^{+0.17}_{-0.24}$	$553 \pm 18$	$21.47 \pm 0.86$	217.93/109	Band*	
		$-0.86 \pm 0.03$	...	$454 \pm 15$	...	171.30/110	CPL	
seq9	69.82-79.82	$-0.84 \pm 0.03$	$-3.07^{+0.22}_{-0.34}$	$441 \pm 16$	$15.32 \pm 0.64$	152.08/109	Band*	
		$-0.87 \pm 0.03$	...	$428 \pm 13$	...	177.97/110	CPL	
061202	seq2	71.42-80.92 (sl)	$-0.86 \pm 0.03$	$-3.48^{+0.35}_{-0.77}$	$422 \pm 14$	$13.28 \pm 0.53$	171.25/109	Band*
			$-0.92 \pm 0.04$	...	$346 \pm 18$	...	73.82/109	CPL*
	seq2-3	71.42-86.92 (sl)	$-0.92 \pm 0.04$	$-3.88^{+0.87}_{-6.12}$	$345 \pm 19$	$8.83 \pm 0.61$	73.23/108	Band
			$-1.67 \pm 0.07$	...	...	...	111.47/110	PL
	seq3	80.92-86.92 (sl)	$-1.52 \pm 0.12$	...	$293^{+397}_{-125}$	...	96.03/109	CPL*
			$-1.53 \pm 0.11$	$-9.20^{+19.20}_{-0.80}$	$309 \pm 146$	$1.00 \pm 0.24$	96.04/108	Band
	seq2	71.42-80.92 (sl)	$-1.59 \pm 0.05$	...	...	...	113.70/87	PL
			$-1.43 \pm 0.08$	...	$311^{+183}_{-92}$	...	87.14/86	CPL*
	seq2-3	71.42-86.92 (sl)	$-1.21 \pm 0.26$	$-2.06^{+0.18}_{-0.26}$	$131^{+138}_{-44}$	...	83.36/85	Band
			$-1.58 \pm 0.05$	...	...	...	125.83/87	PL
seq3	80.92-86.92 (sl)	$-1.42 \pm 0.07$	...	$346^{+166}_{-92}$	...	90.54/86	CPL*	
		$-1.42 \pm 0.07$	$-9.37^{+19.37}_{-0.63}$	$346^{+175}_{-90}$	...	90.54/85	Band	
061222A	slew	34.29-89.29 (sl)	$-1.51 \pm 0.07$	...	...	...	102.37/87	PL
			$-1.39 \pm 0.11$	...	$407^{+548}_{-173}$	...	91.48/86	CPL*
	seq7-9	75.29-99.79 (sl)	$-1.39 \pm 0.11$	$-9.37^{+19.37}_{-0.63}$	$406^{+550}_{-179}$	...	91.48/85	Band
			$-1.36 \pm 0.03$	...	...	...	188.39/74	PL
seq8	80.29-89.79	$-1.16 \pm 0.06$	...	$456^{+195}_{-121}$	...	66.80/73	CPL*	
		$-1.14 \pm 0.09$	$-2.60^{+0.61}_{-7.40}$	$415^{+210}_{-159}$	...	66.24/72	Band	
070107	seq1	-20.61-1.11 (sl)	$-1.35 \pm 0.03$	...	...	...	215.51/74	PL
			$-1.13 \pm 0.06$	...	$427^{+150}_{-98}$	...	52.97/73	CPL*
	seq2	-1.11-14.39	$-1.01 \pm 0.13$	$-2.00^{+0.15}_{-0.44}$	$248^{+163}_{-68}$	...	47.06/72	Band
			$-1.00 \pm 0.05$	...	$488^{+115}_{-85}$	...	68.54/73	CPL
seq2	-1.11-14.39	$-0.89 \pm 0.11$	$-1.99^{+0.13}_{-0.25}$	$299^{+122}_{-80}$	...	52.60/72	Band*	
		$-1.42 \pm 0.06$	...	...	...	150.82/72	PL	
070318	seq1	-22.89-22.39	$-1.01 \pm 0.11$	...	$566^{+143}_{-101}$	...	77.07/71	CPL*
			$-1.01 \pm 0.10$	$-9.34^{+7.24}_{-0.66}$	$566^{+143}_{-101}$	...	77.07/70	Band
	seq1	-22.89-22.39	$-1.35 \pm 0.07$	...	...	...	108.61/72	PL
			$-1.11 \pm 0.11$	...	$782^{+397}_{-218}$	...	79.11/71	CPL*
seq1	-22.89-22.39	$-1.11 \pm 0.11$	$-9.06^{+7.45}_{-0.94}$	$783 \pm 225$	...	79.11/70	Band	
		$-1.54 \pm 0.05$	...	...	...	104.92/89	PL	
seq1	-22.89-22.39	$-1.34 \pm 0.08$	...	$572^{+264}_{-145}$	...	74.30/88	CPL	
		$-0.90 \pm 0.40$	$-1.75 \pm 0.09$	$117^{+233}_{-39}$	$1.07 \pm 0.19$	65.53/87	Band*	
070328	seq1	-17.81-2.31	$-1.39 \pm 0.06$	...	...	...	142.57/84	PL
			$-1.00 \pm 0.13$	...	$1903^{+742}_{-491}$	...	104.75/83	CPL*
			$-0.99 \pm 0.09$	$-9.32^{+7.19}_{-0.68}$	$1886^{+915}_{-543}$	...	105.67/82	Band

**Table 5**  
(Continued)

GRB	Sequence	Interval	$\alpha$	$\beta$	$E_{\text{peak}}$ (keV)	$E_{\text{iso}}$ ( $10^{52}$ erg s)	$\chi^2/\text{dof}$	Model
	preslew	-17.81-11.19	$-1.17 \pm 0.04$	...	$1731 \pm 226$	...	97.59/82	CPL*
			$-1.17 \pm 0.02$	$-9.19^{+6.81}_{-0.81}$	$1726^{+248}_{-206}$	...	97.61/81	Band
	seq2	-2.31-11.19	$-1.18 \pm 0.04$	...	$1647 \pm 202$	...	89.61/82	CPL*
			$-1.16 \pm 0.02$	$-2.35^{+0.23}_{-7.65}$	$1503 \pm 297$	...	88.79/81	Band
	seq3	11.19-23.69	$-1.13 \pm 0.05$	...	$862^{+124}_{-104}$	...	83.49/82	CPL*
			$-1.14 \pm 0.04$	$-9.37^{+19.37}_{-0.63}$	$862^{+124}_{-62}$	...	83.50/81	Band
	slew	11.19-77.19 (sl)	$-1.45 \pm 0.03$	...	...	...	196.24/83	PL
			$-1.22 \pm 0.05$	...	$1064^{+318}_{-237}$	...	61.99/82	CPL*
			$-1.21 \pm 0.04$	...	$996^{+403}_{-171}$	...	62.21/81	Band
	seq4	23.69-77.19 (sl)	$-1.45 \pm 0.07$	...	...	...	75.66/74	PL
			$-1.30 \pm 0.11$	...	$736^{+1080}_{-375}$	...	60.62/73	CPL*
			$-1.25 \pm 0.18$	...	$842^{+1052}_{-420}$	...	61.26/72	Band
070419B	seq1	-11.89-15.11	$-1.48 \pm 0.05$	...	...	...	137.32/73	PL
			$-1.23 \pm 0.08$	...	$519^{+218}_{-135}$	...	72.99/72	CPL*
			$-1.23 \pm 0.08$	$-9.37^{+6.95}_{-0.63}$	$519^{+219}_{-165}$	...	72.99/71	Band
	seq1-3	-11.89-69.11 (sl)	$-1.59 \pm 0.04$	...	...	...	115.27/73	PL
			$-1.40 \pm 0.07$	...	$292^{+109}_{-67}$	...	53.78/72	CPL*
			$-1.40 \pm 0.07$	$-9.37^{+19.37}_{-0.63}$	$292^{+109}_{-67}$	...	53.79/71	Band
	seq2	15.11-60.11 (sl)	$-1.63 \pm 0.06$	...	...	...	99.73/73	PL
			$-1.39 \pm 0.12$	...	$169^{+88}_{-41}$	...	67.84/72	CPL*
			$-1.40 \pm 0.12$	$-9.37^{+6.73}_{-0.63}$	$170^{+87}_{-42}$	...	67.84/71	Band
	slew	15.11-69.11 (sl)	$-1.66 \pm 0.05$	...	...	...	91.97/73	PL
			$-1.44 \pm 0.10$	...	$176^{+90}_{-42}$	...	58.04/72	CPL*
			$-1.44 \pm 0.10$	$-9.37^{+19.37}_{-0.63}$	$177^{+89}_{-43}$	...	58.04/71	Band
	seq3	60.11-69.11 (sl)	$-1.73 \pm 0.08$	...	...	...	72.91/73	PL
			$-1.60 \pm 0.15$	...	$198^{+484}_{-88}$	...	66.17/72	CPL*
			$-1.60 \pm 0.15$	$-9.36^{+7.32}_{-0.64}$	$198^{+212}_{-88}$	...	66.17/71	Band
070508	seq1-8	-13.93-10.07	$-1.19 \pm 0.04$	...	$280 \pm 20$	...	76.66/86	CPL*
			$-1.19 \pm 0.03$	$-9.05^{+6.16}_{-0.95}$	$280^{+20}_{-10}$	$5.06 \pm 0.23$	76.67/85	Band
	seq12	0.00-0.00	$-1.81 \pm 0.06$	...	...	...	101.32/89	PL
			$-1.47 \pm 0.14$	...	$95^{+28}_{-16}$	...	69.93/88	CPL*
			$-1.48 \pm 0.15$	$-3.56^{+1.07}_{-6.44}$	$95^{+28}_{-18}$	$0.31 \pm 0.06$	69.69/87	Band
	seq2	0.07-1.57	$-1.76 \pm 0.08$	...	...	...	93.94/89	PL
			$-1.44 \pm 0.25$	...	$97^{+83}_{-25}$	...	82.97/88	CPL*
			$-1.30 \pm 0.31$	$-2.61^{+0.52}_{-7.39}$	$82^{+53}_{-17}$	$0.17 \pm 0.06$	81.39/87	Band
	seq4	2.07-4.07	$-1.19 \pm 0.06$	...	$260^{+40}_{-32}$	...	99.64/88	CPL*
			$-1.19 \pm 0.06$	$-5.26^{+13.94}_{-4.74}$	$260^{+40}_{-56}$	$0.86 \pm 0.15$	99.62/87	Band
	seq6	5.57-6.57	$-1.12 \pm 0.07$	...	$296^{+40}_{-33}$	...	112.75/88	CPL*
			$-1.10 \pm 0.08$	$-2.71^{+0.36}_{-1.37}$	$280 \pm 43$	$0.74 \pm 0.09$	109.25/87	Band
	seq7	6.57-8.57	$-0.92 \pm 0.05$	...	$307 \pm 16$	...	109.16/88	CPL*
			$-0.92 \pm 0.05$	$-4.06^{+0.85}_{-5.94}$	$306 \pm 16$	$1.67 \pm 0.11$	108.44/87	Band
	seq8	8.57-10.07	$-1.67 \pm 0.05$	...	...	...	253.38/89	PL
			$-1.20 \pm 0.10$	...	$154^{+27}_{-20}$	...	90.82/88	CPL*
			$-1.21 \pm 0.10$	$-9.37^{+19.37}_{-0.63}$	$155^{+26}_{-21}$	$0.40 \pm 0.00$	90.83/87	Band
	seq9	10.07-12.57	$-0.87 \pm 0.05$	...	$213 \pm 9$	...	86.31/88	CPL*
			$-0.87 \pm 0.05$	$-4.08^{+0.76}_{-5.92}$	$212 \pm 10$	$1.96 \pm 0.11$	85.93/87	Band
	seq9-10	10.07-14.57	$-0.97 \pm 0.04$	...	$211 \pm 9$	...	97.35/86	CPL*
			$-0.97 \pm 0.04$	$-9.37^{+5.64}_{-0.63}$	$212 \pm 9$	$2.81 \pm 0.10$	97.37/85	Band
	seq10	12.57-14.57	$-1.16 \pm 0.06$	...	$203^{+22}_{-19}$	...	105.74/88	CPL*
			$-1.19 \pm 0.06$	...	$204 \pm 20$	$0.89 \pm 0.06$	110.98/87	Band
	seq11	14.57-16.07	$-0.94 \pm 0.06$	...	$187 \pm 13$	...	95.97/88	CPL*
			$-0.91 \pm 0.07$	$-3.10^{+0.34}_{-0.84}$	$177 \pm 15$	$0.99 \pm 0.08$	91.18/87	Band
070612A	seq1	-20.61-1.11	$-0.41 \pm 0.21$	...	$186^{+26}_{-21}$	...	83.33/88	CPL*
			$-0.41 \pm 0.22$	$-4.61^{+1.85}_{-5.39}$	$186 \pm 26$	$0.58 \pm 0.11$	83.27/87	Band
070616	seq3	120.45-132.45	$-1.29 \pm 0.11$	...	...	...	88.44/72	PL
			$-1.10 \pm 0.20$	...	$304^{+710}_{-129}$	...	82.35/71	CPL*
			$-1.11 \pm 0.20$	$-9.22^{+19.22}_{-0.78}$	$310^{+688}_{-128}$	...	82.35/70	Band
	seq4	132.45-173.95	$-1.44 \pm 0.04$	...	...	...	121.72/72	PL
			$-1.10 \pm 0.10$	...	$181^{+44}_{-29}$	...	47.98/71	CPL*
			$-1.10 \pm 0.12$	$-3.32^{+1.04}_{-6.68}$	$179 \pm 43$	...	47.84/70	Band
070704	seq1	-57.08-49.08	$-1.20 \pm 0.06$	...	...	...	155.93/72	PL
			$-0.37 \pm 0.26$	...	$124^{+28}_{-17}$	...	76.83/71	CPL
			$-0.08 \pm 0.34$	$-2.48^{+0.42}_{-0.59}$	$105^{+19}_{-14}$	...	66.95/70	Band*
	seq2	-49.08-15.58	$-1.61 \pm 0.05$	...	...	...	74.50/72	PL
			$-0.79 \pm 0.76$	$-1.76^{+0.10}_{-0.14}$	$63^{+30}_{-16}$	...	64.66/70	Band*

