RHESSI TESTS OF QUASI-THERMAL GAMMA-RAY BURST SPECTRAL MODELS

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ABSTRACT

Prompt gamma-ray burst (GRB) spectra evolve on short timescales, suggesting that time-resolved spectral fits may help diagnose the still unknown prompt emission mechanism. We use broadband gamma-ray data from the Ramaty High-Energy Solar Spectroscopic Imager spacecraft to test quasi-thermal models with high signal-to-noise time-resolved spectra of nine bright GRBs. In contrast to results reported in more narrow energy bands, the quality of the fits of quasi-thermal models is poor in relation to fits of the phenomenological Band function. Moreover, the best-fit parameters for the simplest quasi-thermal model, a blackbody plus a nonthermal power law, show significant dependence on the fit band. Models that replace the power law with more complicated nonthermal functions are not robust for the data considered here and decrease the physical relevance of the fit blackbody.

Key words: gamma-ray burst: general

1. INTRODUCTION

One of the most distinct features of the initial gamma-ray emission of gamma-ray bursts (GRBs) is its temporal variability. Significant evolution of the light curve and the spectrum occurs on timescales shorter than the total burst duration. Accordingly, spectral fits of subintervals of a burst may provide improved insight into the burst emission mechanism, at the cost of increased complexity.

When the Band et al. (1993) phenomenological spectral model (the “Band function,” a smoothly connected broken power law) was found to successfully fit the GRB prompt emission observed by BATSE, systematic time-resolved analyses of large burst samples focused on identifying patterns in the fit parameter evolution in an attempt to gain insight into the emission mechanism of long GRBs. Ford et al. (1995), Crider et al. (1997), and Prece et al. (1998b) considered the evolution of the peak energy $E_{\text{peak}}$, low-energy index $\alpha$, and high-energy index $\beta$, respectively. Broadly, these authors found a typical hard-to-soft decay of the emission and a general correlation of spectral hardness with intensity.

The observation of hard low-energy spectral slopes ($\alpha \sim +1$) in the initial portions of GRB pulses raised concerns about the viability of the synchrotron shock model, as $\alpha > -2/3$ violated the “line of death” for optically thin synchrotron (OTS) emission (Crider et al. 1997; Prece et al. 1998a; Ghirlanda et al. 2002). These violations, in concert with theoretical expectations from the fireball model (e.g., Mészáros & Rees 2000), led authors to suggest that such emission could have a thermal origin (Crider et al. 1997; Prece 2000). Ghirlanda et al. (2003) found that time-resolved BATSE LAD spectra with hard low-energy indices could be acceptably fit with a blackbody spectrum. This result was confirmed by Ryde (2004) for hard, single pulses. In some cases, the addition of a simple power law improved the correspondence with the high-energy LAD data. These successes led Ryde (2005) to propose that all GRB emission might be decomposed into thermal and nonthermal components of similar magnitude, with the blackbody emission providing the spectral peak of the prompt emission. Within the LAD band, a simple power law proved a sufficient approximation to the more complicated true nonthermal emission, with the resulting blackbody plus power-law (BBPL) model fits having similar $\chi^2$ values as the Band function for identical degrees of freedom. In Ryde et al. (2006), the authors noted that the power law slope of the BBPL model avoided the OTS line of death and sought to interpret the blackbody fit results in the context of a photospheric model. Most recently, Ryde & Pe’er (2009; hereafter, RP09) identified regularity in the time evolution of the temperature and flux of the blackbody component for single-pulse bursts and linked the normalization of the blackbody component to the size of the thermal emitting region (also see Pe’er et al. 2007).

While the simple power law approximating the nonthermal emission in the BBPL model is effective over the moderate energy band (28 keV–1.8 MeV) of the BATSE LAD detectors, tests of the BBPL model using data covering a broader bandpass have had mixed results. McBreen et al. (2006) successfully fit the BBPL model to GRB 041219A data from the International Gamma-Ray Astrophysics Laboratory-Space Platform Interferometry (INTEGRAL-SPI) spanning the range 20 keV–8 MeV, although the blackbody contributed only a small portion of the flux of the main burst. Foley et al. (2008) obtained acceptable time-integrated fits of the BBPL model to GRBs observed by INTEGRAL-IBIS and -SPI, although the IBIS detection requirement created a burst sample with relatively low-peak spectral energies ($E_{\text{peak}} \lesssim 150$ keV). Ghirlanda et al. (2007) considered BATSE bursts co-observed in the X-ray by the BeppoSAX WFC. Time-resolved spectra were not available for the WFC data, but a summation of the time-resolved BBPL fits to the BATSE data led to a significant overprediction of the WFC flux, while a similar extrapolation of the summed time-resolved Band function fits was much more successful.

