Broadband Spectral Investigations of Magnetar Bursts

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Abstract

We present our broadband (2–250 keV) time-averaged spectral analysis of 388 bursts from SGR J1550–5418, SGR 1900+14, and SGR 1806–20 detected with the *Rossi X-ray Timing Explorer (RXTE)* here and as a database in a companion web-catalog. We find that two blackbody functions (BB+BB), the sum of two modified blackbody functions (LB+LB), the sum of a blackbody function and a power-law function (BB+PO), and a power law with a high-energy exponential cutoff (COMPT) all provide acceptable fits at similar levels. We performed numerical simulations to constrain the best fitting model for each burst spectrum and found that 67.6% of burst spectra with well-constrained parameters are better described by the Comptonized model. We also found that 64.7% of these burst spectra are better described with the LB+LB model, which is employed in the spectral analysis of a soft gamma repeater (SGR) for the first time here, than with the BB+BB and BB+PO models. We found a significant positive lower bound trend on photon index, suggesting a decreasing upper bound on hardness, with respect to total flux and source. We compare this result with bursts observed from SGR and AXP (anomalous X-ray pulsar) sources and suggest that the relationship is a distinctive characteristic between the two. We confirm a significant anticorrelation between burst emission area and blackbody temperature, and find that it varies between the hot and cool blackbody temperatures differently than previously discussed. We expand on the interpretation of our results in the framework of a strongly magnetized neutron star.

*Key words:* stars: individual (SGR J1550–5418, SGR 1900+14, SGR 1806–20) – stars: magnetars – stars: neutron – X-rays: bursts

*Supporting material:* machine-readable tables

1. Introduction

Magnetars are neutron stars whose various energetic radiation mechanisms are thought to be governed by the decay of their extremely strong magnetic fields \((B \sim 10^{14}–10^{15} \text{ G})\); Mereghetti et al. 2015). Emission of energetic hard X-ray bursts is the most characteristic signature of magnetar-like behavior. There are currently 29 known magnetars (23 confirmed + 6 candidates), 18 of which (whose spin has also been measured) emitted short-duration (lasting only a fraction of a second) but very luminous bursts (Manchester et al. 2005; Turolla et al. 2015; Kaspi & Beloborodov 2017). Magnetar bursts occur sporadically on random occasions, and the total number of bursts varies from a few to hundreds during any given burst-active episode of the underlying magnetar. Each burst has the potential to reveal new insights into the mechanisms triggering the burst and the emission of radiation.

The principal ingredient of magnetar bursts is some type of disturbance caused by the extremely strong magnetic fields. According to the magnetar model, the solid crust of a neutron star could fracture when extremely large magnetic pressure builds up on it (Thompson & Duncan 1995). In this view, the scale of burst energetics would be related to the size of the fractured crustal site. Thompson et al. (2002) suggested that the magnetospheres of these objects are globally twisted. As an alternative burst trigger mechanism, Lyutikov (2003) proposed that magnetic reconnection might take place in the twisted magnetosphere of magnetars. Such magnetic reconnection accounts for energetic flares emitted from the Sun. It is important to note that whether the trigger for short magnetar bursts is crustal or magnetospheric is still unresolved.

The observed bursts are the end products of their initial triggers. Therefore, photons radiated away as a burst might not be the direct consequence of the ignition, but a number of processes in between are likely involved. In the magnetar view, the trigger mechanism leads to the formation of a trapped fireball in the magnetosphere, composed of \(e^+e^-\)-pairs as well as photons (see, e.g., Thompson & Duncan 1995; Beloborodov & Thompson 2007a). Bursts are due to radiation from these trapped pair-rich fireballs. Additionally, emerging radiation is expected to be modified as it propagates through the strongly magnetized and highly twisted magnetosphere (Lyubarsky 2002). It is therefore not straightforward to unfold the underlying mechanism from the burst data.

Spectral and temporal studies on magnetar bursts are the most important probes to help distinguish mechanisms that could modify the emerging radiation of bursts. In previous spectral investigations, both thermal and non-thermal scenarios were invoked (e.g., Feroci et al. 2004; Israel et al. 2008; Lin et al. 2012; van der Horst et al. 2012). In the non-thermal view (often expressed analytically as a power law with an exponential cutoff), the photons emerging from the ignition region are repeatedly Compton upscattered by the hot \(e^+e^-\)-pairs present in the magnetosphere. The corona of hot electrons may emerge in the inner dynamic magnetosphere due to twisting of field lines (Thompson et al. 2002; Thompson & Beloborodov 2005; Beloborodov & Thompson 2007a, 2007b). Such coronas are expected to be anisotropic due to the intense and likely multipolar magnetic field around the magnetar. The density and optical thickness of the corona, as well as the electron temperature, set the characteristics of a spectral cutoff energy. Consequently, the peak energy parameter of the Comptonized (often labeled as COMPT) model is interpreted in relation to the
electron temperature. Time-integrated spectral analysis of nearly 300 bursts from SGR J1550–5418 results in an average power-law photon index of $-0.92$, and the peak energy ($E_{\text{peak}}$) is typically around 40 keV (van der Horst et al. 2012).

An alternative approach to interpreting magnetar burst spectra is the thermal emission due to a short-lived thermal equilibrium of electron–phonon pairs, usually described with the sum of two blackbody functions (see, e.g., Feroci et al. 2004; van der Horst et al. 2012). This dual blackbody scheme approximates a continuum temperature gradient due to the total energy dissipation of photons throughout the magnetosphere. The corona is expected to be hotter at low altitudes than the outer layers. Therefore, the coronal structure suggests that the high-temperature blackbody component be associated with a smaller volume than the cold component. Previous studies of magnetar burst spectra with the two-blackbody model yield $3–4$ keV and 10–15 keV for the temperature of the cold and hot blackbodies, respectively (Olive et al. 2003; Feroci et al. 2004; Lin et al. 2012; van der Horst et al. 2012).

In this paper, we present the results of our systematic time-averaged spectral analysis of a total of 388 single-peak bursts observed with the Rossi X-ray Timing Explorer (RXTE) between 1996 and 2009 from three magnetars: SGR J1550–5418, SGR 1900+14, and SGR 1806–20. We utilized data collected with both instruments on board RXTE. Therefore, we performed our investigations in a broad energy range of 2–250 keV, which is the widest energy coverage used for the analysis of SGR 1806–20 bursts. We modeled the time-integrated burst spectra with four different photon models, including the sum of two modified blackbody models (Lyubarsky 2002), which is employed in spectral analysis on these sources for the first time. It is important to note that this work is focused on time-averaged spectral aspects of typical short bursts, since most events analyzed are too weak and not sufficiently long for us to perform time-resolved spectroscopy, and the signal-to-noise ratio of HEXTE data would be too low to constrain any applied models on broadband time-resolved spectroscopy. For longer events included in the analysis, the results may not completely represent the instantaneous burst properties since SGR burst spectra are known to evolve (see, e.g., Israel et al. 2010).