**Table 5**  
(Continued)

GRB	Sequence	Interval	$\alpha$	$\beta$	$E_{\text{peak}}$ (keV)	$E_{\text{iso}}$ ( $10^{52}$ erg s)	$\chi^2/\text{dof}$	Model	
070714B	seq2	-0.38-0.12	$-1.31 \pm 0.06$	...	...	...	167.98/89	PL	
			$-0.74 \pm 0.12$	...	$1152^{+305}_{-237}$	...	75.16/88	CPL*	
	seq4	0.62-1.12	$-0.69 \pm 0.10$	$-3.16^{+1.16}_{-6.84}$	$1146 \pm 335$	$0.58 \pm 0.15$	76.71/87	Band	
			$-1.30 \pm 0.12$	...	...	...	125.28/89	PL	
070808	seq1	-0.61-2.39	$-0.68 \pm 0.24$	...	$490^{+338}_{-172}$	...	89.19/88	CPL*	
			$-0.64 \pm 0.00$	$-2.22^{+0.72}_{-0.24}$	$424^{+213}_{-364}$	$0.16 \pm 0.09$	88.79/87	Band	
	seq1-2	-0.61-7.39	$-1.27 \pm 0.11$	...	...	...	122.19/87	PL	
			$-0.86 \pm 0.22$	...	$270^{+179}_{-90}$	...	92.62/86	CPL*	
	070917	seq3	0.00-0.00	$-0.87 \pm 0.18$	$-9.37^{+19.37}_{-0.63}$	$273 \pm 90$	...	92.62/85	Band
				$-1.33 \pm 0.10$	...	...	...	105.86/87	PL
seq2		0.01-6.01	$-1.04 \pm 0.21$	...	$251^{+232}_{-96}$	...	86.70/86	CPL*	
			$-1.04 \pm 0.19$	$-9.37^{+19.37}_{-0.63}$	$252^{+243}_{-97}$	...	86.70/85	Band	
071003	seq1	-7.23-1.23	$-1.45 \pm 0.04$	...	...	...	72.47/72	PL	
			$-1.36 \pm 0.06$	...	$560^{+472}_{-202}$	...	54.70/71	CPL*	
	seq2	-1.23-4.77	$-1.36 \pm 0.05$	$-9.37^{+0.28}_{-0.63}$	$560^{+522}_{-171}$	...	54.70/70	Band	
			$-1.55 \pm 0.04$	...	...	...	74.26/73	PL	
	071010B	seq1	-7.23-1.23	$-1.46 \pm 0.08$	...	$468^{+665}_{-213}$	...	56.03/72	CPL*
				$-1.34 \pm 0.17$	$-1.99^{+0.20}_{-8.01}$	$203^{+507}_{-74}$	...	53.91/71	Band
seq2		-1.23-4.77	$-1.37 \pm 0.15$	...	...	...	90.26/73	PL	
			$-1.15 \pm 0.21$	...	$955^{+1774}_{-562}$	...	81.51/72	CPL*	
080319C	seq1	-0.54-1.96	$-1.15 \pm 0.21$	$-9.36^{+7.73}_{-0.64}$	$962^{+1773}_{-582}$	$1.09 \pm 0.75$	81.51/71	Band	
			$-0.88 \pm 0.06$	...	$1082 \pm 122$	...	67.26/72	CPL*	
	seq2-4	-1.23-16.77	$-0.87 \pm 0.04$	...	$998^{+246}_{-53}$	$9.07 \pm 1.06$	68.66/71	Band	
			$-1.00 \pm 0.05$	...	$1044 \pm 92$	...	84.16/82	CPL*	
	seq2-5	-1.23-20.77	$-0.99 \pm 0.04$	$-3.30^{+0.60}_{-6.70}$	$992^{+187}_{-57}$	$17.02 \pm 1.39$	84.19/81	Band	
			$-1.06 \pm 0.05$	...	$1011 \pm 100$	...	76.89/72	CPL*	
080328	seq2	15.11-69.11 (sl)	$-1.05 \pm 0.04$	$-9.36^{+6.40}_{-0.64}$	$998^{+120}_{-76}$	$16.76 \pm 1.42$	76.95/71	Band	
			$-2.06 \pm 0.04$	...	...	...	98.26/87	PL	
	seq1	-0.54-13.46	$-1.79 \pm 0.15$	...	$41 \pm 9$	...	77.88/86	CPL	
			$-1.42 \pm 0.38$	$-2.43^{+0.20}_{-0.34}$	$45^{+4}_{-5}$	$2.27 \pm 0.34$	65.37/85	Band*	
080413A	seq1	-0.54-1.96	$-1.54 \pm 0.04$	...	...	...	290.68/110	PL	
			$-1.11 \pm 0.08$	...	$1247^{+245}_{-195}$	...	168.07/109	CPL*	
	seq1-2	-0.54-13.46	$-1.05 \pm 0.05$	$-2.65^{+0.47}_{-7.35}$	$1210 \pm 245$	$7.70 \pm 1.04$	168.86/108	Band	
			$-1.56 \pm 0.03$	...	...	...	297.18/109	PL	
	seq2	1.96-13.46	$-1.22 \pm 0.06$	...	$947^{+190}_{-148}$	...	128.53/108	CPL*	
			$-1.23 \pm 0.03$	$-9.02^{+19.02}_{-0.98}$	$997^{+147}_{-202}$	$19.34 \pm 2.05$	128.77/107	Band	
080605	seq1	-2.76-9.24	$-1.58 \pm 0.04$	...	...	...	214.38/110	PL	
			$-1.28 \pm 0.07$	...	$828^{+253}_{-177}$	...	120.96/109	CPL*	
	seq2	0.00-0.00	$-1.27 \pm 0.07$	$-2.58^{+0.51}_{-7.42}$	$773^{+247}_{-183}$	$11.84 \pm 1.50$	120.10/108	Band	
			$-1.34 \pm 0.07$	...	...	...	124.79/88	PL	
	seq1	-2.76-9.24	$-0.99 \pm 0.21$	...	$185^{+171}_{-52}$	...	106.79/87	CPL*	
			$-0.91 \pm 0.29$	$-2.15^{+0.44}_{-7.85}$	$157^{+132}_{-50}$	...	104.44/86	Band	
080623	seq2	0.00-0.00	$-1.23 \pm 0.05$	...	...	...	151.03/88	PL	
			$-0.96 \pm 0.09$	...	$456^{+165}_{-108}$	...	77.33/87	CPL*	
	seq1	5.57-6.57	$-0.92 \pm 0.10$	$-2.14^{+0.32}_{-7.86}$	$379^{+160}_{-104}$	...	75.02/86	Band	
			$-1.54 \pm 0.05$	...	...	...	128.79/73	PL	
080727C	seq1	-5.31-1.31	$-1.17 \pm 0.15$	...	$130^{+46}_{-24}$	...	90.13/72	CPL*	
			$-1.18 \pm 0.14$	$-4.41^{+1.99}_{-5.59}$	$131^{+45}_{-26}$	$4.93 \pm 1.08$	90.06/71	Band	
	preslew	-5.31-11.19	$-1.53 \pm 0.08$	...	...	...	74.84/73	PL	
			$-1.22 \pm 0.20$	...	$152^{+121}_{-46}$	...	57.09/72	CPL*	
	seq2	-1.31-4.19	$-1.24 \pm 0.28$	...	$160^{+113}_{-71}$	$1.44 \pm 0.55$	57.12/71	Band	
			$-1.18 \pm 0.04$	...	$321^{+40}_{-33}$	...	88.04/82	CPL*	
080727C	seq2	-1.31-4.19	$-1.17 \pm 0.05$	$-2.73^{+0.33}_{-1.08}$	$301 \pm 42$	$24.79 \pm 2.15$	84.37/81	Band	
			$-1.21 \pm 0.07$	...	$236^{+58}_{-40}$	...	80.82/72	CPL*	
	seq3	4.19-11.19	$-1.20 \pm 0.09$	$-3.16^{+0.79}_{-6.84}$	$230 \pm 60$	$6.56 \pm 1.07$	80.39/71	Band	
			$-1.08 \pm 0.05$	...	$354 \pm 31$	...	92.18/82	CPL*	
seq4	11.19-14.19 (sl)	$-1.07 \pm 0.05$	$-2.83^{+0.32}_{-0.91}$	$336 \pm 36$	$16.72 \pm 1.29$	87.58/81	Band		
		$-1.86 \pm 0.09$	...	...	...	77.38/73	PL		
080727C	seq1	-2.86-9.64	$-1.09 \pm 0.46$	...	$54^{+16}_{-7}$	...	65.57/72	CPL	
			$-0.82 \pm 0.86$	$-2.52^{+0.43}_{-1.08}$	$49 \pm 11$	$1.00 \pm 0.24$	59.56/71	Band*	
	seq1	14.57-16.07 (sl)	$-1.47 \pm 0.13$	...	...	...	82.22/72	PL	
			$-1.22 \pm 0.27$	...	$203^{+438}_{-90}$	...	74.92/71	CPL*	
seq1	-2.86-9.64	$-1.21 \pm 0.78$	$-2.87^{+1.19}_{-7.13}$	$195^{+442}_{-135}$	...	74.90/70	Band		
		$-1.49 \pm 0.11$	...	...	...	84.56/70	PL		
			$-0.10 \pm 0.34$	...	$63^{+12}_{-7}$	...	63.64/69	CPL*	

**Table 5**  
(Continued)

GRB	Sequence	Interval	$\alpha$	$\beta$	$E_{\text{peak}}$ (keV)	$E_{\text{iso}}$ ( $10^{52}$ erg s)	$\chi^2/\text{dof}$	Model
			0.43 ± 1.14	-2.35 <sup>+0.49</sup> <sub>-1.79</sub>	54 <sup>+17</sup> <sub>-11</sub>	...	63.25/71	Band
	preslew	-2.86-16.64	-1.32 ± 0.05	...	...	...	114.68/70	PL
			-0.83 ± 0.24	...	126 <sup>+63</sup> <sub>-27</sub>	...	86.78/69	CPL
			-0.23 ± 0.53	-1.92 <sup>+0.25</sup> <sub>-0.43</sub>	76 <sup>+24</sup> <sub>-19</sub>	...	65.32/68	Band*
	seq1-4	-2.86-61.14 (sl)	-1.39 ± 0.04	...	...	...	145.38/73	PL
			-1.16 ± 0.08	...	351 <sup>+168</sup> <sub>-93</sub>	...	73.36/72	CPL
			-0.60 ± 0.26	-1.90 <sup>+0.14</sup> <sub>-0.17</sub>	108 <sup>+23</sup> <sub>-18</sub>	...	51.17/71	Band*
	seq2	9.64-16.64	-1.24 ± 0.06	...	...	...	113.25/70	PL
			-0.99 ± 0.13	...	266 <sup>+166</sup> <sub>-83</sub>	...	82.53/69	CPL
			-0.55 ± 0.29	-1.95 <sup>+0.26</sup> <sub>-0.31</sub>	116 <sup>+41</sup> <sub>-26</sub>	...	67.94/68	Band*
	seq3	16.64-34.14 (sl)	-1.22 ± 0.04	...	...	...	137.62/70	PL
			-0.93 ± 0.09	...	263 <sup>+80</sup> <sub>-53</sub>	...	58.11/69	CPL
			-0.58 ± 0.23	-1.98 <sup>+0.19</sup> <sub>-0.23</sub>	128 <sup>+45</sup> <sub>-24</sub>	...	48.73/68	Band*
	slew	16.64-61.14 (sl)	-1.24 ± 0.04	...	...	...	129.80/70	PL
			-1.05 ± 0.07	...	345 <sup>+139</sup> <sub>-83</sub>	...	79.23/69	CPL
			-0.61 ± 0.22	-1.79 <sup>+0.16</sup> <sub>-0.19</sub>	119 <sup>+38</sup> <sub>-23</sub>	...	62.79/68	Band*
	seq4	34.14-61.14 (sl)	-1.31 ± 0.08	...	...	...	70.55/70	PL*
			-1.22 ± 0.11	...	736 <sup>+4383</sup> <sub>-387</sub>	...	66.55/69	CPL
			-0.90 ± 1.03	-1.60 <sup>+0.23</sup> <sub>-0.31</sub>	140 <sup>+151</sup> <sub>-91</sub>	...	62.04/68	Band
080916A	seq1	-2.90-10.10	-1.21 ± 0.04	...	...	...	186.84/89	PL
			-0.83 ± 0.12	...	226 <sup>+70</sup> <sub>-44</sub>	...	95.02/88	CPL*
			-0.82 ± 0.30	-2.85 <sup>+1.05</sup> <sub>-7.15</sub>	220 <sup>+71</sup> <sub>-102</sub>	0.77 ± 0.46	94.63/87	Band
	preslew	-2.90-13.10	-1.27 ± 0.04	...	...	...	152.27/89	PL
			-0.95 ± 0.12	...	235 <sup>+92</sup> <sub>-53</sub>	...	87.84/88	CPL*
			-0.77 ± 0.30	-2.04 <sup>+0.29</sup> <sub>-7.96</sub>	158 <sup>+155</sup> <sub>-46</sub>	1.13 ± 0.53	87.25/87	Band
	seq2	10.10-22.10 (sl)	-1.87 ± 0.07	...	...	...	102.24/89	PL
			-1.13 ± 0.30	...	57 <sup>+9</sup> <sub>-5</sub>	...	76.94/88	CPL*
			-1.24 ± 0.30	...	61 <sup>+5</sup> <sub>-12</sub>	0.22 ± 0.07	77.80/87	Band
081025	seq1	54.71-64.21 (sl)	-1.07 ± 0.06	...	...	...	208.94/72	PL
			-0.62 ± 0.11	...	304 <sup>+74</sup> <sub>-54</sub>	...	73.21/71	CPL*
			-0.62 ± 0.11	-9.37 <sup>+19.37</sup> <sub>-0.63</sub>	304 <sup>+74</sup> <sub>-54</sub>	...	73.21/70	Band
	seq3	73.71-79.71 (sl)	-1.35 ± 0.12	...	...	...	87.84/72	PL
			-1.06 ± 0.22	...	291 <sup>+356</sup> <sub>-117</sub>	...	73.24/71	CPL*
			-1.02 ± 0.30	-2.34 <sup>+0.59</sup> <sub>-7.66</sub>	248 <sup>+318</sup> <sub>-125</sub>	...	72.55/70	Band
090301A	seq2	0.00-0.00	-1.05 ± 0.02	...	604 ± 32	...	98.38/108	CPL
			-1.04 ± 0.02	-3.01 <sup>+0.29</sup> <sub>-0.58</sub>	582 ± 35	...	90.22/107	Band*
	seq3	0.00-0.00	-1.60 ± 0.04	...	...	...	238.25/109	PL
			-1.26 ± 0.07	...	697 <sup>+180</sup> <sub>-130</sub>	...	103.41/108	CPL*
			-1.26 ± 0.07	-2.98 <sup>+0.71</sup> <sub>-7.02</sub>	676 <sup>+188</sup> <sub>-128</sub>	...	103.08/107	Band
	seq4	0.00-0.00	-1.03 ± 0.03	...	637 ± 40	...	162.65/108	CPL
			-1.00 ± 0.03	-2.40 <sup>+0.12</sup> <sub>-0.15</sub>	572 ± 39	...	113.35/107	Band*
	seq5	0.00-0.00	-1.61 ± 0.05	...	...	...	116.80/89	PL
			-1.50 ± 0.06	...	712 <sup>+536</sup> <sub>-253</sub>	...	89.54/88	CPL*
			-1.49 ± 0.06	-2.23 <sup>+0.32</sup> <sub>-7.77</sub>	594 <sup>+419</sup> <sub>-202</sub>	...	87.88/87	Band
090401A	seq2	113.13-117.13	-1.80 ± 0.07	...	...	...	159.68/107	PL
			-1.48 ± 0.11	...	145 <sup>+44</sup> <sub>-29</sub>	...	107.70/106	CPL*
			-1.27 ± 0.30	-2.55 <sup>+0.23</sup> <sub>-7.45</sub>	94 <sup>+67</sup> <sub>-23</sub>	...	105.53/105	Band
	seq3	117.13-131.13	-1.77 ± 0.04	...	...	...	143.12/107	PL
			-1.60 ± 0.06	...	304 <sup>+91</sup> <sub>-59</sub>	...	85.91/106	CPL*
			-1.55 ± 0.13	-2.22 <sup>+0.15</sup> <sub>-0.42</sub>	209 ± 98	...	80.85/105	Band
090401B	seq1	0.13-2.63	-1.27 ± 0.06	...	...	...	84.17/72	PL
			-0.96 ± 0.16	...	207 <sup>+124</sup> <sub>-57</sub>	...	55.68/71	CPL*
			-0.93 ± 0.20	-2.70 <sup>+0.71</sup> <sub>-7.30</sub>	180 <sup>+141</sup> <sub>-54</sub>	...	55.59/70	Band
	preslew	0.13-7.13	-0.81 ± 0.08	...	276 <sup>+63</sup> <sub>-45</sub>	...	79.86/72	CPL
			-0.69 ± 0.11	-2.24 <sup>+0.17</sup> <sub>-0.24</sub>	208 <sup>+48</sup> <sub>-33</sub>	...	62.23/71	Band*
	seq2	2.63-4.63	-1.44 ± 0.11	...	...	...	56.40/72	PL
			-0.78 ± 0.44	...	92 <sup>+67</sup> <sub>-19</sub>	...	48.38/71	CPL*
			-0.78 ± 0.39	-9.37 <sup>+19.37</sup> <sub>-0.63</sub>	91 <sup>+34</sup> <sub>-17</sub>	...	48.40/70	Band
	seq3	4.63-6.63	-1.24 ± 0.06	...	...	...	149.99/73	PL
			-0.97 ± 0.11	...	600 <sup>+614</sup> <sub>-250</sub>	...	77.31/72	CPL
			-0.78 ± 0.18	-1.87 <sup>+0.17</sup> <sub>-0.23</sub>	258 <sup>+150</sup> <sub>-82</sub>	...	62.09/71	Band*
	seq4	6.63-7.13	-0.46 ± 0.08	...	325 <sup>+51</sup> <sub>-41</sub>	...	119.12/72	CPL
			-0.26 ± 0.17	-2.24 <sup>+0.14</sup> <sub>-0.22</sub>	219 <sup>+57</sup> <sub>-44</sub>	...	91.40/71	Band*
	seq5	7.13-8.13	-0.76 ± 0.09	...	270 <sup>+63</sup> <sub>-45</sub>	...	100.99/72	CPL
			-0.46 ± 0.19	-2.15 <sup>+0.14</sup> <sub>-0.18</sub>	159 <sup>+47</sup> <sub>-25</sub>	...	71.88/71	Band*