In this work, we have employed data from the Ramaty High-Energy Solar Spectroscopic Imager (RHESSI; Lin et al. 2002) to investigate the behavior of quasi-thermal spectral models over a broad energy band. RHESSI’s nine coaxial germanium detectors image the Sun at X-ray to gamma-ray energies (3 keV–17 MeV) with excellent resolution in energy (1–5 keV) and time (1 binary $\mu$s) (Smith et al. 2002). RHESSI’s detectors are effectively unshielded above $\sim 30$ keV and receive emission from astrophysical sources like GRBs with a total effective area of $\sim 150$ cm$^2$. Each coaxial detector is electronically segmented into thin front and thick rear segments; most off-axis emission is recorded in the rear segments. The satellite rotates with a period of about 4 s.
2. DATA ANALYSIS

2.1. Sample Selection

The identification of optimal fit intervals for time-resolved spectral fitting requires balancing the need for high signal-to-noise ratio (S/N) in order to constrain the fit parameters of the spectral models with the goal of the finest possible time resolution. In our previous systematic analysis of RHESSI GRBs (Bellm et al. 2008), we found that an S/N of at least 45 was required for adequate fitting of the most complicated models. This value is also consistent with those adopted by previous studies of time-resolved BATSE spectra (Crider et al. 1997; Kaneko et al. 2006).

Because bursts may have periods of high signal which are degraded to low S/N when integrated over the whole burst, we chose candidate bursts from the RHESSI sample with localizations and total S/N > 30. Radiation damage to RHESSI’s germanium detectors has slowly degraded spectral performance; we restricted our analysis to detectors that do not show signs of radiation damage. We therefore considered bursts from the RHESSI launch in 2002 February through 2006 June, after which all nine RHESSI detectors were damaged. Forty-five GRBs met these criteria.

To identify subintervals within each candidate burst, we used the Bayesian Blocks algorithm (Scargle 1998), which identifies the most probable segmentation of a burst light curve into intervals of constant Poisson rate. We modified the stopping criterion to generate subintervals of appropriate S/N. Since the RHESSI data are stored event by event, this “top–down” identification of the burst subintervals is more natural than building up data accumulated on fixed timescales until a minimum S/N is reached. While previous work on quasi-thermal models has focused on spectral evolution within pulses, our segmentation method does not require pulse modeling. This approach was necessary, as the bright bursts in this sample generally have irregular temporal structure, but it also avoids imposing additional implicit selection effects on the burst sample.

We applied the Bayesian Blocks algorithm to the raw RHESSI eventlist to identify the most probable segmentation points. The time variation of the background, while present, does not dominate the GRB variability. In our modified stopping criterion, we computed the background-subtracted S/N (in the 60 keV–3 MeV band) for each proposed subinterval. If the S/Ns of both subintervals were greater than 15, the segmentation was allowed. For each subinterval, we applied the Bayesian Blocks algorithm again if the S/N of that interval was greater than 45. After segmentation halted, we dropped any leading or trailing subintervals with S/N < 45 and combined any “interior” subintervals with low S/N with the adjacent subinterval with lower S/N. All the resulting subintervals have S/N > 45. We conducted spectral fitting only on bursts with at least three subintervals.

The resulting burst sample consists of nine bursts and a total of 88 subintervals. Table 1 lists the bursts and intervals considered in this work. Figure 1 shows the distribution of subinterval length and S/N. These bursts are predominantly from early in the RHESSI mission because for those bursts a greater number of the detectors remained unaffected by radiation damage.

In order to investigate the spectral evolution of single GRB pulses in Section 4.3, it was necessary to set a lower S/N threshold. We used our modified Bayesian Blocks routine to identify subintervals with S/N > 25 within single, separated pulses. This “single-pulse” sample yielded 25 subintervals within 3 GRBs (Table 1).

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Note. The intervals are quoted relative to the start time $T_0$.

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1 http://grb.web.psi.ch/
2.2. Spectral Fitting

2.2.1. Fit Methods

The RHESSI data were extracted in SSW-IDL. We fit a third-order polynomial to background intervals immediately before and after the burst, allowing for a potential periodic modulation of the background with the RHESSI rotation. We selected energy binning for the spectra by requiring at least 10 counts in each bin of the raw source spectrum. We used the same energy bins for all subintervals of each burst. Both the source and background spectra covered the energy range 30 keV–17 MeV.