2. Data and Burst Selection

For our broadband spectral investigations, we used data collected with the RXTE mission, which was operational for $\sim$16 years from 1995 December until the end of 2011. Throughout its mission, magnetar bursts were observed by RXTE on many occasions, especially during burst-active phases. SGR J1550–5418 bursts included in our study were sampled from 179 pointed RXTE observations that were performed between 2008 October and 2010 April. SGR 1900+14 bursts were among 432 RXTE observations between 1998 June and 2010 December. SGR 1806–20 bursts were observed between 1996 November and 2011 June with a total of 924 pointed RXTE observations.

We used data collected from the Proportional Counter Array (PCA) and High Energy X-ray Timing Experiment (HEXTE) instruments carried on board RXTE. PCA and HEXTE are co-aligned with the same view but operate in different energy ranges so that a broadband energy range analysis using data collected from the two instruments (between 2 and 250 keV) is possible with an overlap between 15 and 60 keV.

The PCA instrument consisted of an array of five nearly identical proportional counter units (PCUs) filled with xenon. Each unit had a collecting area of 1600 cm$^2$ and was optimally sensitive in the energy range 2–30 keV (Jahoda et al. 2006). Magnetar burst data collected with the PCA provide medium energy resolution (64 or 256 energy channels) and a superb time resolution of 1 μs. HEXTE consisted of two clusters each containing four NaI/CsI scintillation counters. It was sensitive in the energy range 15–250 keV. The time resolution of HEXTE was 8 μs and the total collecting area of one cluster was 800 cm$^2$.

We performed a two-step burst identification scheme using RXTE/PCA observations to identify bursts within the data from these three magnetars. We first analyzed the signal-to-noise ratio to roughly identify the time of events, then applied a Bayesian blocks algorithm provided in Scargle et al. (2013) and the procedure discussed in Lin et al. (2013) for final identification and morphological characterization of bursts (the details of the temporal investigation part will be presented elsewhere: S. Sasmaz Mus et al. 2017, in preparation). In this manner, we identified 179, 432, and 924 bursts from SGR J1550–5418, SGR 1806–20, and SGR 1900+14, respectively. We note that some of these bursts were very weak, consisting of only $\sim$10 counts. Therefore, we first examined spectra of these bursts at varying intensities, and concluded that we would need at least 80 burst counts for the PCA instrument only (after background subtraction) in order to constrain crucial spectral parameters at a statistically acceptable level. Therefore, we only included single-peak bursts with more than 80 PCA counts in our analysis.

2.1. Generation of Burst Spectra

We determined the integration time intervals for burst and background spectra using PCA observations as follows. For each burst, we first generated a light curve in the 2–30 keV band with 0.125 s resolution spanning from 100 s before the peak time until 100 s after to extract background information. We defined two nominal background extraction intervals: from 80 to 5 s before the burst, and from 5 to 80 s in the post-burst episode. We excluded the time intervals of other short bursts from the background spectral integration (see the bottom panel of Figure 1). We then generated a finer light curve (2 ms resolution) in the same energy interval and selected the time interval for the burst spectrum. We excluded time interval(s) during which the count rate exceeded 18,000 counts s$^{-1}$ per PCU in order to avoid any issues related to pulse pile-up (Figure 1, top panel).

We used the time intervals obtained from our PCA data to generate HEXTE source and background spectra. At this point, we excluded bursts that happened while one of the two HEXTE clusters was in “rocking mode,” switching to a different direction to obtain background emission, or when no associated HEXTE data were available. For the remaining bursts, we combined the spectra obtained from both clusters. When only one of the clusters was operating during an observation, we extracted spectra using data collected with that particular cluster only. Finally, we grouped the extracted spectra of PCA and HEXTE to ensure that each spectral bin contained a minimum of 20 burst counts.
As a result of the aforementioned eliminations, the final numbers of bursts included in our spectral analysis are: 42 for SGR J1550−5418, 125 for SGR 1900+14 and 221 for SGR 1806−20. In Tables 1–3, we list these bursts from these three magnetars individually, together with the durations of extracted spectra with saturated parts excluded (T_{Exp}). Bursts included have an average duration of 0.46 s (σ = 0.28) for SGR J1550−5418, 0.46 s (σ = 0.3) for SGR 1900+14, and 0.72 s (σ = 0.72) for SGR 1806−20.

3. Spectral Analysis

In our broadband spectral analysis, we used four models, three of which have been commonly used in describing short magnetar bursts in previous studies: the sum of two blackbody functions (BB+BB), the sum of a blackbody model and a power-law model (BB+PO), and a Comptonized model (COMPT). Additionally, we employed the sum of two modified blackbody functions (LB + LB) as set forth by Lyubarsky (2002). Note that the COMPT model is simply a power law with a high-energy exponential cutoff expressed as

\[ f = A E^{-\alpha} \exp(-E/E_{\text{cut}}), \]

where \( f \) is the photon flux in photons cm\(^{-2}\) s\(^{-1}\) keV\(^{-1}\) at 1 keV, \( E_{\text{cut}} \) is the cutoff energy (in keV), and \( \alpha \) is the photon index. The LB function is a modified version of the blackbody function where the spectrum is flattened at low energies. In terms of the photon flux, the function is expressed as

\[ f = 0.47 \varepsilon^2 \left[ \exp \left( \frac{\varepsilon^2}{T_0 \sqrt{\varepsilon^2 + (3\pi^2/5) T_0^2}} \right) - 1 \right]^{-1}, \]

where \( T_0 \) is the bolometric blackbody temperature (temperature of a blackbody that would have its mean frequency at the peak of the observed spectrum) in keV and \( \varepsilon \) is the photon energy (Lyubarsky 2002). To display intrinsic differences of these models, we present in Figure 2 the best-fit model spectra generated with the fitted parameters for the event with Burst ID 79 observed from SGR 1806−20. In Figure 3, we present the broadband spectrum of the same burst along with the fit residuals of all these four models.

Before performing the joint analysis, we first investigated possible cross-calibration discrepancies between PCA and HEXTE detector responses using a small sample (11) of bursts of various flux levels. In this task, we first introduced a multiplicative constant for HEXTE parameters to account for possible discrepancies. We repeated the same analysis with the same burst sample without this scaling term. We found that the results from the spectral analysis with and without the constant term are in agreement with each other within 1\( \sigma \) errors for all these bursts. Therefore, we concluded that the constant term was not needed in the analysis, and continued our investigations without including the term so as to limit the number of fit parameters.