**Table 5**  
(Continued)

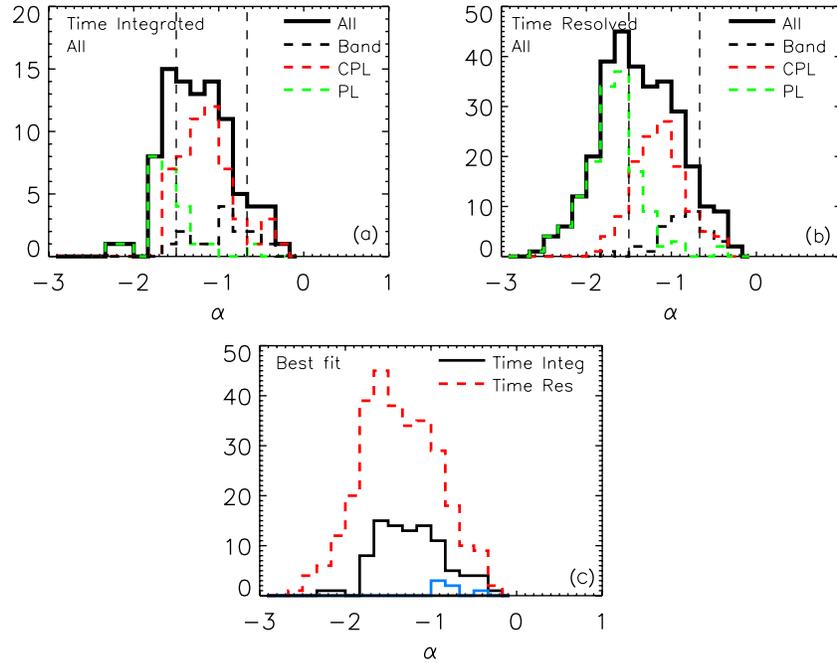
GRB	Sequence	Interval	$\alpha$	$\beta$	$E_{\text{peak}}$ (keV)	$E_{\text{iso}}$ ( $10^{52}$ erg s)	$\chi^2/\text{dof}$	Model
090410	slew	7.13–39.13 (sl)	$-1.38 \pm 0.04$	...	...	...	162.04/73	PL
			$-1.08 \pm 0.11$	...	$235^{+103}_{-55}$	...	66.17/72	CPL*
			$-1.01 \pm 0.16$	$-2.39^{+0.34}_{-1.59}$	$194^{+89}_{-50}$	...	63.11/71	Band
	seq6	8.13–8.63	$-0.53 \pm 0.10$	...	$312^{+73}_{-56}$	...	82.82/72	CPL
			$-0.15 \pm 0.23$	$-2.32^{+0.16}_{-0.22}$	$169^{+49}_{-29}$	...	66.61/71	Band*
	seq7	8.63–11.13 (sl)	$-1.32 \pm 0.04$	...	...	...	124.94/72	PL
			$-1.05 \pm 0.11$	...	$248^{+103}_{-59}$	...	59.61/71	CPL*
			$-0.99 \pm 0.14$	$-2.51^{+0.42}_{-7.49}$	$210^{+98}_{-55}$	...	58.13/70	Band
	seq1	–49.48–42.48	$-1.11 \pm 0.20$	...	...	...	96.53/87	PL
			$-0.69 \pm 0.37$	...	$401^{+615}_{-207}$	...	84.97/86	CPL*
			$-0.38 \pm 0.00$	$-1.89^{+0.53}_{-0.70}$	$185^{+711}_{-122}$	...	84.68/85	Band
			$-1.53 \pm 0.08$	...	...	...	253.90/89	PL
			$-0.50 \pm 0.18$	...	$312^{+64}_{-49}$	...	88.49/88	CPL*
			$-0.51 \pm 0.14$	$-9.37^{+19.37}_{-0.63}$	$313^{+62}_{-50}$	...	88.50/87	Band
			$-0.36 \pm 0.09$	...	$343 \pm 24$	...	93.14/88	CPL*
			$-0.36 \pm 0.10$	$-3.98^{+1.27}_{-6.02}$	$341^{+26}_{-31}$	...	92.96/87	Band
			$-0.45 \pm 0.12$	...	$278^{+30}_{-30}$	...	53.87/88	CPL*
	seq5	11.52–15.02	$-0.41 \pm 0.15$	$-2.81^{+0.48}_{-7.19}$	$258 \pm 46$	...	52.10/87	Band
$-1.42 \pm 0.07$			...	...	...	216.49/89	PL	
$-0.69 \pm 0.14$			...	$315^{+75}_{-55}$	...	82.67/88	CPL*	
seq6	15.02–32.52	$-0.56 \pm 0.34$	$-2.15^{+0.24}_{-2.39}$	$231^{+134}_{-95}$	...	79.81/87	Band	
		$-1.59 \pm 0.07$	...	...	...	74.79/89	PL	
		$-1.39 \pm 0.16$	...	$189^{+278}_{-66}$	...	66.52/88	CPL*	
seq9	82.52–139.52	$-1.27 \pm 0.39$	$-2.13^{+0.37}_{-0.81}$	$131^{+169}_{-68}$	...	62.75/87	Band	
		$-1.59 \pm 0.06$	...	...	...	225.57/89	PL	
		$-1.00 \pm 0.13$	...	$179^{+39}_{-28}$	...	89.06/88	CPL*	
090418B	seq1	5.96–17.96 (sl)	$-1.00 \pm 0.13$	...	$179 \pm 37$	...	89.06/87	Band
			$-1.00 \pm 0.13$	$-7.12^{+17.12}_{-2.88}$	...	...	216.50/89	PL
			$-1.77 \pm 0.03$	...	...	...	101.43/88	CPL
	seq2	17.96–30.96 (sl)	$-1.52 \pm 0.06$	...	$152^{+29}_{-21}$	...	101.43/88	CPL
			$-1.10 \pm 0.19$	$-2.33^{+0.13}_{-0.15}$	$83^{+12}_{-9}$	...	79.17/87	Band*
			$-1.92 \pm 0.04$	...	...	...	116.92/89	PL
seq3	30.96–40.96 (sl)	$-1.74 \pm 0.10$	...	$89^{+37}_{-17}$	...	93.19/88	CPL*	
		$-1.75 \pm 0.09$	$-9.37^{+19.37}_{-0.63}$	$90^{+35}_{-18}$	...	93.19/87	Band	
		$-1.21 \pm 0.06$	...	$232 \pm 23$	...	110.96/108	CPL*	
090424	seq1	–0.62–0.88	$-1.20 \pm 0.06$	$-3.25^{+0.43}_{-6.75}$	$224 \pm 25$	$1.47 \pm 0.11$	108.69/107	Band
			$-1.33 \pm 0.05$	...	$207^{+27}_{-22}$	...	112.10/108	CPL
	preslew	–0.62–14.38	$-1.01 \pm 0.17$	$-2.50^{+0.11}_{-0.13}$	$113^{+29}_{-13}$	$4.17 \pm 0.32$	105.78/107	Band*
			$-1.77 \pm 0.06$	...	...	...	205.95/109	PL
	seq2	0.88–1.88	$-1.36 \pm 0.13$	...	$120^{+32}_{-21}$	...	120.88/108	CPL
			$-0.86 \pm 0.30$	$-2.67^{+0.24}_{-0.30}$	$75^{+14}_{-9}$	$0.40 \pm 0.06$	108.71/107	Band*
seq4	2.88–4.88	$-1.11 \pm 0.07$	...	$194 \pm 20$	...	119.94/108	CPL*	
		$-1.11 \pm 0.07$	$-4.57^{+1.39}_{-5.43}$	$194 \pm 21$	$1.24 \pm 0.09$	119.84/107	Band	

**Notes.** *Interval*: times are with respect to the *Swift*/BAT trigger. See also notes to Table 2.

with  $\alpha$  greater than this “death line.” We find, by contrast, that the bulk of our sample does not violate the limit and in fact for the brightest long bursts ( $F(15\text{--}150 \text{ keV}) > 5 \times 10^{-6} \text{ erg cm}^2$  and those with higher  $E_{\text{peak}} > 150 \text{ keV}$ , that  $\alpha$  falls in the narrower range  $-1.6 < \alpha < -1.0$ . We note, however, that these bursts are predominantly fitted with the CPL model, and as discussed in Section 3.2, in this model, there is a tendency to fit an  $\alpha$  value softer than the true low-energy index. By contrast, in bursts fit with the Band model and those with lower  $E_{\text{peak}}$  values, we can fit the “true”  $\alpha$  and these bursts do tend to straddle the  $\alpha = -2/3$  line; however, our sample is too small and our error estimates include  $\alpha < -2/3$ , so it is not possible to say definitively whether the synchrotron shock model is violated or whether there is a need to include a thermal component. Short bursts also tend to have harder  $\alpha > -1.0$ , which suggests that there is another emission mechanism at work in short bursts. Ghirlanda et al. (2003) have found that the early phase of bursts tends to have harder spectra that soften as the burst progresses.

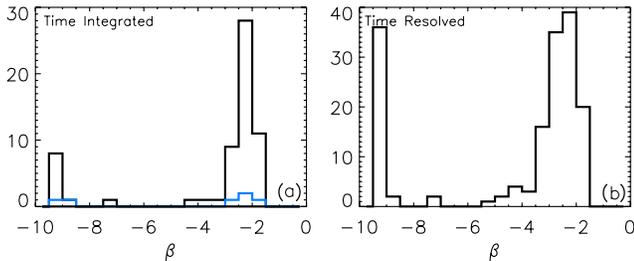
This would suggest that time-resolved spectra should show more cases of  $\alpha > -2/3$  than time-integrated spectra. Our study of time-resolved spectra (Figure 2(b)) does not show this effect.