We determined RHESSI’s spectral response by simulating monoenergetic photons impinging on a detailed mass model in the Monte Carlo suite MGEANT (Sturmer et al. 2000). For a grid of angles relative to the spacecraft rotation axis, we simulated photons along 60° arcs in rotation angle. After interpolating to the appropriate off-axis angle, we weighted the 60° sector responses by the burst light curve to generate the total response. Since many of the subintervals considered in this work were shorter than one-sixth of RHESSI’s 4 s rotation period, responses for short intervals were often single sector responses. Our simulations indicate that the spectral response does not vary appreciably on shorter scales in rotation angle.

We utilized ISIS v1.4.9 (Houck & Denicola 2000) for spectral fitting. Fitting was automated via an ISIS script and the results stored in a database.

We used data from the RHESSI rear segments only for all bursts except for GRBs 021206 and 021008A, which had off-axis angles small enough (18° and 50°, respectively) so that appreciable counts were recorded in the front segments. (Coincidentally, both these bursts also had data decimation in the rear segments—only a fraction of the observed counts were recorded.) The fit energy band was 30 keV–17 MeV, with some exceptions: GRB 021206 had significant atmospheric backscatter in the rear segments (Wigger et al. 2008), so the front and rear segment data were kept separate and fit over the range 30 keV–2800 keV and 300 keV–17 MeV. (For all other bursts, data from all detectors were combined into a single spectrum.) GRBs 030519B and 040228 came through the extreme rear of the RHESSI cryostat (166° and 163°), where the low-energy response is more sensitive to the detailed mass modeling, so a fit range of 50 keV–17 MeV was employed. Finally, GRB 021008A required a fit band of 100 keV–17 MeV for adequate fitting; Wigger et al. (2008) found similar behavior in a time-integrated fit of this data.

2.2.2. Spectral Models

We fit both the time-resolved and the time-integrated spectra with a variety of spectral models commonly used to represent the GRB prompt emission. The Band function (Band) is a phenomenological model which fits the vast majority of broadband prompt spectra (Band et al. 1993). It is a broken power law with a smooth transition between the upper and lower power laws:

\[ N_E = \begin{cases} A \left( \frac{E}{E_{piv}} \right)^{\alpha} \exp\left( -\frac{E}{E_{peak}} \right), & E < E_{break} \\ B \left( \frac{E}{E_{piv}} \right)^{\beta}, & E > E_{break} \end{cases} \]

with \( E_{peak} \equiv E_0 (\alpha - \beta) \) and \( B = A \left( \frac{\alpha - \beta}{E_{peak}} \right)^{\alpha - \beta} \exp(\beta - \alpha). \)

For \( \beta < -2 \) and \( \alpha > -2 \), \( E_{peak} \) corresponds to the peak of the \( vF_v \) spectrum. The normalization \( A \) has units of photons cm\(^{-2}\) s\(^{-1}\) keV\(^{-1}\), and \( E_{piv} \) is here taken to be 100 keV.

While the Band function is often assumed to be the “true” spectral model in fits of GRB spectra, data obtained over a more limited energy band or at lower S/N may not be sufficient to constrain its parameters. We also tested other empirical models with fewer free parameters. The cutoff power law (CPL) is equivalent to the Band function below \( E_{break} \):

\[ N_E = A \left( \frac{E}{E_{piv}} \right)^{\gamma} \exp\left( -\frac{E}{E_{peak}} \right). \]

We also fit a single power law (PL): \( N_E = A \left( \frac{E}{E_{piv}} \right)^{\gamma}. \) While the PL model was a poor fit to these spectra, its fit spectral index was useful in comparison with the other models.

The simplest quasi-thermal spectral model is a BBPL model. Proposed by Ryde (2005), it consists of Planck function and a
simple power law:

\[ N_E = A \frac{(E/E_{\text{piv}})^2}{\exp E/kT - 1} + B(E/E_{\text{piv}})^\beta \exp(-E(2+\alpha)/E_{\text{peak}}). \]

(3)

The approximation of the nonthermal emission by a simple power law is generally sufficient over the BATSE energy band (Ryde 2005). However, it is not expected to fit over a broader band (Ryde 2004, 2005; Ryde & Pe’er 2009). Like the PL model, it diverges unphysically.