Finally, as mentioned above, we used the model of a power law with an exponential cutoff (COMPT) to represent the non-thermal emission spectrum. However, a different parameterization of the same model has been used in previous studies (see, e.g., Feroci et al. 2004; Lin et al. 2012; van der Horst et al. 2012) and expressed as

\[ f = A \exp(-E(2 + \lambda)/E_{\text{peak}})(E/E_{\text{cutoff}})\lambda, \]

where \( f \) is the photon flux in photons cm\(^{-2}\) s\(^{-1}\) keV\(^{-1}\), \( A \) is the amplitude in the same units as \( f \), \( E_{\text{peak}} \) is the energy (in keV) at which the spectral distribution function makes its peak in a \( \nu F_\nu \) representation, \( \lambda \) is the photon index (defined as \(-\alpha\) where \( \alpha \) is the photon index of the COMPT model), and \( E_{\text{cutoff}} \) is the pivot energy fixed at a certain value (20 keV, Lin et al. 2012). It is then possible to convert the cutoff energy of the COMPT model into the spectral peak energy, \( E_{\text{peak}} \), as follows:

\[ E_{\text{peak}} = (2 - \alpha) \times E_{\text{cutoff}}, \]

in order to be able to compare our results to the previous studies. For all spectral analyses presented here, we used the sum of two blackbody models (BB+BB; bbbody+bbbody on XSPEC), the sum of a blackbody model and a power-law model (BB+PO; bbbody+powerlaw), and the cutoff power-law model (COMPT; cutoffpl) on XSPEC version 12.9.1 with \( \chi^2 \) minimization. We generated the LB+LB model on XSPEC as given in Equation (2). There are four free parameters for the BB+BB model (hot and cold blackbody temperatures, and their normalizations), the LB+LB model (same as BB+BB), and the BB+PO model (photon index, photon index normalization, temperature, and temperature normalization).
### Table 1

Times and Durations of SGR J1550–5418 Bursts Included in Our Analysis

| Burst ID<sup>a</sup> | Start time in MET | Start time in UTC | $T_{\text{Exp}}$<sup>b</sup> (s) | ObsID          |
|---------------------|-------------------|-------------------|-------------------|----------------|
| 1                   | 47527776.845      | 2009-01-22T20:46:14| 0.197             | 93017-10-17-00 |
| 2                   | 475275167.175     | 2009-01-22T20:52:44| 0.445             | 93017-10-17-00 |
| 3                   | 475276110.459     | 2009-01-22T21:08:27| 0.189             | 93017-10-17-00 |
| 4<sup>+</sup>       | 475276179.299     | 2009-01-22T21:09:36| 0.395             | 93017-10-17-00 |
| 5                   | 475276430.580     | 2009-01-22T21:13:47| 0.447             | 93017-10-17-00 |

**Notes.**

- <sup>a</sup> Burst IDs of saturated bursts are marked with asterisks.
- <sup>b</sup> $T_{\text{Exp}}$ refers to the duration of the spectral extraction interval.

(This table is available in its entirety in machine-readable form.)

### Table 2

Burst Times and Durations of SGR 1900+14 Bursts Included in Our Analysis

| Burst ID<sup>a</sup> | Start time in MET | Start time in UTC | $T_{\text{Exp}}$<sup>b</sup> (s) | ObsID          |
|---------------------|-------------------|-------------------|-------------------|----------------|
| 1                   | 139434279.341     | 1998-06-02T13:40:50| 0.213             | 30197-02-01-00 |
| 2                   | 139439198.455     | 1998-06-02T13:22:22| 0.364             | 30197-02-01-03 |
| 3                   | 139607213.183     | 1998-06-02T13:25:25| 0.364             | 30197-02-03-00 |
| 4<sup>+</sup>       | 146929244.714     | 1998-06-02T13:40:50| 0.471             | 30197-02-03-00 |

**Notes.**

- <sup>a</sup> Burst IDs of saturated bursts are marked with asterisks.
- <sup>b</sup> $T_{\text{Exp}}$ refers to the duration of the spectral extraction interval.

(This table is available in its entirety in machine-readable form.)

For the COMPT model, the number of free parameters is three ($\alpha$, $E_{\text{cut}}$, and normalization). For PCA and HEXTE joint spectral analysis, we made the PCA and HEXTE parameters (excluding normalizations) equal, which results in six free parameters for BB+BB, BB+PO, and LB+LB models and four for the COMPT model in joint spectral analysis.

### 4. Results

In general, we find that all of the four models can successfully describe most of the bursts from all three sources based on the resulting $\chi^2$ statistics. This can be seen in Table 4, in which we present the percentage of spectra that resulted in statistically acceptable fits for each model. Here, we define the fits to be “acceptable” when the probability of obtaining $\chi^2$ greater than the resulting $\chi^2$ value based on the $\chi^2$ distribution for the corresponding degrees of freedom (DOF) is greater than 0.2. This means that the fits that do not match this criterion have unacceptably large $\chi^2$ values with a low probability of occurring by chance. We see that all of these models can adequately represent the burst spectra at similar levels.

In this section, we present the spectral fit results with errors calculated at 1σ for all bursts for all models. Note that the comparisons among these spectral models to determine those best describing burst spectra were done using simulations, which is discussed in detail in the next section. In Tables 5–7 we present the spectral fit results of all four models for each burst, for the three sources separately. For our fits, we fixed the interstellar hydrogen column density to $3.4 \times 10^{22}$ cm$^{-2}$ for SGR J1550–5418 (Halpern et al. 2008), $2.36 \times 10^{22}$ cm$^{-2}$ for SGR 1900+14 (Gogus et al. 2011), and $6.8 \times 10^{22}$ cm$^{-2}$ for SGR 1806–20 (Gogus et al. 2007; Woods et al. 2007).

Detailed statistical investigations (i.e., generating reliable parameter and fluence distributions) were possible for SGR 1900+14 and SGR 1806–20 due to their large sample size. However, for SGR J1550–5418, the sample size was not sufficiently large to provide reliable distributions for its burst spectral parameters and fluence. It is important to note that our burst samples involve partially saturated bursts, for which the reported burst flux should be taken as a lower bound.

#### 4.1. SGR 1900+14

We list the resulting spectral model parameters and fit statistics for each of the SGR 1900+14 bursts in Table 5. In order to generate distributions of spectral fit parameters, we selected events whose spectral fit parameters yielded less than 50% uncertainty. We then modeled the distributions with a Gaussian to determine the mean value. We obtained a mean of $15.8 \pm 0.2$ keV for SGR 1900+14, $14.38 \pm 0.02$ keV with a width of $\sigma = 7.96 \pm 1.1$ keV for SGR 1806–20, and $17.23 \pm 1.0$ keV with a width of $\sigma = 5.4 \pm 0.2$ keV, for SGR J1550–5418. We then conducted their study using BeppoSAX data in the 1.5–100 keV band and obtained a mean of $15.8 \pm 2.3$ keV. For the BB+BB model, the mean temperature of the cooler blackbody is $1.76 \pm 0.02$ keV, and the mean temperature of the hotter blackbody is $6.2 \pm 0.2$ keV ($\sigma = 4.3 \pm 0.2$ keV). We then computed the $2\sigma$–250 keV flux for all of the bursts, and found that it is between $4.02 \times 10^{-9}$ and
6.9 \times 10^{-8} \text{ erg cm}^{-2} \text{ s}^{-1}. Finally, we present the fluence distributions for PCA and HEXT detections in the right panel of Figure 5. We find that the majority of SGR 1900+14 bursts have fluences $<10^{-8} \text{ erg cm}^{-2}$ with only a few exceptions.

4.2. SGR 1806–20

We report all resulting parameters for SGR 1806–20 bursts in Table 6. On average, spectral model parameters of SGR 1806–20 bursts span narrower intervals than those of SGR 1900+14 bursts.