The distribution of  $E_{\text{peak}}$  values found in this study extends from roughly 60 keV up to 2000 keV in the observer frame, or 100–3000 keV in the source frame. The lower limit is instrumental, as other missions (see below) do find significant numbers of bursts with  $E_{\text{peak}} < 60 \text{ keV}$ . The upper bound is not sharp and the slow fall-off suggests a convolution of reduced effective area at high energies with a falling intrinsic distribution. The total bolometric energy for long bursts covers the fairly narrow range  $10^{52} \text{ erg} < E_{\text{iso}} < 10^{54} \text{ erg}$ . The lower bound, which is not met for short bursts or the subenergetic GRB 060505, is likely a consequence of the instrumental lower limit on  $E_{\text{peak}}$  and the correlation between  $E_{\text{peak}}$  and  $E_{\text{iso}}$  discussed in Section 4. The upper limit is more likely to have a physical origin, but we cannot rule out that it is also an instrumental



**Figure 2.** Distributions of the low-energy power-law index,  $\alpha$ , values for different samples. In panels (a) and (b), the distributions are for the bursts for which each of the given models is the best fit, with the sum of all individual model histograms overlaid. Panel (c) overlays the time-integrated and time-resolved histograms (the “All” histograms from panels (a) and (b), respectively). In panel (c), the blue or light gray solid histogram represents short bursts. The dashed vertical lines represent limits to  $\alpha$  for the synchrotron shock model (see text).

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



**Figure 3.** Distributions of the high-energy power-law index,  $\beta$ , values from the Band model fit values for the time-integrated (panel (a)) and time-resolved spectra (panel (b)). In panel (a), the blue or light gray solid histogram represents short bursts.

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

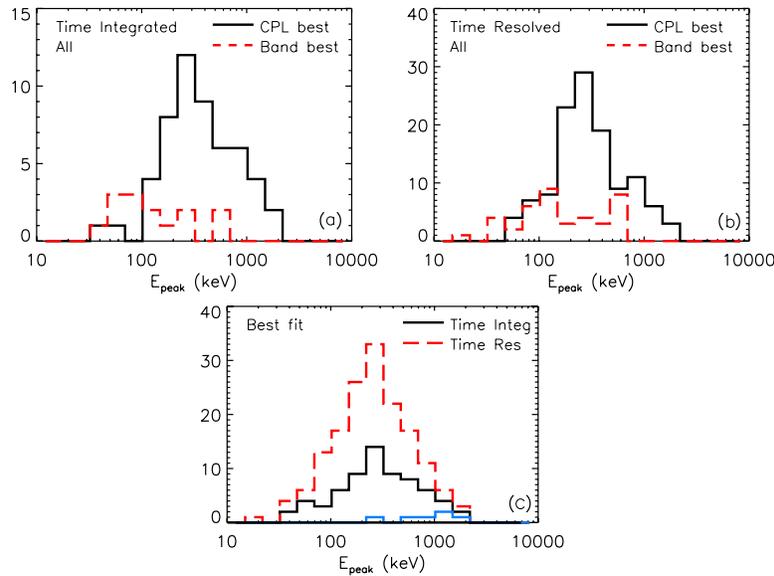
effect convolved with the  $E_{\text{peak}}-E_{\text{iso}}$  correlation. In any case, the narrow distribution we find for  $E_{\text{iso}}$  is consistent with that seen by other authors (e.g., Amati et al. 2002; Bloom et al. 2003; Amati 2006)

We also see that the fit parameters  $\alpha$ ,  $\beta$ , and  $E_{\text{peak}}$  have nearly identical distributions for sequences as for whole bursts. This result that sequences have similar energetic properties to whole bursts is important because it shows that with regard to at least this particular set of prompt emission properties, sequences behave just like whole bursts, or conversely, that long GRBs can be modeled as superpositions of individual burst events, each of which has energetic properties similar to a whole burst. Since there is often considerable spectral evolution within bursts and across sequences, it is useful to study individual burst sequences where there is less time for spectral evolution to smear out burst properties.

In Figure 8, we compare the best values of model fit parameters with the results from two other experiments: the BATSE results of Kaneko et al. (2006, hereafter K06) and the

HETE-2 results of Pélagéon et al. (2008). In Figure 8(a), we see that the best distributions of the low-energy index  $\alpha$  have very similar distributions for BAT/WAM, BATSE, and HETE-2. The BAT/WAM distribution is skewed toward slightly lower  $\alpha$  values and has a median of  $-1.23 \pm 0.28$ , compared with  $-1.14 \pm 0.21$  for BATSE (K06) and  $-1.08 \pm 0.20$  for HETE-2 (derived from the data of Pélagéon et al. 2008). The BAT-only sample contains only bursts that can be fitted with a CPL or Band model and it has a softer  $\alpha$  distribution as expected since only soft bursts can be fitted with BAT data alone. Similarly, as shown in Figure 8(b), we see that the high-energy index  $\beta$  has a very similar distribution in the BAT/WAM and BATSE samples. The median values are identical to within error:  $-2.23^{+0.12}_{-2.00}$  for BAT/WAM,  $-2.33^{+0.24}_{-0.26}$  for BATSE, and  $-2.30^{+0.20}_{-0.07}$  for HETE-2.

In Figure 8(c), the best value of  $E_{\text{peak}}$  for this sample is plotted along with the best values from the BATSE results of K06, the HETE-2 results of Pélagéon et al. (2008), and the bursts from S08 for which a CPL or Band model can be fitted. We see that although the medians of the BATSE and BAT/WAM distributions are consistent, the BAT/WAM distribution has larger wings at both the high- and low-energy ends. The high-energy wing is consistent with the larger effective area above 300 keV in the WAM as compared to BATSE (Yamaoka et al. 2009a). This allows us to fit bursts more effectively with  $E_{\text{peak}} > 300$  keV. The low-energy wing is attributed to the lower threshold of BAT compared to BATSE, leading to more triggers on bursts with  $E_{\text{peak}} < 100$  keV. Although the BAT/WAM distribution is wider than the BATSE distribution, the median values are quite comparable. For this sample, the median  $E_{\text{peak}}$  is  $291^{+283}_{-119}$  keV, compared with  $251^{+122}_{-68}$  keV for the BATSE sample. We note that our results are consistent with BATSE results even though we include many more faint bursts. The inclusion criterion used by K06 is  $F(\sim 20\text{--}2000 \text{ keV}) >$



**Figure 4.** Distributions of  $E_{\text{peak}}$  values from the best model fit values for the time integrated-spectra (panel (a)) and the time-resolved spectra (panel (b)). In panels (a) and (b), the distributions are for the bursts for which each of the given models is the best fit, with the sum of all individual model histograms overlaid. Panel (c) overlays the best-fit curves from the time-integrated and time-resolved spectra. The blue or light gray solid histogram represents short bursts.

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

**Table 6**  
Median Parameter Values for the Best and Acceptable Model Fits

Model	Time Integrated			Time Resolved		
	$\alpha$	$\beta$	$E_{\text{peak}}$	$\alpha$	$\beta$	$E_{\text{peak}}$
PL best	$-1.64^{+0.15}_{-0.09}$	...	...	$-1.68^{+0.16}_{-0.21}$	...	...
PL acceptable	$-1.52^{+0.10}_{-0.18}$	...	...	$-1.53^{+0.19}_{-0.18}$	...	...
CPL best	$-1.16^{+0.18}_{-0.17}$	...	$324.6^{+282.5}_{-108.6}$	$-1.13^{+0.20}_{-0.25}$	...	$291.7^{+177.5}_{-98.4}$
CPL acceptable	$-1.19^{+0.14}_{-0.44}$	...	$302.9^{+99.8}_{-176.0}$	$-1.03^{+0.17}_{-0.31}$	...	$312.6^{+214.6}_{-155.6}$
Band best	$-0.93^{+0.23}_{-0.40}$	$-2.29^{+0.29}_{-0.27}$	$117.0^{+121.9}_{-21.0}$	$-0.82^{+0.21}_{-0.18}$	$-2.40^{+0.28}_{-0.43}$	$128.8^{+249.8}_{-44.8}$
Band acpt (CPL best)	$-1.11^{+0.24}_{-0.15}$	$-2.23^{+0.12}_{-1.99}$	$264.0^{+174.6}_{-127.1}$	$-1.11^{+0.22}_{-0.16}$	$-2.88^{+0.55}_{-6.19}$	$248.4^{+175.4}_{-75.5}$
Overall best	$-1.23^{+0.27}_{-0.28}$	$-2.23^{+0.12}_{-1.99}$	$265.1^{+256.2}_{-111.2}$	$-1.40^{+0.39}_{-0.28}$	$-2.88^{+0.55}_{-6.19}$	$258.1^{+204.0}_{-108.2}$
Short bursts	$-0.72^{+0.24}_{-0.04}$	...	$1037.1^{+318.6}_{-474.6}$	...	...	...
1st Quarter				$-0.99^{+0.21}_{-0.18}$	$-2.33^{+0.41}_{-0.46}$	$270.9^{+200.4}_{-116.5}$
2nd Quarter				$-1.08^{+0.29}_{-0.19}$	$-2.33^{+0.61}_{-6.15}$	$236.8^{+119.6}_{-103.2}$
3rd–4th Quarter				$-1.16^{+0.22}_{-0.26}$	$-2.48^{+0.09}_{-0.34}$	$223.1^{+91.3}_{-139.2}$

**Notes.** Each pair of rows gives the medians and the quartile dispersions for the free parameters of the model. The indicators “best” and “acceptable” divide the bursts as to whether a given model was the best fit for a burst or merely an acceptable model, as defined in Section 2.

$2.0 \times 10^{-5}$  erg  $\text{cm}^{-2}$ . Our sample (see Section 4.2) includes bursts down to  $F(15\text{--}2000 \text{ keV}) \approx 2.0 \times 10^{-6}$  erg  $\text{cm}^{-2}$ . This tells us that the fit parameters are not affected by burst fluence.

The “BAT only” and HETE-2 histograms have very different distributions that result from the narrow energy range of the BAT and the low-energy response of HETE-2. Only bursts with  $15 \text{ keV} < E_{\text{peak}} < 150 \text{ keV}$  can be fitted with the BAT data alone. Although the parent distribution is still rising at 150 keV, it becomes more and more difficult to fit a Band or CPL spectrum to the BAT data alone as  $E_{\text{peak}}$  increases. As expected from its 2–400 keV energy range, the HETE-2 distribution includes more high  $E_{\text{peak}}$  bursts than does the “BAT only” distribution. The HETE-2 distribution also includes more bursts with very low  $E_{\text{peak}}$  values and in fact extends below the range of the figure to 2.6 keV. Clearly, the distribution of  $E_{\text{peak}}$  values depends critically on the nature of the instrument.

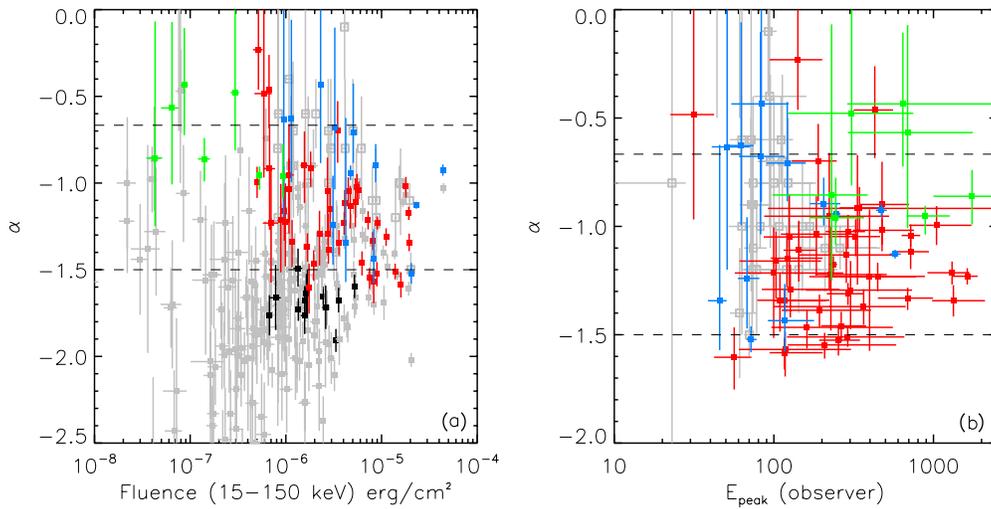
## 4. RESULTS OF CORRELATIONS

### 4.1. Comparison with Previously Published Relations

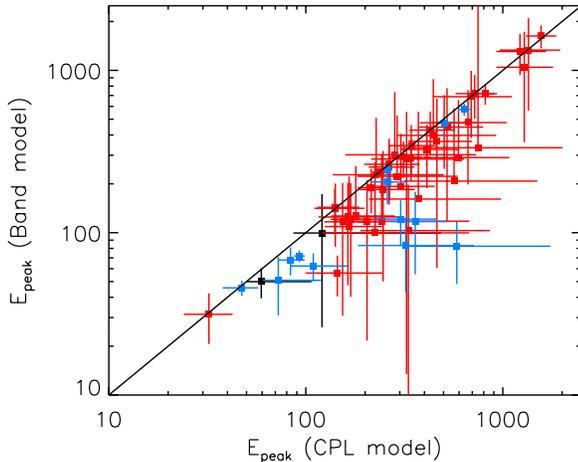
#### 4.1.1. The $E_{\text{peak}}\text{--}E_{\text{iso}}$ Relation

For 29 of the *Swift/Suzaku* bursts in the study set, we have a measurement of both  $E_{\text{peak}}$  and a spectroscopic redshift. For these bursts, we can compare the parameters derived in this work with the results published by A06, Campana et al. (2007), and Cabrera et al. (2007).

In Figure 9, we plot the “Amati relation,” showing  $E_{\text{peak}}$  versus  $E_{\text{iso}}$ . In this plot, we have included the original A06 data points, with *Swift* bursts in the A06 sample shown in green and other bursts as black diamonds. We have also added other *Swift* bursts for which  $E_{\text{peak}}$  and  $E_{\text{iso}}$  have been derived by other authors (Campana et al. 2007; Cabrera et al. 2007); these points are indicated by open black squares. The bursts from the BAT/WAM sample are indicated by red filled squares



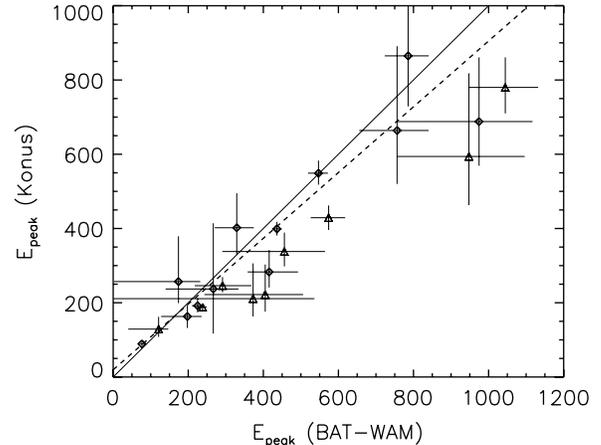
**Figure 5.** Low-energy power-law index  $\alpha$  is plotted relative to the fluence in the 15–150 keV energy band in panel (a) and relative to  $E_{\text{peak}}$  in panel (b). For both panels, the colors of data points represent the following classes. Colored points are GRBs from this study where long bursts are distinguished by which model is the best fit: blue: Band, red: CPL, black: PL. Short bursts (all CPL best) are shown as green points. The light gray points are taken from S08, where the open squares are bursts for which  $E_{\text{peak}}$  can be fit. In panel (a), the fluences for the blue, red, and green points are derived from fits to the best model from the current sample and the fluences for the black and gray points are from S08. The dashed lines represent limits to  $\alpha$  for the synchrotron shock model (see text).