More sophisticated quasi-thermal models replace the non-thermal PL in the BBPL with an empirical function with more free parameters. We attempt to fit a blackbody plus cutoff power law (BBCPL) model as well:

\[ N_E = A \frac{(E/E_{\text{piv}})^2}{\exp E/kT - 1} + B(E/E_{\text{piv}})^\beta \exp(-E(2+\alpha)/E_{\text{peak}}). \]

(4)

We retain the notation of \( E_{\text{peak}} \) for the cutoff parameter of the BBCPL model for the clarity of comparison, but in some cases the true peak of the \( \nu F_\nu \) spectrum may be due to the peak of the blackbody component at \( 3.92kT \). However, the addition of more free fit parameters leads to convergence problems even with our relatively high S/N broadband spectra. In addition to the unconstrained fits of the BBCPL model, then, we also perform fits in which the variation of the model temperature is constrained to an expected range. We describe the specifics of this constrained quasi-thermal model in the text below.

Given the convergence problems faced by the BBCPL model, we have not attempted fits of a blackbody + Band model, which contains an additional free parameter. In most cases, the simple CPL model provides an adequate representation of the RHESSI data, with the Band model offering only moderate improvements. Accordingly, the BBCPL model should provide a sufficient test of the importance of the blackbody component over the RHESSI band.

3. FIT RESULTS

We present the time evolution of the fit parameters of the Band and BBPL models in Figures 2–10. The quality of the fits and the constraint of their parameters were generally good. For GRB 021206, the goodness of fit was poorer for some subintervals because of the separation of front and rear data. Slight offsets in the background subtraction created disagreements about the overall model normalization and increased the \( \chi^2 \). We elected to take the averaged fluence value produced by the fit rather than introduce a fit normalization offset between the front and rear data for this burst. For GRB 021008A, the only other burst with front segment data, our combination of front and rear segment spectra averaged out such background subtraction problems and obviated the need for such offsets.

Wigger et al. (2008) fit RHESSI data for many of these bright bursts using an identical mass model but independent analysis and fit procedures. Our fits of the total burst intervals are a good match to those results (Table 2). In the case of GRB 021206, the presence of excess high-energy emission not well modeled by the Band function increased the \( \chi^2 \) value for the fit to 17 MeV. (This component likely also contributed to the poor goodness of fit for this burst in the time-resolved fits, as discussed above, although its impact is harder to ascertain.) HETE-2 also observed three bursts in this sample. RHESSI fit higher \( E_{\text{peak}} \) values for all three bursts; in two of the cases, the peak energies were above the 400 keV upper bound of the HETE energy band.

The distributions of our best-fit parameters differ somewhat from the BATSE results obtained by Kaneko et al. (2006). For our time-resolved Band function fits, the mean \( \alpha \) is \(-1.00 \) with standard deviation \( 0.47 \) (Figure 11). The RHESSI mean \( E_{\text{peak}} \) is \( 580 \pm 280 \) keV, and \( \beta \) has mean \(-3.50 \) and standard deviation \( 0.89 \). The time-resolved BATSE results for all good Band fits are \( \alpha = -0.90^{+0.54}_{-0.39} \), \( E_{\text{peak}} = 268^{+188}_{-145} \) keV, and \( \beta = -2.33^{+0.49}_{-0.47} \), where we have converted the quartile dispersions to 1σ confidence intervals.
uncertainties under the simplifying assumption of an underlying normal distribution. Using Levene’s test, we find that the variances of the BATSE and RHESSI distributions are consistent. Since the RHESSI distributions are not normal, we cannot compare the means using Student’s $t$-test. The nonparametric Kolmogorov–Smirnov test rejects the null hypothesis that the BATSE and RHESSI parameter samples are drawn from the same distribution. However, this result is not surprising, given the different fit energy ranges and the few RHESSI bursts fit here. Of the three parameters, the alpha distributions are most consistent despite the apparent bimodality of the RHESSI sample (Figure 11).

4. EVALUATING QUASI-THERMAL MODELS

We did not attempt to determine the best-fit model for each spectrum fit in this work. The Maximum Likelihood Ratio Test and the related $F$-test frequently used in model comparisons are not applicable for the models we employ here—the model parameters are not nested subsets of one another, and so the distribution of the likelihood ratio is unknown (Eadie et al. 1971; Freeman et al. 1999). Instead, we have opted to evaluate the effectiveness of the quasi-thermal models in three ways: first, by directly comparing goodness of fit for those pairs of quasi-thermal and empirical models with identical degrees of freedom; second, by assessing the physical plausibility of the model fits; and third, by considering the robustness of the fits and their relative consistency with each other and previous work.