We generated spectral parameter distributions for SGR 1806–20 with the same procedure as for SGR 1900+14. For the COMPT model, we find a mean of the photon index distribution of $0.62 \pm 0.005 \ (\sigma = 0.22 \pm 0.005)$. The distribution of the exponential cutoff energy peaks at $21.1 \pm 1.3 \text{ keV}$ with $\sigma = 15.58 \pm 1.5 \text{ keV}$ and the inferred mean of $E_{\text{peak}}$ is $32.02 \pm 1.84 \text{ keV}$ (see Figure 6, top panels). The BB+BB model yields a mean cooler blackbody temperature of $2.02 \pm 0.02 \text{ keV}$ with $\sigma = 0.24 \pm 0.02 \text{ keV}$. The mean hotter blackbody temperature is $9.6 \pm 0.2 \text{ keV}$ with $\sigma = 2.7 \pm 0.2 \text{ keV}$ (Figure 6, bottom panel).
### Table 5
Spectral Properties of SGR 1900+14 Bursts

| Burst ID | BB+BB$^d$ | BB+PO$^d$ | LB+LB$^d$ | COMPT$^d$ |
|----------|-----------|-----------|-----------|-----------|
|          | \(kT_1\) (keV) | \(kT_2\) (keV) | \(\chi^2\)/DOF | \(kT_1\) (keV) | \(kT_2\) (keV) | \(\chi^2\)/DOF | \(E_{\text{cut}}\) (keV) | \(\alpha\) | \(\chi^2\)/DOF | PCA Flux (erg cm\(^{-2}\) s\(^{-1}\)) | HEXTE Flux (erg cm\(^{-2}\) s\(^{-1}\)) |
| 1        | 2.3 ± 0.2  | 24.2\(^{+2.3}_{-1.9}\) | 22.0/22 | 2.1\(^{+0.3}_{-0.4}\) | 1.1 ± 0.2 | 18.8/22 | 2.6\(^{+0.2}_{-0.2}\) | 32.2\(^{+3.3}_{-3.1}\) | 18.8/22 | 171.2\(^{+111.8}_{-76.5}\) | 1.2 ± 0.1 | 25.1/24 | (2.3 ± 0.1) \(\times 10^{-8}\) | (9.6\(^{+15.2}_{-9.6}\) \(\times 10^{-8}\) |
| 2        | 1.5 ± 0.3  | 5.4\(^{+3.9}_{-0.9}\) | 9.54/11 | 1.8\(^{+0.0}_{-1.8}\) | 1.3\(^{+0.7}_{-0.6}\) | 10.2/11 | 1.6\(^{+0.5}_{-0.4}\) | 6.5\(^{+1.9}_{-1.4}\) | 9.86/11 | 83.1\(^{+26.9}_{-24.3}\) | 1.3\(^{+0.2}_{-0.1}\) | 10.2/13 | (6.4\(^{+0.4}_{-0.3}\) \(\times 10^{-9}\) | (2.3\(^{+2.4}_{-1.4}\) \(\times 10^{-8}\) |
| 3        | 1.6 ± 0.6  | 11.4\(^{+6.6}_{-4.4}\) | 9.11/6  | 1.5\(^{+0.3}_{-0.3}\) | 0.2\(^{+0.2}_{-0.2}\) | 9.10/6 | 1.7\(^{+0.3}_{-0.3}\) | 32.4\(^{+26.4}_{-16.2}\) | 9.08/6 | 500.0\(^{+500.0}_{-250.0}\) | 1.1\(^{+0.1}_{-0.1}\) | 9.95/8 | (1.2 ± 0.2) \(\times 10^{-9}\) | (2.1 ± 0.1) \(\times 10^{-10}\) |
| 4        | 1.9 ± 0.1  | 6.4\(^{+3.6}_{-0.9}\) | 25.6/29 | 2.6 ± 0.3 | 1.7 ± 0.1 | 25.0/29 | 2.3 ± 0.1 | 10.0\(^{+2.1}_{-2.1}\) | 19.5/29 | 17.7\(^{+4.1}_{-3.9}\) | 1.1\(^{+0.1}_{-0.1}\) | 27.5/31 | (4.7 ± 0.1) \(\times 10^{-8}\) | (3.8\(^{+0.5}_{-0.4}\) \(\times 10^{-8}\) |
| 5        | 2.1 ± 0.2  | 7.5 ± 1.3  | 26.2/25 | 3.7\(^{+0.3}_{-0.2}\) | 2.7\(^{+0.4}_{-0.2}\) | 30.7/25 | 2.5\(^{+0.3}_{-0.2}\) | 8.7\(^{+0.7}_{-1.5}\) | 23.8/25 | 14.9\(^{+4.9}_{-3.5}\) | 0.8 ± 0.2 | 24.9/27 | (2.1 ± 0.1) \(\times 10^{-8}\) | (1.9 ± 0.3) \(\times 10^{-8}\) |

Notes.

$^a$ PCA Flux Energy Range: 2–30 keV.

$^b$ HEXTE Flux Energy Range: 15–250 keV.

$^c$ All errors are reported at 1σ and the error information is blank if it is not available for the given fit.

$^d$ The number of free parameters is the same for BB+BB, BB+PO, and LB+LB models, and is four for each model and six for PCA and HEXTE joint spectral analysis. The number of free parameters is three for the COMPT model and is four in joint spectral analysis. See Section 3 for a list of free model parameters.

(This table is available in its entirety in machine-readable form.)
Table 6
Spectral Properties of SGR 1806–20 Bursts

| Burst ID | BB+BB | BB+PO | LB+LB | COMPT |
|----------|-------|-------|-------|-------|
|          | $kT_1$ (keV) | $kT_2$ (keV) | $\chi^2$/DOF | $kT_1$ (keV) | $kT_2$ (keV) | $\chi^2$/DOF | $E_{\text{cut}}$ (keV) | $\alpha$ | $\chi^2$/DOFe | PCA Flux (erg cm$^{-2}$ s$^{-1}$) | HEXTE Flux (erg cm$^{-2}$ s$^{-1}$) |
| 1        | 2.7 ± 0.2 | 11.6 ± 1.6 | 54.0/31 | 4.5 ± 0.3 | 2.1 ± 0.1 | 49.0/32 | 3.3 ± 0.3 | 14.1 $^{+2.0}_{-1.0}$ | 47.5/31 | 30.7 ± 2.0 | 0.9 ± 0.1 | 49.4/33 | 3.1 ± 0.1 | $10^{-8}$ | (4.1 ± 0.5) | $10^{-8}$ |
| 2        | 2.6 $^{+0.5}_{-0.4}$ | 9.6 $^{+0.3}_{-0.3}$ | 25.2/16 | 8.2 $^{+1.5}_{-1.3}$ | 1.2 $^{+0.9}_{-0.2}$ | 25.2/15 | 3.0 $^{+0.7}_{-0.8}$ | 10.7 $^{+0.8}_{-1.0}$ | 24.8/16 | 22.3 $^{+0.1}_{-0.0}$ | 0.5 ± 0.2 | 24.6/17 | (2.1 ± 0.1) | $10^{-8}$ | (3.2 ± 0.6) | $10^{-8}$ |
| 3        | 2.6 ± 0.3 | 14.9 $^{+4.3}_{-3.5}$ | 7.68/13 | 3.9 $^{+1.1}_{-0.7}$ | 1.5 ± 0.3 | 12.4/14 | 3.0 ± 0.4 | 17.4 $^{+5.4}_{-3.8}$ | 8.36/14 | 69.0 $^{+97.5}_{-32.4}$ | 1.1 ± 0.2 | 12.3/15 | (1.2 ± 0.1) | $10^{-8}$ | (1.8 ± 0.3) | $10^{-8}$ |
| 4        | 3.1 $^{+0.7}_{-1.0}$ | 23.1 $^{+17.7}_{-3.5}$ | 0.35/3 | 3.9 $^{+2.0}_{-0.5}$ | 1.6 $^{+2.2}_{-0.8}$ | 0.36/3 | 4.1 $^{+1.1}_{-1.0}$ | 10.5 $^{+15.3}_{-1.0}$ | 0.48/3 | 16.1 ± 0.5 | 0.5 ± 0.3 | 0.88/5 | (1.7 ± 0.2) | $10^{-9}$ | (2.7 ± 0.3) | $10^{-9}$ |
| 5        | 2.7 ± 0.1 | 10.0 ± 0.6 | 55.7/63 | 8.8 ± 0.5 | 1.0 $^{+0.2}_{-0.2}$ | 81.5/63 | 3.2 ± 0.3 | 11.5 ± 0.8 | 53.9/63 | 21.9 $^{+1.1}_{-1.9}$ | 0.4 ± 0.1 | 57.9/65 | (9.1 ± 0.2) | $10^{-9}$ | (1.2 ± 0.1) | $10^{-8}$ |