**Figure 6.**  $E_{\text{peak}}$  derived from a Band model fit plotted relative to  $E_{\text{peak}}$  derived from a cutoff power-law fit. Colors of data points indicate which model is the best fit: blue: Band; red: CPL; black: PL. The solid line indicates perfect correlation, showing that the CPL model always slightly overestimates  $E_{\text{peak}}$  with respect to the Band model.

(long bursts) and blue filled triangles (short bursts). The black lines are taken from A06, the red line is the fit to the BAT/WAM long burst sample<sup>17</sup>, and the green line is our fit to all *Swift* long bursts shown in the plot. For clarity, Figure 10 shows only the long bursts that are neither subenergetic nor classified as X-ray flashes.

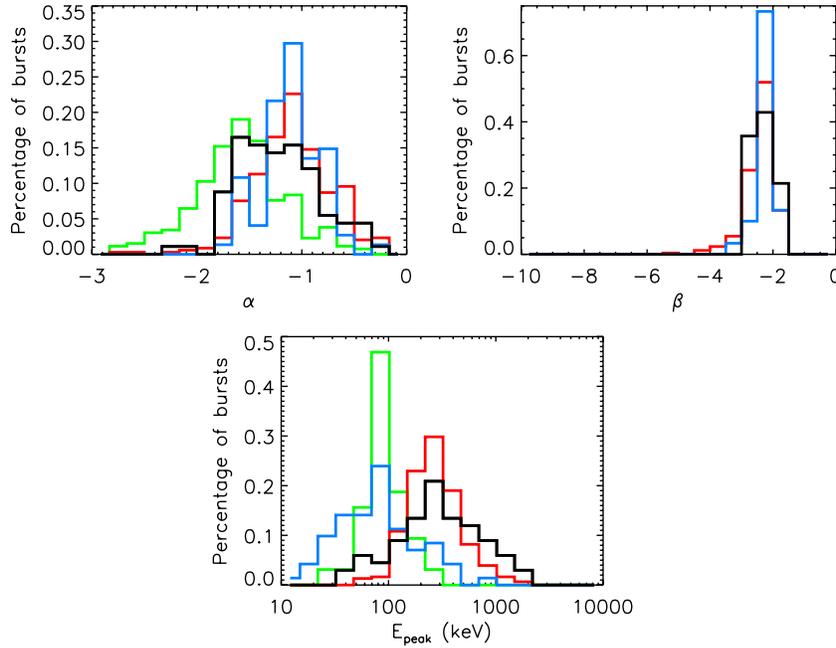
In comparing the bursts from this sample with earlier published samples, two things are apparent. First, there is a relative dearth of bursts in this sample at the lower left of Figure 10 (weak, low  $E_{\text{peak}}$  bursts). We attribute this to not being able to fit BAT–WAM bursts with  $E_{\text{peak}} \lesssim 100$  keV, as discussed in Section 3.1. Secondly, we see an excess of bursts above and to the left of the main distribution (weak, high  $E_{\text{peak}}$  bursts). This is significant and is discussed further in Section 4.2.



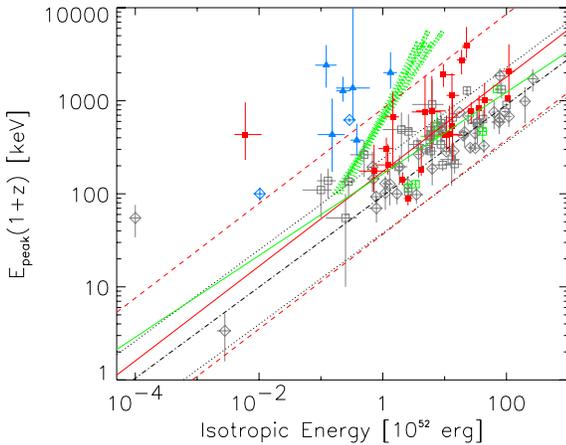
**Figure 7.**  $E_{\text{peak}}$  determined by Konus is plotted vs.  $E_{\text{peak}}$  derived in this work. All Konus values are from the literature (see references below). The diamonds represent bursts for which the BAT–WAM values are derived from T. Sakamoto et al. (2009, in preparation) and the triangles are from this work. See the text for a discussion of the BAT–WAM data selection for this plot. The dashed line is the best fit to the data points represented by diamonds. The solid line represents perfect correlation between  $E_{\text{peak}}^{\text{BAT-WAM}}$  and  $E_{\text{peak}}^{\text{Konus}}$ . References for the Konus points are (in order of increasing  $E_{\text{peak}}^{\text{Konus}}$ ) Golenetskii et al. (2006b, 2008d, 2006f, 2007b, 2006d, 2007c, 2008e, 2006c, 2008c, 2006e, 2006i, 2008b, 2006h, 2005b, 2006a, 2009, 2008a, 2006g, 2007a, 2007d, 2005a).

As other authors have shown, we find that the data are best fitted by a power-law relation,  $E_{\text{peak}} = kE_{\text{iso}}^m$ . Following the discussion in A06, we find that  $\chi^2$  is reduced if we include an additional parameter  $\sigma_v$  in the fit to account for intrinsic scatter in the data, beyond what can be accounted for by simple statistical error bars. The log-likelihood density function  $P$  that we maximized is identical to Equation (5) of Guidorzi et al. (2006), with our parameter  $K$  replacing  $q$  in Guidorzi et al. (2006). In this function, there is a dependence on the parameter  $\sigma_v$  in the normalization of the log-likelihood distribution, so we cannot simply interpret  $\log P = -\frac{1}{2}\chi^2$ . If we examine the original likelihood function (Equation (52), and discussion following, in D’Agostini 2005), we see that the exponential part of the likelihood corresponds to the normal  $\chi^2$  which is multiplied by

<sup>17</sup> The fit and the discussion in the next three paragraphs exclude the outlier GRB 060505; see below.



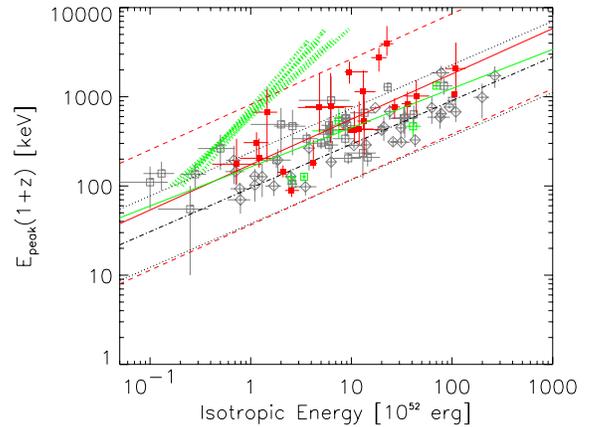
**Figure 8.** Distributions of  $\alpha$ ,  $\beta$ , and  $E_{\text{peak}}$  values for the BAT–WAM joint fits compared with the results from other data sets. The solid black curves are for this sample (the best model fits are shown as the solid black curves in Figures 2(a), 3(a), and 4(c), respectively), the red curves are for BATSE bursts (K06), the blue curves are for HETE bursts (Pélangéon et al. 2008), and the green curves are for BAT-only bursts (S08).



**Figure 9.** Comparison with the results of A06. Filled points are from this work: red squares are long bursts and blue triangles are short bursts. Open squares are *Swift* bursts from earlier studies: green: from A06, black: from Cabrera et al. (2007) and Campana et al. (2007). Open diamonds are non-*Swift* bursts from A06 with short bursts marked in blue. The red solid line is the fit to this data set (excluding GRB 060505 at  $E_{\text{iso}} = 10^{50}$  erg) and the red dashed lines represent a vertical logarithmic deviation of 0.675 (corresponding to  $2.5\sigma_v$ , where  $\sigma_v = 0.27$ ; line 5 of Table 7). The green solid line is the fit to all *Swift* bursts. The black dot-dash line (fit) and dotted lines (deviations) are from A06. The green hashed lines indicate our estimate of the  $E_{\text{peak}}$ -dependent threshold (see discussion in the text).

a normalization. Therefore, to provide a comparison between the goodnesses of fit for different samples, we quote  $\chi_{\text{red}}^2$  in the last column of Table 7 as the minimization of the exponential part of the likelihood function divided by the number of degrees of freedom in the fit.

The current sample shows a clear correlation between  $E_{\text{peak}}$  and  $E_{\text{iso}}$  for long GRBs. The points (accounting for sample variance) are best fitted by the line  $E_{\text{peak}} = (173 \pm 23) E_{\text{iso}}^{0.51 \pm 0.05}$ , where  $E_{\text{peak}}$  is in units of keV, and  $E_{\text{iso}}$  is in units of  $10^{52}$  erg. This shows that even with a slightly different (higher  $E_{\text{peak}}$ ) distribution, the  $E_{\text{peak}}-E_{\text{iso}}$  relation still holds.



**Figure 10.** Zoom in on Figure 9 to show more clearly the samples being studied in this work. Short bursts, subenergetic bursts, and X-ray flashes are eliminated. The symbol and line designations are the same as in Figure 9.

The results from fits to various parts of this data set are given in Table 7. In the first eight rows, we fitted various data sets shown in Figure 10 to the power-law relation  $E_{\text{peak}} = k E_{\text{iso}}^m$ . The first line gives our fit to the original GRB sample of A06 (excluding X-ray flashes). We derive a slope  $m$ , intercept  $K$ , and sample variance  $\sigma_v$  consistent with A06. The next three lines are fits to burst samples previous to this work. We see that there is a significant difference between the fits to the six *Swift* bursts in the A06 sample and the 33 non-*Swift* bursts, with the slope of the fit to the *Swift* bursts being much higher (0.74 versus 0.43) and the intercept being much lower (55 versus 111). Although the correlation is good ( $\rho = 0.94$ ) and  $\chi_{\text{red}}^2$  very close to one, the small sample of A06 *Swift* bursts may be an anomaly. The comparison between the current sample and the earlier sample of *Swift* bursts (lines 4 and 5 in Table 7) is quite close. The intercepts are consistent to within error, although the sample variance  $\sigma_v$  is a good deal larger for the current sample. Neither case shows a great deal of correlation ( $\rho = 0.74$ ).

**Table 7**  
Summary of the Results of the Analysis of the  $E_{\text{peak}}-E_{\text{iso}}$  Correlations

Data set	N	$\rho$	Chance probability	$m$	$K$	$\sigma_v$	$\chi_{\text{red}}^2$
Original Amati (A06) sample	39	0.87	$4.72 \times 10^{-13}$	$0.47 \pm 0.02$	$101 \pm 7$	$0.13 \pm 0.01$	0.7
Swift bursts in Amati sample	6	0.94	$4.80 \times 10^{-3}$	$0.74 \pm 0.05$	$55 \pm 7$	...	0.9
Non-Swift bursts in Amati sample	33	0.88	$1.34 \times 10^{-11}$	$0.43 \pm 0.02$	$111 \pm 7$	$0.12 \pm 0.01$	0.6
All Swift bursts previous to this work	36	0.74	$3.21 \times 10^{-7}$	$0.41 \pm 0.03$	$156 \pm 15$	$0.15 \pm 0.02$	0.7
<b>Current sample</b>	<b>22</b>	<b>0.74</b>	<b><math>7.58 \times 10^{-5}</math></b>	<b><math>0.51 \pm 0.05</math></b>	<b><math>173 \pm 23</math></b>	<b><math>0.27 \pm 0.02</math></b>	<b>0.9</b>
All Swift bursts	58	0.74	$2.51 \times 10^{-11}$	$0.44 \pm 0.03$	$164 \pm 13$	$0.20 \pm 0.02$	0.8
All long bursts	91	0.76	$1.45 \times 10^{-18}$	$0.42 \pm 0.02$	$143 \pm 8$	$0.18 \pm 0.01$	0.8
All short bursts	8	0.24	$5.70 \times 10^{-1}$	$0.53 \pm 0.07$	$1429 \pm 238$	$0.06 \pm 0.10$	1.7
<b>Current sample (sequences)</b>	<b>59</b>	<b>0.80</b>	<b><math>5.32 \times 10^{-14}</math></b>	<b><math>0.45 \pm 0.02</math></b>	<b><math>306 \pm 10</math></b>	<b><math>0.22 \pm 0.01</math></b>	<b>0.9</b>
1st Quarter	24	0.65	$5.17 \times 10^{-4}$	$0.42 \pm 0.02$	$356 \pm 21$	$0.21 \pm 0.05$	1.0
2nd Quarter	23	0.80	$5.71 \times 10^{-6}$	$0.34 \pm 0.03$	$376 \pm 19$	$0.19 \pm 0.01$	0.9
3rd–4th Quarter	12	0.79	$2.22 \times 10^{-3}$	$0.41 \pm 0.05$	$225 \pm 8$	$0.22 \pm 0.01$	1.0
Fluence 15–150 keV	83	0.31	$4.25 \times 10^{-3}$	$0.26 \pm 0.02$	$3857 \pm 985$	$0.33 \pm 0.01$	0.9
Fluence 15–150 keV (BAT only)	24	0.70	$1.43 \times 10^{-4}$	$0.08 \pm 0.02$	$227 \pm 47$	$0.01 \pm 0.03$	0.8
Fluence 15–2000 keV	59	0.44	$5.12 \times 10^{-4}$	$0.45 \pm 0.03$	$34156 \pm 12268$	$0.30 \pm 0.01$	0.9
Fluence 1–10000 keV	59	0.41	$1.25 \times 10^{-3}$	$0.40 \pm 0.04$	$16844 \pm 6899$	$0.31 \pm 0.02$	0.9

**Notes.**  $N$  is the number of bursts in the sample; the number of degrees of freedom is three less than this number. The correlation ( $\rho$ ) is the Spearman's rank correlation. The parameters  $m$ ,  $K$ , and  $\sigma_v$  are defined in Section 4.1.  $\chi_{\text{red}}^2$  is defined as the minimum of the exponential part of the likelihood function divided by the number of degrees of freedom (see text).