To anticipate our conclusions, we find poor goodness of fit of the BBPL model, which may be attributed to the inadequacy of the simple PL over the RHESSI band. However, the potentially
more realistic BBCPL model fit is dominated by its CPL component, which is virtually indistinguishable from the simple Band fit for these data. Accordingly, even statistically rigorous determination of the best-fit model\(^3\) is unlikely to provide insight into the properties of the thermal component. Qualitative assessment of the behavior of the fit blackbody is sufficient to allow us to draw conclusions from these data while avoiding a major reworking of our analysis procedures.

4.1. BBPL

We begin by considering the simplest quasi-thermal model, the blackbody + simple power law (BBPL). This model is not expected to be effective over a broad energy band (e.g., Ryde 2005; Ghirlanda et al. 2007). It is instructive to ask, however, how the properties of the BBPL fits change when fit over a broader band. In particular, evidence of band-dependence calls into question the universality of results obtained even in a narrow band centered on the peak of the prompt emission.

The Band and BBPL models each have four fit parameters (\(\alpha, E_{\text{peak}}, \beta, \) and the normalization for Band; \(kT, s, \) and the two normalizations for the BBPL). Comparing their \(\chi^2\) values for each subinterval (see Figure 12), we found that in 73 of 88 cases, the Band function has a lower \(\chi^2\) value and is thus statistically favored.

As in previous studies, we found that the peak of the blackbody emission (3.92\(kT\)) in BBPL fits corresponded closely to the value of \(E_{\text{peak}}\) obtained in Band fits (Figure 13(b)). Moreover, the contribution of the BBPL blackbody flux to the overall flux in the band was significant (Figure 14).

\(^3\) e.g., via a Monte Carlo bootstrap or Bayesian hypothesis testing.
Contrary to our expectation, we did not find systematic deviation in the residuals of the fit BBPL model at low or high energy. Such deviation would be symptomatic of the need for additional spectral components (e.g., Ryde & Pe’er 2009).

RHESSI’s broader energy band did affect the best-fit value of $s$, the power law index of the BBPL model. The distribution of $s$ reported by Ryde et al. (2006) peaks around $-1.5$, while our histogram of $s$ peaks near $-1.9$ (Figure 11). This shift may be due to the small sample of bursts fit here, although as discussed in Section 3, the fit Band index $\alpha$ shows only a small shift compared to the BATSE sample.

However, a softer fit index is expected when fitting a power law to GRB data extending to higher energies, as GRB spectra generically fall off more sharply above $E_{\text{peak}}$. The fit single PL index is thus a band-dependent average of the more complicated spectral shape. Indeed, the distribution of $s$ obtained is quite similar to that of the index of a simple power law fit to these data (Figure 11), and $s$ is highly correlated with the fit PL index for individual intervals. Since the asymptotic spectral index must be greater than $-2$ below the peak energy and less than $-2$ above it, fitting a power law to a band of sufficient width which includes the peak energy will average to an intermediate value.

One of the strengths of the BBPL model is that its nonthermal component typically is softer than the “line of death” of $-2/3$ predicted for OTS emission. However, this argument appears to be weakened by the sensitivity of the fit PL index to the range of the data above the peak energy. It is not clear that the fit value of $s$ provides useful insight into the nonthermal emission physics, as its value may be an artifact of the fit band.
4.2. BBCPL and Variants

Given the challenges faced by the BBPL model in the RHESSI band, we tried more complicated nonthermal components in an attempt to find a functional broadband quasi-thermal model. We sought to evaluate the efficacy and robustness of such models and to assess whether the thermal component retained physical relevance and realism.

After a simple power law, the CPL model is the next most basic nonthermal model. Unlike the PL model, it has the advantage of providing a generally adequate representation of the RHESSI data considered here over the full band. Accordingly, we tested a BBCPL model.