Notes:

a PCA Flux Energy Range: 2–30 keV.

b HEXTE Flux Energy Range: 15–250 keV.

c All errors are reported at 1σ, the error information is blank if it is not available for the given fit.

d The number of free parameters is the same for BB+BB, BB+PO, and LB+LB models, and is four for each model and six for PCA and HEXTE joint spectral analysis. The number of free parameters is three for the COMPT model and is four in joint spectral analysis. See Section 3 for a list of free model parameters.

e Note that for some bursts, one normalization term was fixed to constrain spectral parameters and therefore the number of free parameters and the corresponding degrees of freedom may differ. (This table is available in its entirety in machine-readable form.)
| Burst ID | BB+BB$^d$ | BB+PO$^d$ | LB+LB$^d$ | COMPT$^d$ |
|---------|-----------|-----------|-----------|-----------|
|         | $kT_1^c$ (keV) | $kT_2^c$ (keV) | $\chi^2$/DOF | $kT^c$ (keV) | $\Gamma^c$ | $\chi^2$/DOF | $kT_1^c$ (keV) | $kT_2^c$ (keV) | $\chi^2$/DOF | $E_{\text{cut}}^c$ (keV) | $\alpha^c$ | $\chi^2$/DOF | PCA Flux$^{ae}$ (erg cm$^{-2}$ s$^{-1}$) | HEXTE Flux$^{bc}$ (erg cm$^{-2}$ s$^{-1}$) |
| 1       | 2.0$^{+0.4}_{-0.3}$ | 9.2$^{+1.1}_{-1.0}$ | 3.21/3 | 2.1$^{+0.2}_{-0.3}$ | 0.6$^{+1.1}_{-0.9}$ | 3.23/3 | 2.5 $\pm$ 0.5 | 27.6$^{+20.6}_{-12.9}$ | 3.31/3 | 10.1$^{+0.6}_{-0.5}$ | 0.6$^{+0.8}_{-0.7}$ | 5.64/5 | (1.3 $\pm$ 0.2) $\times$ 10$^{-9}$ | (3.7$^{+1.2}_{-1.1}$) $\times$ 10$^{-9}$ |
| 2       | 2.2 $\pm$ 0.2 | 29.2$^{+12.8}_{-8.9}$ | 12.1/8 | 2.1$^{+0.3}_{-0.2}$ | 1.1$^{+0.7}_{-0.6}$ | 13.9/8 | 2.6$^{+0.4}_{-0.3}$ | 36.2$^{+12.1}_{-12.9}$ | 12.3/8 | 4.3$^{+0.7}_{-1.3}$ | $-0.3^{+0.7}_{-0.8}$ | 17.9/10 | (6.2 $\pm$ 0.7) $\times$ 10$^{-9}$ | (2.1$^{+0.8}_{-0.9}$) $\times$ 10$^{-9}$ |
| 3       | 1.6 $\pm$ 0.2 | 7.6$^{+2.7}_{-1.4}$ | 6.22/8 | 7.6$^{+1.3}_{-1.1}$ | 1.5 $\pm$ 0.1 | 9.26/8 | 1.7 $\pm$ 0.3 | 8.6$^{+1.4}_{-1.3}$ | 6.57/8 | 25.6$^{+2.0}_{-1.7}$ | 1.2 $\pm$ 0.2 | 10.1/10 | (2.0 $\pm$ 0.2) $\times$ 10$^{-8}$ | (2.2$^{+0.8}_{-0.9}$) $\times$ 10$^{-8}$ |
| 4       | 2.1 $\pm$ 0.2 | 20.7$^{+3.4}_{-3.4}$ | 17.4/14 | 2.0 $\pm$ 0.3 | 1.2 $\pm$ 0.2 | 12.6/14 | 2.5 $\pm$ 0.3 | 27.7$^{+2.8}_{-5.5}$ | 13.8/14 | 500.0$^{+1.1}_{-0.9}$ | 1.5 $\pm$ 0.1 | 21.5/16 | (1.4 $\pm$ 0.1) $\times$ 10$^{-8}$ | (3.4 $\pm$ 10$^{-8}$) |
| 5       | 1.7 $\pm$ 0.2 | 20.1$^{+3.6}_{-3.3}$ | 20.6/17 | 0.6$^{+0.5}_{-0.4}$ | 1.2 $\pm$ 0.1 | 22.4/17 | 1.7 $\pm$ 0.3 | 25.1$^{+3.8}_{-3.3}$ | 16.8/17 | 500.0$^{+3.1}_{-0.2}$ | 1.3$^{+0.1}_{-0.2}$ | 24.4/19 | (1.4 $\pm$ 0.1) $\times$ 10$^{-8}$ | (4.6$^{+0.8}_{-0.9}$) $\times$ 10$^{-8}$ |

Notes.

$^a$ PCA Flux Energy Range: 2–30 keV.

$^b$ HEXTE Flux Energy Range: 15–250 keV.

$^c$ All errors are reported at 1$\sigma$ and the error information is blank if it is not available for the given fit.

$^d$ The number of free parameters is the same for BB+BB, BB+PO, and LB+LB models, and is four for each model and six for PCA and HEXTE joint spectral analysis. The number of free parameters is three for the COMPT model and is four in joint spectral analysis. See Section 3 for a list of free model parameters.

(This table is available in its entirety in machine-readable form.)

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panels). On average, the combined unabsorbed 2–250 keV flux of SGR 1806–20 bursts is higher than that of SGR J1550–5418 and similar to that of SGR 1900+14 with a range of $4.91 \times 10^{-9}$ to $5.46 \times 10^{-8}$ erg cm$^{-2}$ s$^{-1}$. Due to the longer average burst duration, the burst fluences of SGR 1806–20 events tend to be higher than those of both SGR 1900+14 and SGR J1550–5418. We present fluence distributions for PCA and HEXTE detections of SGR 1806–20 bursts in the left panel of Figure 5. Note that for some SGR 1806–20 bursts, an additional normalization term was fixed to a value determined based on the spectral shape to constrain spectral parameters of some models. For these bursts, the number of free parameters and hence the DOF for some models differ (see Burst ID: 2 in Table 6 for an example, where BB+PO DOF differs from BB+BB and LB+LB DOF by 1 due to a fixed HEXTE normalization term).