In comparison with earlier  $E_{\text{peak}}$  relationships, our sample has a higher range of  $E_{\text{peak}}$  values and a significantly broader dispersion (as evidenced by the larger sample variance  $\sigma_v$ ) than does the A06 sample. Nonetheless, we are able to derive a reasonable correlation between  $E_{\text{peak}}$  and  $E_{\text{iso}}$  with a slope that matches that of A06 ( $0.51 \pm 0.05$ ). Similarly, we can show good correlations between  $E_{\text{peak}}$  and  $E_{\text{iso}}$  for both (a) *Swift* long bursts and (b) all long bursts despite the sample variances, and can fit slopes to the relationship ( $m_{(a)} = 0.44 \pm 0.03$  and  $m_{(b)} = 0.42 \pm 0.02$ ) that are consistent with earlier findings. It is important to note that the slope of the relationship is consistent even though the  $E_{\text{peak}}$  range (reflected in the  $K$  intercept parameter) is significantly higher for the *Swift* sample ( $K = 164 \pm 13$ ) than for the pre-*Swift* sample studied by A06 ( $K = 111 \pm 7$ ). A higher value of  $K$  means that a burst with a given  $E_{\text{peak}}$  in the source frame will have, on average, a lower  $E_{\text{iso}}$ . With  $m = 0.43$ , for a given  $E_{\text{peak}}$ ,  $E_{\text{iso}}$  for a *Swift* burst would be ( $\sim 0.3$ – $0.6$ )  $E_{\text{iso}}$  for a pre-*Swift* burst. However, the examination of Figure 9 shows that we are actually sampling roughly the same range of  $E_{\text{iso}}$  as the pre-*Swift* sample, but with a broader distribution of larger  $E_{\text{peak}}$  values. Furthermore, we confirm that this relationship holds for *Swift* bursts over  $\sim 3$  orders of magnitude in  $E_{\text{iso}}$  and nearly  $\sim 2$  orders in  $E_{\text{peak}}$  and over a redshift range of  $0.09 < z < 6.29$  with no indication of any variation in the relationship with redshift. This tells us that we are now sampling a different part and a broader section of the burst population than did earlier experiments, but with similar results.

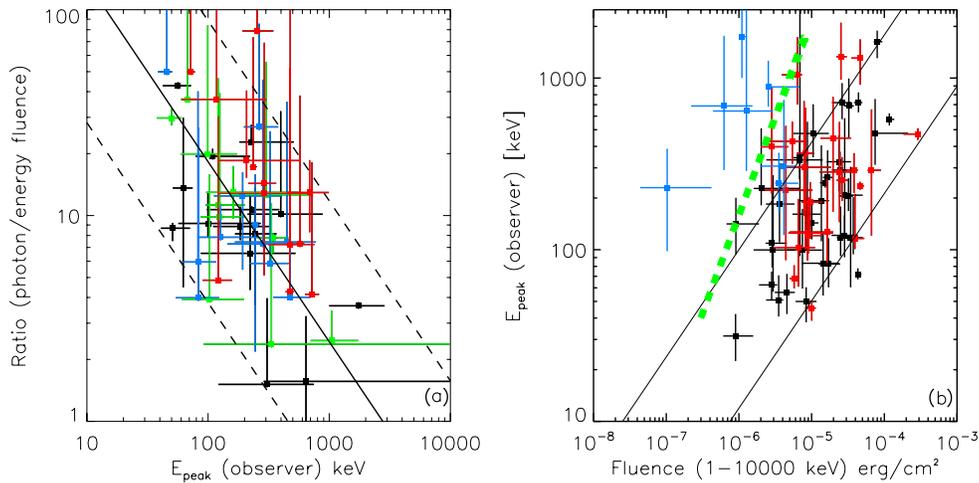
#### 4.1.2. Possible Instrumental Selection Effects

Several authors (e.g., Butler et al. 2007; Ghirlanda et al. 2008) have questioned whether the tightness of the  $E_{\text{peak}}-E_{\text{iso}}$  relation is due to instrumental selection effects. On the low side of the relation, selection effects cannot be important: if an instrument can detect a burst at a given  $E_{\text{peak}}$  and  $E_{\text{iso}}$ , it could certainly detect a burst at the same  $E_{\text{peak}}$  but a larger  $E_{\text{iso}}$ . Thus, the absence of bursts in the lower right of Figures 9 and 10 must be a real physical effect. On the upper side of the relation however, it is possible that instrumental effects are

causing bursts to be missed. This possibility arises because *Swift*/BAT and *Suzaku*/WAM, like other detectors, require a minimum photon flux to trigger or detect a burst. The *Swift*/BAT trigger is particularly complicated, allowing effective triggers on many different time scales, but essentially a trigger requires a particular count rate above background. The relationship between energy fluence, the observer-frame analog of  $E_{\text{iso}}$ , and the photon flux is a complicated one, depending on the spectral and the temporal properties of the burst (rapidly varying spiky bursts with high peak count rates are more likely to trigger than slowly varying bursts), but the general trend is that hard GRBs produce fewer photons than soft GRBs of the same total energy fluence.

Band (2006) has calculated the peak flux threshold for *Swift*/BAT as a function of energy for several different burst spectra. We have attempted to derive such a threshold from the data. Since the *Swift*/BAT trigger operates on many different time scales, we consider photon fluence to be a better determinant of threshold than peak flux. Using our fits to the Band model for long GRBs, we derive for each burst the ratio  $R$  between photon fluence (photons  $\text{cm}^{-2}$ ) and energy fluence (units  $10^{-6}$  erg  $\text{cm}^{-2}$ ) in the 1–10,000 keV band. This ratio is plotted with respect to  $E_{\text{peak}}$  in Figure 11(a). There is a good deal of scatter in the distribution, but the trend is for  $R$  to be smaller for larger  $E_{\text{peak}}$ . We fitted the data and found a weak correlation  $\rho = 0.52$  ( $1.20 \times 10^{-4}$  chance probability).

The next step is to determine the energy fluence threshold at a representative energy. To be included in this study, the burst must trigger the BAT and also be bright enough to be detected in the WAM. It is clear from Figure 5(a), in which bursts from S08 are plotted in gray behind the bursts in the current sample, that the WAM threshold is higher than the BAT threshold. There is also an effective threshold in  $\alpha$  since bursts with  $\alpha < -1.6$  are soft and unlikely to be fitted with a CPL or Band model even if detected in WAM. However, any burst in gray with  $\alpha > -1.6$  since the launch of *Suzaku* could have potentially been detected by *Suzaku*. For such bursts in S08 since 2005 September 1, we find the following statistics. For the 15 long bursts with  $F(15\text{--}150 \text{ keV}) < 9 \times 10^{-7}$  erg  $\text{cm}^{-2}$



**Figure 11.** (a) Vertical axis shows the ratio between the photon fluence (photons  $\text{cm}^{-2}$ ) and the energy fluence (units  $10^{-6}$   $\text{erg cm}^{-2}$ ) when fit to a Band model between 1 keV and 10,000 keV. The colors represent different bands of energy fluence  $F$  (in units  $10^{-6}$   $\text{erg cm}^{-2}$ )—black: ( $F < 5.0$ ), green ( $5.0 < F < 10.0$ ), blue ( $10.0 < F < 25.0$ ), red ( $25.0 < F$ ). The solid line indicates the best fit and the dashed lines are  $3\sigma$  deviations in intercept. (b) The relationship between fluence (1–10,000 keV) and  $E_{\text{peak}}$  in the observer frame. Red points are long bursts in this sample with redshifts, black points without; short bursts are shown as blue points. The green dashed line indicates our estimate of the  $E_{\text{peak}}$ -dependent instrumental threshold. The meaning of the black lines is explained in the text.

(flux from S08), none were detected in WAM, seven were not visible to WAM (due to earth occultation or the detector being disabled during passage through the South Atlantic Anomaly), and eight were visible but not detected. Of the 51 bursts with  $F(15\text{--}150 \text{ keV}) > 9 \times 10^{-7} \text{ erg cm}^{-2}$ , 36 were detected in WAM, 13 were not visible to WAM, and only two were visible but not detected. This shows that there is a very sharp threshold for WAM detection among *Swift* bursts.

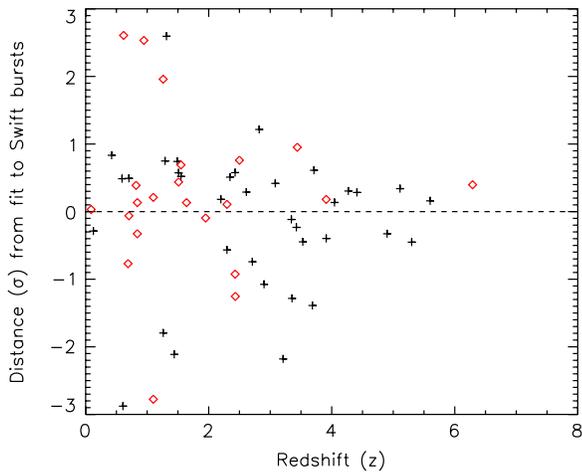
In Figure 11(b), we plot  $E_{\text{peak}}$  with respect to energy fluence (1–10,000 keV). The lowest fluence of any long burst in the sample is  $9.0 \times 10^{-7} \text{ erg cm}^{-2}$  for a burst with  $E_{\text{peak}} = 141 \text{ keV}$ . We take this point to be our detection threshold and then use the best fit to the data of Figure 11(a) to determine an effective energy fluence threshold as a function of  $E_{\text{peak}}$ . This is shown as the green dashed line in Figure 11(b). We see that this threshold line does a reasonable job of bounding the  $E_{\text{peak}}$ -fluence distribution from above. Our empirical energy dependent threshold does not show a flattening above  $\sim 200 \text{ keV}$  as do the plots of Band (2006)—such a flattening would lead to a steepening of the dashed green line in Figure 11(b), moving it away from our burst distribution. We note that several short bursts are detected above this threshold; since all of the fluence is found within a very short time period, short bursts have very different photon-to-energy fluence ratios and can be detected at lower energy fluence levels.

The last step is to translate the observer frame threshold to the  $E_{\text{peak}}-E_{\text{iso}}$  space. Since the transformation depends on redshift, we have indicated the equivalent threshold by green hashed regions in Figures 9 and 10, where the different traces are for different redshift values. What is seen is that the instrumental selection effect does not cut sharply into the distribution of detected bursts: all bursts save one (GRB 070318) are  $\sim 2$  or more times brighter than the threshold. However, the threshold effect would preclude us from seeing bursts more than a factor of 2 fainter than those that are detected. Also, bursts near threshold may be rare and may start to be detected with further observations. Thus, we conclude that for the current study, detector selection effects are not likely to have a strong influence on the distribution of detected bursts in the  $E_{\text{peak}}-E_{\text{iso}}$  space; however, the threshold is near enough to the distribution that it may prove important with an expanded data set.

We also examined whether the shift of the  $E_{\text{peak}}-E_{\text{iso}}$  line toward higher  $K$  is a redshift effect, since *Swift* is sampling from a higher redshift distribution than earlier samples (Jakobsson et al. 2006). Such evolution was suggested by Li (2007), although Ghirlanda et al. (2008) do not confirm the Li (2007) result. Consistent with Ghirlanda et al. (2008), we do not see any bias with regard to redshift (see Figure 12) and no sign of evolution of the slope or the intercept of the  $E_{\text{peak}}-E_{\text{iso}}$  relationship with redshift (Figure 13). We also fitted the entire set of published *Swift*  $E_{\text{peak}}$  and  $E_{\text{iso}}$  values and find a result consistent with that for our sample,  $E_{\text{peak}} = (164 \pm 13)E_{\text{iso}}^{0.44 \pm 0.03}$ . The basic result is that when all bursts are taken into account, a clear  $E_{\text{peak}}-E_{\text{iso}}$  relationship still holds, but the scatter in the distribution is wider than that previously reported. This makes it particularly difficult to use this relationship to determine pseudo-redshifts, given only the  $E_{\text{peak}}$  of the burst.

#### 4.1.3. Outliers to the Relation

There is one peculiar outlier in the BAT/WAM long GRB sample that is not included in the fit. This point, red at the upper left of Figure 9, is GRB 060505 (McBreen et al. 2008; Xu et al. 2009; K. Yamaoka et al. 2009, in preparation). This subluminal GRB triggered WAM and passed the first rate trigger stage in the BAT, but it was too weak to trigger the BAT onboard burst response. However, since the burst duration was only 4 s, the 10 s of event data (collected for such “failed” triggers) allowed us to derive a BAT position and spectrum. It is possible that this GRB is similar to another subluminal event, GRB 980425/SN 1998bw, which is located to the far left of Figure 9 at  $E_{\text{peak}} = 55 \text{ keV}$ ,  $E_{\text{iso}} = 10^{48} \text{ erg}$ . Like GRB 980425, GRB 060505 is relatively nearby ( $z = 0.0894$ ; Fynbo et al. 2006), but unlike the earlier burst, no supernova has been found associated with the burst (Fynbo et al. 2006; Ofek et al. 2007). In order to shift GRB 060505 and GRB 980425 to the right on the plot until they reached the red fit line, we need to multiply  $E_{\text{iso}}$  for each burst by a factor of  $\approx 1000$ . A06 also mention a third possible member of this class, GRB 031203, also nearby ( $z = 0.105$ ) and inconsistent with the main relationship, although they note that there is a particularly large uncertainty in  $E_{\text{peak}}$  for this burst. Ghisellini et al. (2006) point out that another nearby ( $z = 0.033$ ) event associated with a supernova, GRB 060218, is consistent



**Figure 12.** Perpendicular distance from the best-fit line to the  $E_{\text{peak}}-E_{\text{iso}}$  plot for all *Swift* bursts as a function of redshift. The vertical coordinate for each point is calculated in log-log space and scaled by the errors on that point. Thus, the vertical scale can be interpreted as significance ( $\sigma$ ). Bursts in this sample are shown by red diamonds and earlier *Swift* bursts are shown by black crosses. There is no sign of any variation with redshift.