Given the success of the basic CPL model at fitting these data, it is perhaps not surprising that the CPL component of the BBCPL model dominates the fits. Figure 13(c) shows that the $E_{\text{peak}}$ of the BBCPL fits closely corresponds to the peak energy fit by the Band function. The peak energy of the blackbody component alone, however, is almost completely uncorrelated with the peak energy of the phenomenological models (Figures 13(d)–(f)). This behavior is in marked contrast to the success of the BBPL model of identifying the spectral peak with the blackbody peak (Figure 13(b)). Moreover, many of the fit values of $kT$ in the BBCPL model are limits only.\footnote{In the fits of all models, the 90% confidence limit (CL) errors of the peak energies—$E_{\text{peak}}$ for the Band, CPL, and BBCPL models, and $3.92kT$ for the BBPL and BBCPL models—were required to converge within 70% of the lowest energy of the fit data and 130% of the highest energy. The peak energies are reported as upper or lower limits when the CL did not converge before the lower or upper bound. The convergence behavior was not sensitive to the precise limits chosen.} With the CPL

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Figure 9. Spectral evolution of GRB 040228. Symbols as in Figure 2.

Figure 10. Spectral evolution of GRB 040810. Symbols as in Figure 2.
The indices of the PL model and the BBPL model are highly correlated. The limits of the fit band.

Table 2

| GRB  | Instrument | Fit Band       | $\alpha$      | $E_{\text{peak}}$(keV) | $\beta$     | $\chi^2$/dof | Reference |
|------|------------|----------------|---------------|-------------------------|-------------|--------------|-----------|
| 020715 | RHESSI     | 30 keV–17 MeV  | $-0.71^{+0.11}_{-0.10}$ | 477$^{+59}_{-52}$     | $-2.79^{+0.24}_{-0.30}$ | 34.5/26    | (1)       |
|       | RHESSI     | 30 keV–5.7 MeV | $-0.776 \pm 0.072$ | 531 $\pm 39$          | $-3.14 \pm 0.41$     | 106.3/113  | (2)       |
| 021008A | RHESSI     | 100 keV–17 MeV | $-1.36^{+0.055}_{-0.034}$ | 733$^{+16}_{-16}$     | $-3.59^{+0.11}_{-0.14}$ | 59.7/30    | (1)       |
|       | RHESSI     | 300 keV–15.7 MeV | $-1.493 \pm 0.092$ | 677 $\pm 54$         | $-3.73 \pm 0.30$     | 79.5/84    | (2)       |
| 021206 | RHESSI     | 30 keV–17 MeV  | $-0.81^{+0.051}_{-0.030}$ | 718$^{+17}_{-17}$     | $-2.912^{+0.053}_{-0.059}$ | 118/68     | (1)       |
|       | RHESSI     | 70 keV–4.5 MeV | $-0.692 \pm 0.033$ | 711 $\pm 12$         | $-3.19 \pm 0.07$     | 176.5/174  | (2)       |
| 030329A | RHESSI     | 30 keV–17 MeV  | $-1.64^{+0.060}_{-0.053}$ | 139$^{+7}_{-7}$       | $-3.03^{+0.25}_{-0.53}$ | 101.4/46   | (1)       |
|       | RHESSI (peak 1) | 34 keV–10 MeV  | $-1.608 \pm 0.063$ | 157.2 $\pm 8.6$     | $-3.48 \pm 0.87$     | 84.3/90    | (2)       |
|       | RHESSI (peak 2) | 34 keV–7 MeV   | $-1.78 \pm 0.11$ | 85 $\pm 18$         | $-3.04 \pm 0.49$     | 103.3/83   | (2)       |
|       | HETE       | 2 keV–400 keV  | $-1.32 \pm 0.02$ | 70.2 $\pm 2.3$       | $-2.44 \pm 0.08$     | ...        | (3)       |
|       | HETE       | 2 keV–400 keV  | $-1.26^{+0.01}_{-0.02}$ | 68 $\pm 2$         | $-2.28^{+0.05}_{-0.06}$ | 213.7/139  | (4)       |
| 030519B | RHESSI     | 50 keV–17 MeV  | $-1.17^{+0.049}_{-0.046}$ | 437$^{+23}_{-22}$    | $-3.11^{+0.23}_{-0.40}$ | 66/35      | (1)       |
|       | RHESSI     | 70 keV–15 MeV  | $-1.048 \pm 0.069$ | 417.2 $\pm 21$      | $-3.11 \pm 0.30$     | 88.3/75    | (2)       |
|       | HETE       | 2 keV–400 keV  | $-0.8 \pm 0.1$ | 138$^{+18}_{-15}$   | $-1.7 \pm 0.2$       | 92.0/124   | (4)       |
| 031027 | RHESSI     | 30 keV–17 MeV  | $-0.759^{+0.099}_{-0.080}$ | 319$^{+26}_{-24}$    | $< -2.79$          | 63.9/56    | (1)       |
|       | RHESSI     | 60 keV–6 MeV   | $-0.94 \pm 0.13$ | 338 $\pm 25$        | ...                 | ...        | (2)       |
| 031111 | RHESSI     | 30 keV–17 MeV  | $-1.07^{+0.073}_{-0.061}$ | 844$^{+96}_{-89}$    | $-2.83^{+0.22}_{-0.38}$ | 50.2/56   | (1)       |
|       | RHESSI     | 38 keV–15.7 MeV | $-1.102 \pm 0.059$ | 844 $\pm 97$       | $-2.364 \pm 0.11$   | 128.3/117  | (2)       |
|       | HETE       | 2 keV–400 keV  | $-0.82^{+0.05}_{-0.05}$ | 404$^{+68}_{-51}$   | ...                 | ...        | (5)       |
| 040228 | RHESSI     | 50 keV–17 MeV  | $-1.60^{+0.037}_{-0.034}$ | 769$^{+120}_{-99}$   | $-2.50^{+0.18}_{-0.36}$ | 107.9/84  | (1)       |
| 040810 | RHESSI     | 30 keV–17 MeV  | $-1.45^{+0.12}_{-0.10}$ | 321$^{+50}_{-45}$    | $< -2.52$          | 55.7/56   | (1)       |