4.3. SGR J1550–5418

In Table 7, we present spectral fit results of SGR J1550–5418 bursts. For this source, we did not construct distribution plots because of the small sample size, especially after taking into account the constraint on parameters. For the COMPT model, the photon index ranges from $-0.28$ to $1.77$ with a mean of $1.21$, while the exponential cutoff energy ranges from $4.30$ keV to $118.26$ keV, with an average of $54.46$ keV. The average $E_{\text{peak}}$ of SGR J1550–5418 bursts calculated using Equation (4) is $44.59$ keV, with a minimum of $20.46$ keV and a maximum of $77.04$ keV, and is consistent with the values found by Lin et al. (2012) ($39 \pm 13$ keV) and van der Horst et al. (2012) ($45 \pm 2.1$ keV) using data from the Swift/X-ray Telescope and the Fermi/Gamma-ray Burst Monitor for the same source. The combined unabsorbed flux (in the 2–250 keV band) varies from $3.72 \times 10^{-9}$ to $2.62 \times 10^{-8}$ erg cm$^{-2}$ s$^{-1}$. For the BB+BB model, the temperature of the cooler component (in keV) ranges from $1.02$ to $2.6$ with a mean of $1.76$, and that of the hot blackbody component ranges from $5.67$ to $29.24$ with a mean of $13.71$. Note that the parameter ranges and averages presented here exclude fits where either the upper or lower bound error is not available, so that the constraints on parameters are known and possible issues due to local $\chi^2$ minima are excluded.

4.4. Companion Web-catalog of Magnetar Burst Spectral and Temporal Characteristics

We also made the results of our analyses available in a companion web-catalog, which includes general properties (burst time, total photon counts, peak counts, and five PCU plots where the amount of time excluded due to saturation for saturated bursts can also be found), results of temporal analysis (including burst duration with start and end times obtained with the Bayesian Blocks algorithm for single-peak and multi-peak bursts), and results of spectral analysis (BB+BB temperatures, BB+PO temperature and photon index, COMPT photon index and cutoff energy, and LB+LB temperatures for single-peak bursts). Note that our spectral analysis involves single-peak bursts only. Additionally, the web-catalog provides all temporal and spectral data in FITS format for interested researchers to download and perform their independent analysis.
investigations. The address of the companion web-catalog is http://magnetars.sabanciuniv.edu.

5. Simulations for Model Comparisons

Even though one of the four models that were employed to fit the broadband X-ray spectra of magnetar bursts yields the minimum reduced $\chi^2$ value, it is statistically not possible to disregard the alternatives simply by a $\Delta \chi^2$ test. This issue becomes more complicated given the fact that the COMPT model involves one less free parameter than thermal models, resulting in one more DOF on average. The additional degree of freedom enhances the fitting power of COMPT in the cases where the spectrum could be statistically represented by two or more models. In such cases, competing models can be better compared by using simulations based on fit results.

To achieve this objective, we performed extensive simulations for each burst as follows: overall the COMPT model is expected to perform the best in fitting magnetar burst spectra based on the number of parameters. Therefore, we took the COMPT model as the null hypothesis and generated 1000 spectra using the resulting COMPT fit parameters for each burst whose COMPT model parameters were sufficiently constrained (parameter error less than 50% of the parameter).
As an alternative hypothesis (test model), we selected the one of the three thermal models whose reduced $\chi^2$ value was the smallest. Note that the remaining models have an equal number of parameters, and a simple $\Delta \chi^2$ test is applicable for comparison.

When the test model did not provide well-constrained parameters (i.e., less than 50% errors), we selected the model with the next smallest reduced $\chi^2$ value to be the test model. If none of the test models provided well-constrained parameters, we did not perform the simulation for that event. We found that four out of 42 events examined for SGR J1550$-$5418, 21 out of 125 events examined for SGR 1900$+$14, and 77 out of 221 bursts from SGR 1806$-$20 provided such well-constrained parameters for the seed and test models, and were included in our simulations. We have then fit the 1000 generated spectra for each burst with the COMPT model and its alternative test model.

We used a significance level (i.e., probability of rejecting the null hypothesis given that it is true) of 0.05 for each burst included in the simulation. For a $\chi^2$ distribution with dof = 1 (since the DOFs on the test and seed models differ by one in each case), this corresponds to a $\chi^2$ value of 3.84. Therefore, we defined our rejection region of the null hypothesis (i.e., when we accept the test model) as the region where the test model $\chi^2$ is less than the seed model $\chi^2$ by at least 3.84. We suggest that if a truly Comptonized spectrum in fact provides better fit statistics within a significance of 0.05, then our fit results where COMPT provides lower $\chi^2$ values indicate that the true emission mechanism most likely is Comptonized rather than thermal, at least on time-averaged spectra.

Similar to the procedure in Lin et al. (2012), we define our $p$-value to be the fraction of simulated spectra better fitted by the COMPT model with the significance of 0.05. If the $p$-value exceeds 0.9, we conclude that the COMPT model provides better fit statistics than the test model when it is the underlying emission mechanism. In Figure 7, we present the distributions for the difference between seed model (COMPT) $\chi^2$ and test model $\chi^2$ for three example events of SGR 1806$-$20 with different test models for a visual description of the simulation results. Our rejection region of the COMPT model (null hypothesis) is where $\chi^2_{\text{COMPT}} - \chi^2_{\text{Test Model}} \geq 3.84$, as described above. We also list the resulting $p$-values for the entire sample in Table 8.

We found that the COMPT model is the most frequently preferred model based on simulation results: the COMPT model provides significantly better fit statistics in more than 90% of trials for 16/19 events compared to the BB$+$PO model, 12/17 events compared to the BB$+$BB model, and 41/66 events compared to the LB$+$LB model. Overall, COMPT provides statistically better fits to more than 67.6% of cases than its alternatives.

Also, the LB$+$LB model emerges as the best fitting of the thermal models, providing better fits than the BB$+$BB and BB$+$PO models for the majority (66 out of 102) of events. It is important to emphasize that the LB$+$LB was selected as the test model in each of these cases because it provided the lowest reduced $\chi^2$ value among the thermal models with well-constrained parameters and that it is possible to compare the thermal models with a simple $\Delta \chi^2$ test since these models have the same number of parameters.

**Figure 7.** Distributions of COMPT $\chi^2$ – test model $\chi^2$ for three SGR 1806$-$20 bursts. Blue shaded regions represent rejection regions of the seed (COMPT) model (where $\chi^2_{\text{COMPT}} - \chi^2_{\text{Test Model}} > 3.84$). (a) Test model: BB$+$BB for Burst ID: 20. (b) Test model: BB$+$PO for Burst ID: 1. (c) Test model: LB$+$LB for Burst ID: 5.
To check whether the simulation procedure forms a bias toward COMPT, we repeated the same procedure with BB+BB as the null hypothesis (seed model) for one event with COMPT as the alternative hypothesis (test model). In this reverse simulation scenario, we similarly defined our rejection region for the null hypothesis as when the COMPT $\chi^2$ value was less than the BB+BB $\chi^2$ by at least $\chi^2_{0.05,1} = 3.84$. The BB+BB model was accepted in 100% of trials when it acted as the seed model. The COMPT model was accepted in 99.7% of trials when COMPT was the seed model in the original simulation for the same event. By comparing these results, we concluded that the simulation procedure accepts the inherent emission mechanism within the level of significance with no bias toward any model. Therefore, we continued the simulations with COMPT as the seed model.