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

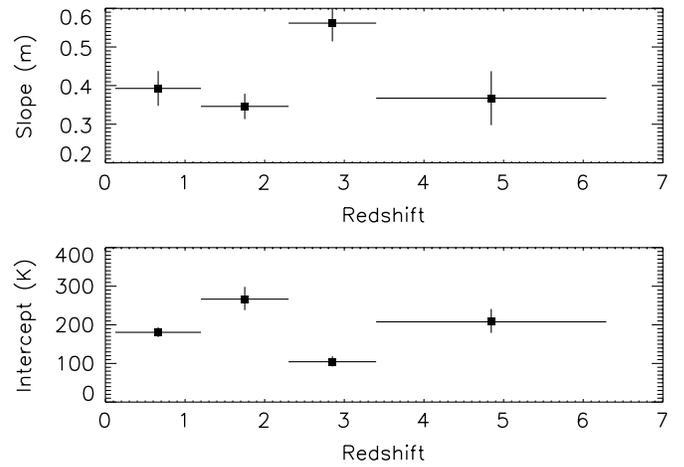
with the  $E_{\text{peak}}-E_{\text{iso}}$  relation. They go on to show that strong spectral evolution in the other outliers may have meant that  $E_{\text{peak}}$  could have been much lower and  $E_{\text{iso}}$  somewhat larger than what was measured, meaning that these bursts might not be outliers. Although more such bursts will need to be studied to verify this, it is possible that GRBs 060505 and 980425 are examples of a separate class of underluminous GRBs with  $E_{\text{peak}}$  values within the range of “normal” long bursts, but isotropic energy values three orders of magnitude lower than would be expected from the main  $E_{\text{peak}}-E_{\text{iso}}$  relation.

As has been seen by previous authors (e.g., A06), short GRBs do not follow the  $E_{\text{peak}}-E_{\text{iso}}$  relation and lie outside the main distribution in the direction of lower  $E_{\text{iso}}$  for a given  $E_{\text{peak}}$ . If we include GRB 050709 from A06, we can make a tentative fit to the short burst distribution, deriving a fit to  $E_{\text{peak}} = (1429 \pm 238)E_{\text{iso}}^{0.53 \pm 0.07}$ , but this fit is heavily weighted by this single burst, while all other short bursts are in a broad cluster for which no correlation is found. And, even with GRB 050709 we calculate a correlation factor of only  $\rho = 0.24$ . Thus, we cannot claim that there is any significant  $E_{\text{peak}}-E_{\text{iso}}$  relation for short GRBs.

Another important relation was discovered by Yonetoku et al. (2004), who found a good correlation between the time-integrated burst  $E_{\text{peak}}$  and the luminosity in the brightest one second of the burst,  $L_{\text{iso}}$ . We do not examine this relationship in the current work, but given its importance, we will investigate it in a later paper.

#### 4.2. Other Correlations from This Work

Since we have fits to a great number of individual burst pulses, we can compare  $E_{\text{peak}}$  and  $E_{\text{iso}}$  for individual burst pulses. This result is shown in Figure 14. The best fit to this sample is  $E_{\text{peak}} = (306 \pm 11)E_{\text{iso}}^{0.45 \pm 0.02}$ , which is shown by the solid red line in Figure 14. On the whole, this distribution shows a tighter correlation (and a less sample variance) than does the time-integrated sample (see Table 7), indicating that the  $E_{\text{peak}}-E_{\text{iso}}$  relation is intrinsic to burst pulses. The slope of this fit (0.45) is consistent with the slope of the fits to the full burst samples, telling us that the full burst  $E_{\text{peak}}-E_{\text{iso}}$  relation arises

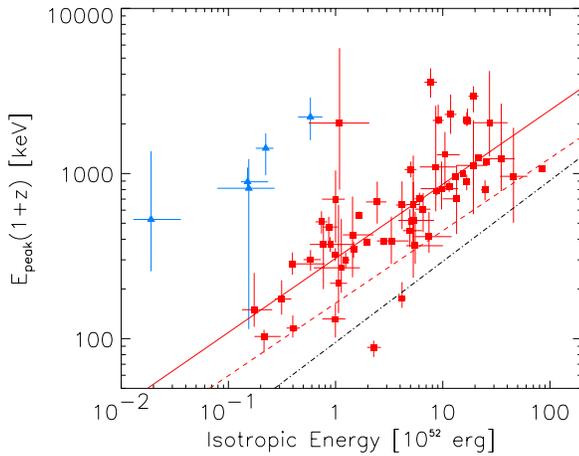


**Figure 13.** Data for all *Swift* bursts are divided into four redshift bins so as to put roughly the same number of bursts in each bin. The bin edges are:  $z < 1.2$ ,  $1.2 < z < 2.3$ ,  $2.3 < z < 3.4$ ,  $3.4 < z$ . The top plot shows the slope,  $m$ , of the  $E_{\text{peak}}-E_{\text{iso}}$  relation and the bottom the intercept,  $K$ , both as a function of redshift. There is no sign of any variation with redshift.

from a superposition of burst pulses, each of which fits the relation. The offset of this distribution from the time-integrated fit is easily understood. Burst pulses have a distribution of  $E_{\text{peak}}$  values similar to time-integrated  $E_{\text{peak}}$  values (see Figure 4(c) and Table 6), but since the durations of pulses are shorter, there is less integrated flux in a pulse. Because a total burst is made up of a compilation of pulses, each with its own point on the  $E_{\text{peak}}-E_{\text{iso}}$  plot, it is not surprising that the time-integrated distribution has a larger intrinsic scatter. This shows that the total burst  $E_{\text{peak}}-E_{\text{iso}}$  relation is a consequence of the relation holding for individual burst pulses. Using a different relation, Firmani et al. (2009) also find that burst pulses follow the same correlations as full bursts.

It is interesting to ask whether there is any time evolution of the  $E_{\text{peak}}-E_{\text{iso}}$  relation within bursts. To study this, we divided the burst pulses into three bins according to when they occurred within the burst. The total duration of each burst ( $T_{100}$ ) was divided into quarters and the mid time of each pulse was placed into one of the three time bins according to whether it was in the first quarter of the burst, the second quarter of the burst, or the second half of the burst. The results are shown in Figure 15, where pulses are colored or shaded according to their time bin. There is scatter in all distributions, but we can see some differences in the distributions. The earlier sequences (red) have a higher  $E_{\text{peak}}$  distribution and tend to be clustered in a region of high  $E_{\text{iso}}$ . As line 10 of Table 7 shows, the correlation between  $E_{\text{peak}}$  and  $E_{\text{iso}}$  is somewhat poorer for this group. The fits to all three groups have roughly the same slope, and the first two sequences have the same intercept to within error. Comparing the second quarter and the second half sequences, we see a drop in the line intercept showing that  $E_{\text{peak}}$  falls (successive peaks soften) while  $E_{\text{iso}}$  covers the same range in the two groups. This result suggests that along with the well-known softening of bursts with time, the  $E_{\text{peak}}-E_{\text{iso}}$  relation for burst sequences also evolves with time, with less correlation early in the burst and more later on. As for the time-integrated sample, short burst pulses are outliers to the overall relationship. There are not enough short burst pulses to be able to say whether or not there is any correlation in this sample.

Since we see a correlation in the source frame, it is important to ask whether a similar correlation exists in the observer



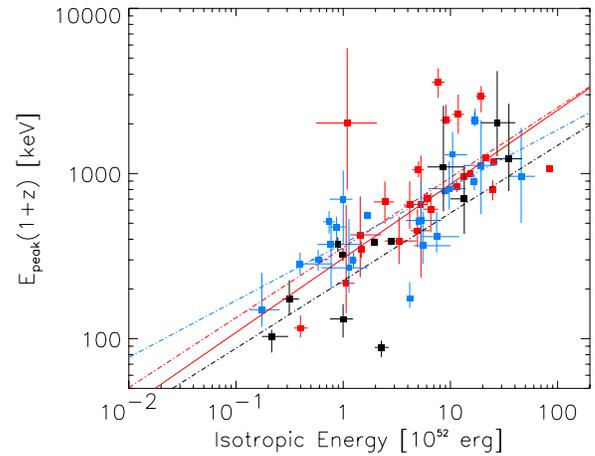
**Figure 14.** Plot of the individual sequences for the burst sample. Long bursts are shown by red or black squares and short bursts are shown by blue or gray triangles. The solid red line is the best fit to this distribution (see text), the dashed red line is the best fit to the time-integrated bursts (Figure 9), and the black dash-dotted line is the fit from A06.

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

frame. When the redshift is known, transforming  $E_{\text{peak}}^{\text{obs}}$  to  $E_{\text{peak}}^{\text{source}}$  is effected by simply multiplying  $E_{\text{peak}}^{\text{obs}}$  by  $(1+z)$ . The transformation from observed flux to isotropic flux is given in Section 2. There is a factor of  $(1+z)$  in the denominator, but since the luminosity distance  $L$  is directly proportional to redshift, the net effect is that  $E_{\text{iso}} \sim z * F(\text{obs})$ . Thus, to first order both  $E_{\text{peak}}$  and  $E_{\text{iso}}$  should scale from observer frame quantities by a similar factor of  $z$ .

Therefore, in the absence of evolution with redshift, we would expect to see a correlation between  $E_{\text{peak}}^{\text{obs}}$  and measured fluence. This relationship is plotted in Figure 11(b) for fluence in the 1–10,000 keV (extrapolated) band. The fluence was calculated by fitting the data to a Band model, allowing the total area under the curve between the low- and high-energy bounds to be a free parameter. Bursts with and without known redshift are distinguished by color (red and black points, respectively), and we see no systematic bias between these two data sets, telling us that bursts with redshifts sample well the total distribution of bursts. Since the transformation of the ensemble of non-redshift bursts to the source frame should be the same as for redshift-detected bursts, we conclude that almost all of the data points, both with and without redshift, can be made consistent with the source frame  $E_{\text{peak}}-E_{\text{iso}}$  relationship at some reasonable redshift. This is in sharp contrast to the result found for the BATSE data sample (K06; Band & Preece 2005) in which it was determined that a large fraction of bursts were inconsistent with the relationship in the observer frame.

We can use Figure 11(b) to understand this result and compare it with those of other authors. The two solid black lines in Figure 11(b) are placed to represent the envelope of points in the  $E_{\text{peak}}$ -fluence plane shown in Figure 4 of Ghirlanda et al. (2008). Comparing with these lines (which are approximate), we see only one outlier in the bottom right (low  $E_{\text{peak}}$ , high fluence), but a number of outliers in the upper left (high  $E_{\text{peak}}$ , low fluence), which are, however, below our estimated instrumental threshold. These outliers correspond to the points above and to the left of the main distribution in Figure 10. This is the region that Ghirlanda et al. (2008) and Butler et al. (2007), and others, have discussed as being due to instrumental threshold effects. And, in fact, this is a region that is excluded in the arguments of



**Figure 15.** Plot of the individual sequences (pulses) for the burst sample. Pulses are distinguished by their time sequence within the burst. Pulses in the first quarter of the burst are shown in red (black), those in the second quarter are in blue (gray), and those in the last half are shown in black (open). The color-coded dash-dotted lines are the fits to each pulse distribution. The solid red line is the fit to all pulses (same as the solid line in Figure 14).

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

Ghirlanda et al. (2008) for *Swift* alone, because *Swift*/BAT alone cannot determine  $E_{\text{peak}}$  in this region. However, by including an instrument with a much broader energy range, we can extend the threshold into regions that have not been previously explored—not by *Swift* alone because of its narrow energy range and not by other experiments because of their relatively poorer sensitivity. The relative sparseness of this region for other instruments is understandable: *Swift* is more likely to trigger on bursts with higher fluence and lower  $E_{\text{peak}}$ .

The correlation in the observer frame is not as strong as it is in the source frame. The correlation coefficient in the source frame is only  $\rho = 0.41$ , compared with  $\rho = 0.74$  in the observer frame. Also, the intrinsic scatter in the data is higher,  $\sigma_v^{\text{obs}} = 0.31$  and  $\sigma_v^{\text{source}} = 0.27$ . The result that the  $E_{\text{peak}}$ -fluence relationship becomes narrower when transformed into the source frame  $E_{\text{peak}}-E_{\text{iso}}$  relationship is consistent with the source frame relationship having a physical basis and not just arising as a reflection of an artificial observer frame relationship. Recently, Butler et al. (2009) have developed tests for determining whether selection effects significantly affect apparent GRB correlations. We will study and apply these tests in a later paper.

## 5. SUMMARY AND DISCUSSION

We present here a complete set of time-integrated and time-resolved spectral fits for the prompt emission for a set of 91 bursts, 35 of which have measured redshifts. This provides a very useful addition to the *Swift*/BAT catalog (S08), an expansion of previous compilations of bursts for which both  $E_{\text{peak}}$  and redshift are known (A06; Cabrera et al. 2007; Campana et al. 2007), and a companion to the *CGRO*/BATSE (Preece et al. 2000, K06) and HETE-2 (Pélangéon et al. 2008) spectral catalogs. This work shows the power and utility of joint fits with *Swift*/BAT and other instruments with larger energy ranges and we hope that this work will give guidance to future joint fit efforts, such as between *Swift*/BAT and *Fermi*/GBM and LAT.

It is also important to compare our results with those from these other missions. We first compare our  $E_{\text{peak}}$  distribution with that of BATSE (K06; see Figure 8). We find that, while

our distribution has wider tails, the median values of  $E_{\text{peak}}$  for BATSE ( $265^{+256}_{-111}$  keV) and BAT/WAM ( $291^{+283}_{-119}$  keV) are the same to within error. The comparisons of other spectral parameters are similarly within error of each other (see Section 3.5). As do K06, we do not see any clustering in the low-energy power-law index at any values other than  $\sim 1$ . We also make a direct comparison between our derived values of  $E_{\text{peak}}$  and those from the *WIND*/Konus experiment (Figure 7) and see that the two sets of values agree to within errors.