Notes. Results of the closest analogous fit are shown. Only the limits of the RHESSI fit energy band are presented when different ranges were used for the front and rear segments. Parameter uncertainties have been converted to 90% CL where necessary.

References. (1) This work; (2) Wigger et al. 2008; (3) Vanderspek et al. 2004; (4) Sakamoto et al. 2005; (5) Pélangeon et al. 2008.

Figure 11. Histogram of the fit low-energy PL indices for the Band model (solid black), BBPL model (solid gray), and simple PL model (dashed black). The indices of the PL model and the BBPL model are highly correlated. The apparent bimodality of the Band $\alpha$ index is likely an artifact of the limited burst sample (Section 3).

Figure 12. Difference in the chi-squared values for fits to the BBPL and Band models, which have identical degrees of freedom. The BBPL chi-squared value is larger in the majority of cases, indicating that the Band model is generally preferred.

The bolometric blackbody flux is obtained by integrating the differential energy spectrum of the Planck function $E N_E$ over all energies; it equals $A(kT)^4 E_{\text{ph}}^2 \pi^2/15$. Its value is fairly similar.
Figure 13. Comparison of peak energies obtained in Band, CPL, BBPL, and BBCPL fits. As expected, there is good agreement between the $E_{\text{peak}}$ values of the Band and CPL models (panel a). Notably, the blackbody peak (3.92$kT$) of the BBPL model and the BBCPL $E_{\text{peak}}$ parameter also match the Band function $E_{\text{peak}}$ (panels b and c). However, the blackbody peak of the BBCPL model shows little correlation with the spectral peak identified by the other models (panels d–f). A few points which were completely unconstrained in one dimension are omitted in the plot.

for the BBPL and BBCPL models. However, since the best-fit blackbody temperature is often near the limits of the RHESSI band, the fraction of the flux in the RHESSI band provided by the blackbody drops sharply in the BBCPL model (Figure 14). The blackbody component is accordingly of less relevance in explaining the observed data.

Following Ghirlanda et al. (2007), we also attempted “constrained” fits of the BBCPL model in an attempt to force the blackbody component to provide the peak of the spectral emission. We fit a BBCPL model with the blackbody peak energy (3.92$kT$) constrained to lie within the 90% CL of the best-fit Band $E_{\text{peak}}$ value. While the $\chi^2$ of the BBCPL fit is similar to that of the Band fits, as expected the $\chi^2$ value for the constrained BBCPL fits increases dramatically (Figure 15). Moreover, the best-fit $kT$ value typically does not have 90% CLs within the specified band. The blackbody contribution to the total flux in the RHESSI band is not significantly different than for the regular BBCPL model and remains small.

4.3. Time Evolution

One of the most notable features of the BATSE BBPL fits presented by RP09 is the remarkably universal behavior of the time evolution obtained in the BBPL fits. For their sample of single-pulse bursts, they found that both the fit blackbody temperature and the bolometric blackbody flux exhibit a regular power law rise and decay. They found identical break times for the flux and temperature evolution in a given burst. Moreover, a dimensionless proxy for the blackbody normalization, $R(t) \equiv (F_{\text{BB}}/\sigma T^4)^{1/2} = 1.01 \times 10^{-16} A^{1/2} E_{\text{peak}}^{1/2}$, is related to the size of the photospheric emission region and increases monotonically even for bursts with complex light curves.