6. Discussion

The models involving non-thermal and thermal emission processes are commonly discussed in the context of magnetar bursts (e.g., Feroci et al. 2004; Lin et al. 2012; van der Horst et al. 2012). In the Comptonization view, the photons emerging from the ignition point are repeatedly upscattered by the $e^\pm$-pairs present in the corona. The density and optical thickness of the corona, the incoming photon distribution, and the electron temperature set a spectral break point for energy, realized as the peak energy parameter for the power-law-shaped Comptonized spectrum. For magnetar bursts, the Comptonized spectrum resembles the models for accretion disks and active galactic nuclei, but the underlying mechanism differs due to the strong magnetic field of magnetars. The corona of hot electrons may emerge in the inner dynamic magnetospheric corona could give rise to a similar magnetospheric corona that could give rise to a similar Comptonization process and therefore upscatter emergent photons. This type of corona is expected to be anisotropic due to the intense and likely multipolar magnetic field around the magnetar. The anisotropy of the corona sets a different
slopes for the emission spectrum. The emission spectrum, however, is similar in its exponential tail and peak energy, which are now controlled by the thermal and spatial parameters of the corona in the magnetosphere. The distinction between persistent and burst emissions is further explained in this model because the bursts may be triggered closer to the surface where the density of $e^\pm$-pairs is high, and persistent <10 keV signals may originate at higher altitudes with a lower $e^\pm$ density (Beloborodov & Thompson 2007a).

The alternative approach to interpreting magnetar burst spectra is thermal emission due to a short-lasting plasma of electron–photon pairs in quasi-thermal equilibrium, usually described with the superposition of two blackbody functions (see, e.g., Feroci et al. 2004; van der Horst et al. 2012). This dual blackbody scheme approximates a continuum temperature gradient due to the total energy dissipation of photons throughout the magnetosphere. The corona is expected to be hotter at low altitudes than in the outer layers. Therefore, the coronal structure suggests that the high-temperature blackbody component be associated with a smaller volume than the cold component; van der Horst et al. (2012) report a strong negative correlation between emission area and blackbody temperature, indicating that if the underlying emission mechanism is quasi-thermal with gradually changing temperatures, and if the dual blackbody is a good approximation of the continuum gradient as expected, then the relationship between temperature and coronal structure is in fact apparent in the spectrum. Modeling the corona with such a temperature gradient is a hard task, especially in the hotter zone because of its anisotropic structure, the intense magnetic field, the twisted magnetosphere geometry, and the polarization dependence of the scattering process. Temporal and spectral studies over broad energy ranges as a result help in getting a better view of the underlying structure as well as in distinguishing between non-thermal and thermal models, as in our investigations, which suggest that a non-thermal model describes spectra best for the majority of bursts.

Although the sum of two blackbody functions is commonly used to describe magnetar burst spectra, it was shown that the spectrum of photon flux per unit energy band may be flat at energies lower than the temperature when the magnetic field is not too high ($B < 10^{15}$ G). In this model, the spectrum of photons escaping the bubble formed during the burst is considered. The emergent spectrum was shown by Lyubarsky (2002) to be close to the blackbody spectrum although the observed radiation within the bubble comes from photons with different temperatures throughout the bubble. In a hot, optically thick bubble in a strong magnetic field, the photon energy is well below the excitation energy of the first Landau level and Compton scattering dominates. Considering SGR burst bubbles in such a scenario, photons with ordinary orthogonal (O-mode) polarization will undergo many more scatterings than the extraordinary linearly polarized (E-mode) photons, whose cross sections are strongly hindered (Lyubarsky 2002). Because of this dependence of scatterings on radiation cross section, which in turn depends on frequency in a strong magnetic field, the burst spectrum alters from the blackbody spectrum at low energies and may be observed as flat.

In our investigations, the LB+LB model emerged as the most frequently chosen test model. That is, compared to the other two models with the same DOF (namely BB+PO and BB+BB), the LB+LB model shows the best test statistics for 48 out of 77 bursts for SGR 1806−20, 16 out of 21 for SGR 1900+14, and 2 out of 4 for SGR J1550−5418 when error constraints of <50% of the parameter are enforced. This suggests that the modified blackbody scheme, where a frequency-dependent scattering cross section distorts the blackbody emission at low energies, explains burst emission mechanisms better than a thermal emission resulting from short-lasting electron–positron pairs through a gradient of temperature, at least on time-averaged burst spectra.

6.1. Spectral Correlations

We have also explored whether there exist any correlations between the spectral parameters of magnetar bursts. We investigated spectral correlations of the COMPT model because our simulation results show that the COMPT model describes the majority of well-restricted bursts best. We also investigated spectral correlations of BB+BB model parameters for comparison purposes with previous studies. In the correlation analyses, we chose unsaturated bursts that have well-restricted (<50% of the parameter) parameter and flux errors for the given model fit (COMPT model for Section 6.1.1 and BB+BB model for Section 6.1.2) out of all bursts included in the spectral analysis. For the COMPT model, our correlation analysis consists almost entirely of SGR 1806−20 and SGR 1900+14 bursts (total of 63) except for one SGR J1550−5418 burst, because of error restrictions.

6.1.1. COMPT Model

For the COMPT model, we checked for correlations including only unsaturated bursts that yield well-constrained (<50% of the
parameter) errors for all parameters and flux. For these bursts, we find a weak positive correlation (Spearman’s rank correlation coefficient, $\rho = 0.54$, chance probability = $4.05 \times 10^{-5}$) between photon index (defined as $\alpha$ in Equation (1)) and total fluence (see Figure 8, right panel). Note that we do not find any significant correlation between $E_{\text{peak}}$ and total flux ($\rho = 0.22$, chance probability = 0.075). We find that although the correlation between photon index and total flux is not significant ($\rho = 0.43$, chance probability = $4.06 \times 10^{-3}$), there is a positive lower bound trend on photon index with respect to total flux (see Figure 8, left panel). That is, for the lower-flux bursts, photon index spans a wider range (−1.1 to 1.3) while the range of photon index is higher for bursts with higher total flux. We assume that the negative photon index (−$\alpha$) is a good indicator of the hardness of burst spectra since $E_{\text{peak}}$ values of these bursts are narrowly distributed (a Gaussian fit to the $E_{\text{peak}}$ distribution yields $\sigma = 10.6 \pm 0.7$ for SGR 1806–20 and $\sigma = 8.8 \pm 1.1$ for SGR 1900+14; see also Figures 4 and 6) and since $E_{\text{peak}}$ does not depend significantly on burst flux. Thus, in low flux ranges, we find that the bursts can be spectrally much harder, while with increasing flux, bursts are confined to softer spectra with a clear lower bound (indicated with the dashed line in Figure 8, left panel) on photon index. Our results spectrally confirm the results of Gogus et al. (2001), in which they found that high-fluence SGR 1806–20 and SGR 1900+14 bursts tend to be softer (i.e., anticorrelation between hardness and energy fluence), where hardness ratio is defined as the ratio of photon counts in the 10–60 keV and 2–10 keV bands. Additionally, van der Horst et al. (2012) also found an anticorrelation between hardness and fluence for SGR J1550–5418 bursts inferred from the anticorrelation they find between $E_{\text{peak}}$ and burst fluence from the results of broadband (8–200 keV) spectral analysis. On the other hand, Gavriil et al. (2004) noted a positive correlation between hardness and fluence for the bursts from another magnetar candidate, AXP 1E 2259+586. Overall, we confirm the findings of Gogus et al. (2001) and see that SGR 1806–20 and SGR 1900+14 bursts have opposite trends between hardness and fluence in similar fluence ranges (2.4 x 10$^{-9}$–6.3 x 10$^{-8}$ erg cm$^{-2}$) to those of AXP 1E 2259+586 (Gavriil et al. 2004) and similar trends to those of SGR 1550–5418 (van der Horst et al. 2012). We suggest that this relationship may be a distinctive characteristic between AXP and SGR bursts.