We are able to show that an  $E_{\text{peak}}-E_{\text{iso}}$  relationship holds for most long GRBs. The slope of the fit to our data matches that derived by other authors such as A06, even though we probe a burst distribution with a higher range of  $E_{\text{peak}}$  values than those previously studied. With the addition of our bursts, there are now 58 *Swift* long bursts and 91 long bursts for which both  $E_{\text{peak}}$  and redshift are known. We have now shown that the correlation between  $E_{\text{peak}}$  and  $E_{\text{iso}}$  holds for a large sample ( $\sim 100$ ) bursts observed by six different experiments and that while the region of  $E_{\text{peak}}-E_{\text{iso}}$  space explored is different for different experiments, the degree of correlation and the slope of the relationship hold constant. We are able to confirm that the  $E_{\text{peak}}-E_{\text{iso}}$  relation holds not only for entire bursts but also for statistically separable subintervals (sequences) within bursts, and in fact we find the same slope,  $m = 0.45 \pm 0.02$ , for sequences as for whole bursts. While a full study of possible evolution of the relationships is beyond the scope of this paper, we see no sign (Figures 12 and 13) that the relationships depend on the burst redshift. Although we show a clear correlation between  $E_{\text{peak}}$  and  $E_{\text{iso}}$ , the large scatter in the distribution makes any use of this relationship to determine a pseudo-redshift problematic.

As seen before, short GRBs are outliers to the  $E_{\text{peak}}-E_{\text{iso}}$  relationship with a large scatter and a very poor correlation. All short bursts lie in the part of the  $E_{\text{peak}}-E_{\text{iso}}$  plane at high  $E_{\text{peak}}$  and relatively low  $E_{\text{iso}}$ . This is consistent with the observations that short bursts are subluminal with respect to long bursts and a further indication that short bursts form a physically distinct population. Also, we see that subenergetic bursts (GRB 060505 in this sample and GRB 980425/SN 1998bw in the A06 sample) also form a separate population from the long burst population, though it is, of course, not possible to constrain a correlation with only two data points.

Our sample does not contain any X-ray flashes, because such bursts would be too weak in the WAM energy range to be detected by WAM. Also, too few *Swift* bursts have solid jet breaks for us to comment on collimation-corrected relationships (e.g., Ghirlanda et al. 2004) that involve the jet opening angle.

We find a weak correlation with a great deal of scatter between  $E_{\text{peak}}$  in the observer frame and observer frame fluence  $F$ . The correlation becomes much narrower when working in the source frame which supports but does not prove that the source frame correlation has a physical origin and is not just a reflection of a narrow observer frame correlation. When we compare bursts with redshifts to bursts without redshifts (Figure 11(b)), we see that non-redshift bursts are interspersed with redshift bursts, hence all of the BAT/WAM bursts are in a region of  $E_{\text{peak}}-F$  space to be consistent with the  $E_{\text{peak}}-E_{\text{iso}}$  relation, further supporting the interpretation that the relationship is real and not an artifact of a selection effect.

The large, homogeneous sample of bursts presented here gives us an unbiased picture of the energetic properties of bursts detected by *Swift*. The addition of spectral information from *Suzaku*/WAM allows full fits to be made to nearly all of the

bursts, and we show that this sample is consistent spectrally with the much larger set of BATSE bursts (K06). Since so many *Swift* bursts have measured redshifts, we are also able to confirm that one of the most important empirical relationships of GRB prompt emission, the correlation between  $E_{\text{peak}}$  and  $E_{\text{iso}}$ , holds for our sample. We have shown the validity and importance of combining *Swift*/BAT data with data from another experiment. Since all instruments involved are still functioning, in future years it will be possible to expand the BAT-WAM catalog and carry out similar joint fits between *Swift*/BAT and *WIND*/Konus and *Fermi*/GBM.

H. A. K. and T. S. are supported by the *Swift* project. This research is supported in part by a Grant-in-Aid for Science Research (19047001 KY) of the Japanese Ministry of Education, Culture, Sports, Science and Technology (MEXT). We appreciate the helpful communication with C. Guidorzi about using the log-likelihood function for our fits. We also thank the anonymous referee for his/her insightful comments and suggestions that significantly improved the paper.

*Note added in proof:* After this article was accepted for publication, it was brought to our attention that a revised analysis had significantly changed the best redshift values for two bursts in our sample. According to Fynbo et al. (2009), the redshift for GRB 060908 is  $z = 1.8836$  and GRB 070508 has only an upper limit  $z \lesssim 3.0$ . However, since only two bursts are affected, our scientific conclusions are not changed. Figures, tables, and numbers in this paper reflect the old redshift values and future papers on the BAT-WAM analysis will include the corrected redshifts.

## REFERENCES

- Amati, L. 2006, *MNRAS*, **372**, 233 (A06)  
 Amati, L., et al. 2002, *A&A*, **390**, 81  
 Aptekar, R. L., et al. 1995, *Space Sci. Rev.*, **71**, 265  
 Band, D. L. 2006, *ApJ*, **644**, 378  
 Band, D. L., & Preece, R. D. 2005, *ApJ*, **627**, 319  
 Band, D. L., et al. 1993, *ApJ*, **413**, 281  
 Barthelmy, S. D., et al. 2005a, *Space Sci. Rev.*, **120**, 143  
 Barthelmy, S. D., et al. 2005b, GCN Circ. 4077  
 Barthelmy, S. D., et al. 2008, GCN Circ. 7606  
 Berger, E., Fox, D. B., & Cucchiara, A. 2007a, GCN Circ. 6470  
 Berger, E., Morrell, N., & Roth, M. 2007b, GCN Circ. 7154  
 Berger, E., et al. 2006, GCN Circ. 4815  
 Berger, E., et al. 2007c, *ApJ*, **664**, 1000  
 Bloom, J. S., Frail, D. A., & Kulkarni, S. R. 2003, *ApJ*, **594**, 674  
 Butler, N., Kocevski, D., & Bloom, J. S. 2009, *ApJ*, **671**, 656  
 Butler, N., et al. 2007, *ApJ*, **671**, 656  
 Cabrera, J. I., et al. 2007, *MNRAS*, **382**, 342  
 Campana, S., et al. 2007, *A&A*, **472**, 395  
 Cannizzo, J., et al. 2009, GCN Report 221.1  
 Cenko, S. B., et al. 2006, GCN Circ. 5946  
 Cenko, S. B., et al. 2007, GCN Circ. 6556  
 Chornock, R., et al. 2009, GCN Circ. 9243  
 Copete, A., et al. 2009, GCN Circ. 9159  
 Cucchiara, A., et al. 2006, GCN Circ. 5470  
 Cummings, J., et al. 2007a, GCN Circ. 6821  
 Cummings, J. R., et al. 2007b, GCN Report 85.1  
 Curran, P. A., et al. 2007, *A&A*, **467**, 1049  
 Cusumano, G., et al. 2007, *A&A*, **462**, 73  
 D'Agostini, G. 2005, arXiv:physics/0511182  
 D'Avanzo, P., D'Elia, V., & Covino, S. 2008, GCN Circ. 8350  
 Fenimore, E., et al. 2007, GCN Circ. 6724  
 Fenimore, E., et al. 2008a, GCN Circ. 7913  
 Fenimore, E., et al. 2008b, GCN Circ. 8044  
 Firmani, C., et al. 2006, *MNRAS*, **370**, 185  
 Firmani, C., et al. 2009, *MNRAS*, **393**, 1209  
 Fynbo, J. P. U., et al. 2006, *Nature*, **444**, 1047

- Fynbo, J. P. U., et al. 2009, *ApJS*, submitted (arXiv:0907.3449)
- Gehrels, N., et al. 2004, *ApJ*, 611, 1005
- Ghirlanda, G., Celotti, A., & Ghisellini, G. 2003, *A&A*, 406, 879
- Ghirlanda, G., Ghisellini, G., & Lazzati, D. 2004, *ApJ*, 616, 331
- Ghirlanda, G., et al. 2008, *MNRAS*, 387, 319
- Ghisellini, G., et al. 2006, *MNRAS*, 372, 1699
- Golenetskii, S., et al. 2005a, GCN Circ. 4078
- Golenetskii, S., et al. 2005b, GCN Circ. 4394
- Golenetskii, S., et al. 2006a, GCN Circ. 4439
- Golenetskii, S., et al. 2006b, GCN Circ. 4542
- Golenetskii, S., et al. 2006c, GCN Circ. 4599
- Golenetskii, S., et al. 2006d, GCN Circ. 5446
- Golenetskii, S., et al. 2006e, GCN Circ. 5460
- Golenetskii, S., et al. 2006f, GCN Circ. 5518
- Golenetskii, S., et al. 2006g, GCN Circ. 5710
- Golenetskii, S., et al. 2006h, GCN Circ. 5722
- Golenetskii, S., et al. 2006i, GCN Circ. 5984
- Golenetskii, S., et al. 2007a, GCN Circ. 6230
- Golenetskii, S., et al. 2007b, GCN Circ. 6403
- Golenetskii, S., et al. 2007c, GCN Circ. 6798
- Golenetskii, S., et al. 2007d, GCN Circ. 6849
- Golenetskii, S., et al. 2008a, GCN Circ. 7487
- Golenetskii, S., et al. 2008b, GCN Circ. 7548
- Golenetskii, S., et al. 2008c, GCN Circ. 7854
- Golenetskii, S., et al. 2008d, GCN Circ. 8259
- Golenetskii, S., et al. 2008e, GCN Circ. 8412
- Golenetskii, S., et al. 2009, GCN Circ. 8924
- Graham, J. F., et al. 2007, GCN Circ. 6836
- Grupe, D., et al. 2007, *ApJ*, 662, 443
- Grupe, D., et al. 2009a, GCN Report 194.1
- Grupe, D., et al. 2009b, GCN Report 205.1
- Guidorzi, C., et al. 2006, *MNRAS*, 371, 843
- Guidorzi, C., et al. 2007, *A&A*, 463, 539
- Holland, S. T., et al. 2008, GCN Report 128.1
- Hullinger, D., et al. 2006, GCN Circ. 5142
- Immler, S., et al. 2008, GCN Report 179.1
- Jakobsson, P., et al. 2006, *A&A*, 447, 897
- Jakobsson, P., et al. 2007, GCN Circ. 6398
- Kaneko, Y., et al. 2006, *ApJS*, 166, 298 (K06)
- Katz, J. I. 1994, *ApJ*, 432, L107
- Krimm, H. A., et al. 2007, GCN Report 82.2
- Krimm, H. A., et al. 2009a, GCN Report 193.1
- Krimm, H. A., et al. 2009b, GCN Circ. 8936
- Levan, A. J., et al. 2007, *MNRAS*, 378, 1439
- Li, L.-X. 2007, *MNRAS*, 379, L55
- Mao, J., et al. 2008, GCN Report 175.1
- Markwardt, C. B., et al. 2007a, GCN Report 88.1
- Markwardt, C. B., et al. 2007b, GCN Report 92.1
- Marshall, F. E., et al. 2008, GCN Report 129.1
- McBreen, S., et al. 2008, *ApJ*, 677, L85
- Nakar, E., & Piran, T. 2005, *MNRAS*, 360, L73
- Nava, L., et al. 2008, *MNRAS*, 391, 639
- Ofek, E. O., et al. 2007, *ApJ*, 662, 1129
- Pagani, C., Holland, S. T., & Stamatikos, M. 2008, GCN Report 124.1
- Pagani, C., et al. 2008a, GCN Report 159.1
- Pagani, C., et al. 2008b, GCN Report 162.1
- Panaiteescu, A. 2007, *MNRAS*, 380, 374
- Pélangeon, A., et al. 2008, *A&A*, 491, 157
- Perley, D. A., et al. 2008, *ApJ*, 688, 470
- Perri, M., et al. 2007, GCN Report 103.1
- Perri, M., et al. 2008, GCN Report 123.1
- Preece, R. D., et al. 1998, *ApJ*, 506, L23
- Preece, R. D., et al. 2000, *ApJS*, 126, 19
- Racusin, J., Barbier, L., & Landsman, W. 2007, GCN Report 70.1
- Racusin, J., Schady, P., & Palmer, D. 2008, GCN Report 173.1
- Rol, E., et al. 2006, GCN Circ. 5555
- Rybicki, G. B., & Lightman, A. P. 1979, *Radiative Processes in Astrophysics* (New York: Wiley), 221
- Romano, P., et al. 2006, *A&A*, 456, 917
- Sakamoto, T., et al. 2007, GCN Report 69.3
- Sakamoto, T., et al. 2008a, *ApJS*, 175, 179 (S08)
- Sakamoto, T., et al. 2008b, GCN Report 133.1
- Sakamoto, T., et al. 2009, *ApJ*, 693, 922 (S09)
- Sari, R., Piran, T., & Halpern, J. P. 1999, *ApJ*, 519, L17
- Sato, G., et al. 2007, GCN Circ. 7148
- Sbarufatti, B., et al. 2008, GCN Report 142.1
- Scargle, J. D. 1998, *ApJ*, 504, 405
- Schady, P., et al. 2007a, *MNRAS*, 380, 1041
- Schady, P., et al. 2007b, GCN Report 87.2
- Schady, P., Starling, R. L. C., & Sato, G. 2008, GCN Report 151.1
- Schady, P., Krimm, H. A., & Rowlinson, A. 2009a, GCN Report 206.1
- Schady, P., Krimm, H. A., & Rowlinson, A. 2009b, GCN Report 208.1
- Schaefer, B. E. 2007, *ApJ*, 660, 16
- Soderberg, A. M., et al. 2006, *ApJ*, 650, 261
- Stern, D., et al. 2007, GCN Circ. 6928
- Stratta, G., et al. 2008, GCN Report 183.1
- Sugita, S., et al. 2009, *PASJ*, 61, 521
- Thoene, C. C., Perley, D. A., & Bloom, J. S. 2007, GCN Circ. 6663
- Tsutsui, R., et al. 2009, *J. Cosmol. Astropart. Phys.*, JCAP08(2009)015
- Ukwatta, T. N., et al. 2008a, GCN Report 111.1
- Ukwatta, T. N., et al. 2008b, GCN Report 150.1
- Vetere, L., et al. 2009, GCN Report 198.1
- Xu, D., et al. 2009, *ApJ*, 696, 971
- Yamaoka, K., et al. 2006, *Proc. SPIE*, 6266, 626643
- Yamaoka, K., et al. 2009a, *PASJ*, 61, S35
- Yonetoku, D., et al. 2004, *ApJ*, 609, 935
- Ziaeeepour, H., et al. 2008a, GCN Report 116.1
- Ziaeeepour, H., et al. 2008b, GCN Report 167.3