We consider the time evolution of the blackbody components of the RHESSI BBPL and BBCPL fits in an attempt to reproduce these behaviors. Since the RP09 time-evolution results were obtained from bursts with simple single-pulse time profiles, we...
used a single-pulse burst sample with slightly lower S/N than our high S/N sample of mostly complex bursts. Unfortunately, only three bursts met the selection criteria described in Section 2.1. These bursts, GRBs 020715, 030329A, and 060805B, have 8, 12, and 5 subintervals, respectively. Accordingly, caveats of small sample size and limited time resolution apply to our analysis of their time evolution.

We plot the time evolution of the temperature, bolometric blackbody flux, and $R(t)$ in log–log space in Figures 16, 17, and 18. Within the moderate time resolution of these data, there is a clear suggestion of the correlated power law rise, break, and decay of the temperature and blackbody flux for the BBPL model, as found by RP09.

For these three bursts, the BBPL $R(t)$ values are generally consistent with a constant value. While a minority of the RP09 sample showed such behavior, far more frequently the RP09 bursts had $R(t)$ values which increased as a power law over an order of magnitude. The authors interpreted this increase in terms of the expansion of the photospheric emission region. RP09 also found frequent monotonic increases in $R$ for bursts with complex light curves. Our high S/N sample, consisting primarily of bursts with such light curves, also all have $R(t)$ consistent with a constant. The values of $R$ we obtain are consistent with the RP09 sample, however. Both the single-peak
and the high S/N samples range from $7 \times 10^{-20}$ to $2 \times 10^{-18}$ and peak near $3 \times 10^{-19}$.

The time evolution of the BBCPL blackbody exhibits few clear trends, as expected given the blackbody’s convergence problems and minimal contribution to the fit. For the single-pulse sample, the bolometric blackbody flux seems to track that obtained in the BBPL model (Figures 16–18). There is less correlation between the temperatures of the two models, though, and the time evolution of $R(t)$ for both the single-pulse sample and the high S/N sample shows little temporal regularity. Moreover, the BBCPL $R(t)$ value can be more than an order of magnitude different than that obtained in the BBPL fits, ranging from $10^{-23}$ to $10^{-17}$. Such changes would imply orders of magnitude change in the inferred size of photospheric emission region, casting further doubt on the physical significance of the blackbody component of our BBCPL fits.

5. CONCLUSIONS

We have systematically tested quasi-thermal spectral models of GRB prompt emission over a broader energy band (30 keV–17 MeV) than considered pre-Fermi. Many of the successes of the BBPL model in the BATSE band (acceptable $\chi^2_\nu$, physical spectral slopes for the nonthermal component, universal time evolution) are not reproduced consistently in the RHESSI data considered here. We have attempted to construct more realistic quasi-thermal models by combining a black body with a cutoff power law. However, even using our intervals selected for high quality ($S/N > 45$), the BBCPL model exhibits convergence difficulties within the RHESSI band. More crucially, though, the fit blackbody component loses its relevance as the origin of the spectral peak.

Data obtained over an even wider energy band, particularly from Fermi-GBM and LAT, could clarify the transitions between
thermal and nonthermal emission. Results from GRB 080916C, the first bright long burst observed by both instruments, indicated that a Band function provided a good representation of the burst spectrum over the full 8 keV–200 GeV energy range (Abdo et al. 2009b). In contrast, the Fermi LAT+GBM data for GRB 090902B required a high-energy power law component in addition to the Band function (Abdo et al. 2009a). Ryde et al. (2010) found that the GRB 090902B data, when resolved into sub-second time bins, were also compatible with a new quasi-thermal model. This model retains the simple nonthermal power law component of the BBPL but introduces a multicolor blackbody, a superposition of Plank functions distributed as a power law up to a maximum temperature. Systematic testing of quasi-thermal models with data from multiple bursts and detailed model comparisons will be needed to draw reliable conclusions about the emission mechanisms of GRBs.

The challenges of untangling the origins of the prompt GRB emission from the prompt gamma rays alone are long standing. New observations of higher energy gamma rays by Fermi-LAT, of simultaneous long-wavelength emission by transient monitoring campaigns, and of gamma-ray polarization by Compton telescopes will enrich our view of the prompt emission and provide new clues to its origin.

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Facility: RHESSI

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