6.1.2. BB+BB Model

In the thermal emission view, a temperature gradient throughout the emitting surface is assumed. This gradient from the burst ignition point has been represented in previous studies by two (one hot and one cooler) blackbody components (see, e.g., Lin et al. 2012). We also checked the relationship between thermal emission areas and temperatures between the hot and...
cold blackbody components, expressed as

$$R^2 = \frac{FD^2}{\sigma T^4}$$  \hspace{1cm} (5)

where $R$ is the radius of the thermal emitting region, $D$ is the distance to the source, $F$ is the average total flux per event, and $T$ is the temperature. Here, we used distances of 5 kpc for SGR J1550–5418 (Tieno et al. 2010), 12.5 kpc for SGR 1900+14 (Davies et al. 2009), and 8.7 kpc for SGR 1806–20 (Bibby et al. 2008). We have found a significant anticorrelation between thermal emission area and temperature for both blackbody components.

In the upper left panel of Figure 9, we present the trend of $R^2$ (km²) versus $kT$ (keV) for all unsaturated bursts with well-constrained parameters from all three sources. The dashed line represents the $R^2 \propto T^{-3}$ trend proposed in previous studies (e.g., Israel et al. 2008; Younes et al. 2014) and the solid line represents the $R^2 \propto T^{-4}$ trend that is expected from blackbody emission. These trends are drawn for comparison only. The cooler blackbody components ($kT_1$, shown in black) are well separated from the hot blackbody components ($kT_2$, shown in red) for all sources, similar to the results of van der Horst et al. (2012) and Lin et al. (2012) for SGR J1550–5418 and Israel et al. (2008) for SGR 1900+14. This verifies the thermal emission model that starts from the hot and narrower ignition point and extends to a wider area where it is cooled down (i.e., hotter corona at lower altitudes than the outer layers). To check the extent of this verification, we employed a Spearman rank order correlation test on the trend of emission area versus temperature, and found a correlation coefficient of $-0.933$ with a chance probability close to nil using all bursts. The correlation coefficients are $-0.953$, $-0.962$, and $-0.942$ when the Spearman correlation test is employed individually for SGR J1550–5418, SGR 1900+14, and SGR 1806–20, respectively (with chance probabilities $\sim 0$). We then employed single power-law and broken power-law fits on data of emission area versus blackbody temperature. For SGR 1900+14 and SGR 1806–20 bursts, the reduced $\chi^2$ values for the fits with a broken power law (Table 9, column 6) are less than those for fits with a single power law (Table 9, column 8). This suggests that the behavior of emission area versus temperature differs significantly between the cool and hot blackbody components. Moreover, the hot blackbody component is associated with a narrower emission area than the cool component. Thus, we re-confirm that our findings on this strong anticorrelation between temperature and emission area verify the thermal emission model approximated by a sum of two blackbodies, where emission starts from a hot and narrower ignition point within the bubble and extends to a cooler outer layer associated with larger area.

To check whether similar relationships hold for different burst intensity levels, we grouped the bursts into three intervals based on their total flux and employed a single and a broken power-law fit for each group in the same flux interval individually. We show a color-coded scatterplot of different flux values for SGR 1806–20 in the upper right panel of Figure 9. The dashed lines represent the best-fit broken power-law trends. The color-coded arrows mark the energy of the break in the power law for each intensity group. We present the complete fit results in Table 9. Note that $kT$ uncertainties are included in the fits presented in Table 9 and Figures 9(b)–(d). $R^2$ uncertainties are propagated ignoring covariance terms and therefore are overestimated.

We find that as burst intensity increases, power-law index and power-law break ($kT$) tend to increase for all three groups. We note that the power-law trends between the temperature and emitting area are similar for cool and hot blackbody components at flux values below $10^{-9.9}$ erg cm$^{-2}$ s$^{-1}$; that is, a single power-law represents the trends for both cooler and hot components. For the highest flux group, the power-law trends for the cool and hot components differ significantly. In line with this result, the difference between broken power-law indices as well as reduced $\chi^2$ values of single and broken power-law fits increase with increasing burst intensity, indicating that with increasing burst intensity, the temperature and emission area relation varies more between the two blackbody components.

We could not split the burst sample of SGR J1550–5418 and SGR 1900+14 into intensity groups since these sources have many fewer unsaturated bursts with well-constrained parameters. For SGR J1550–5418 bursts (see Figure 9, lower left panel), the power indices of the low- and high-temperature components are very similar, suggesting a single power-law trend could represent the whole sample. A single power-law fit to SGR J1550–5418 yields $R^2 \sim T^{-3.3 \pm 0.07}$ with a reduced $\chi^2$ of 0.88. Note that bursts from this magnetar have lower intensity, the temperature and emission area relation varies more between the two blackbody components.

These relations between emission area and temperature differ significantly from the relations discussed in Younes et al. (2014), where the emitting area decreases more with increasing temperature for the hot blackbody component. However, we note that the flux range analyzed by Younes et al. (2014) for SGR J1550–5418 (above $10^{-6.5}$ erg cm$^{-2}$ s$^{-1}$) is much higher than the flux range covered in our investigation ($10^{-9}$–$10^{-8}$ erg cm$^{-2}$ s$^{-1}$). It is possible that the area versus $kT$ behavior of the two blackbody components differs more significantly with increasing flux than previously discussed or that the relationship

### Table 9

| Source       | log$_{10}$ Flux Interval (erg cm$^{-2}$ s$^{-1}$) | Low-energy Index | High-energy Index | $kT_{\text{break}}$ | $\chi^2$/DOF | Source       | log$_{10}$ Flux Interval (erg cm$^{-2}$ s$^{-1}$) | Low-energy Index | High-energy Index | $kT_{\text{break}}$ | $\chi^2$/DOF |
|--------------|-----------------------------------------------|-----------------|-----------------|-------------------|---------------|--------------|-----------------------------------------------|-----------------|-----------------|-------------------|---------------|
| SGR 1806–20  | $-8.31$–$7.91$                                | $-3.79 \pm 0.03$| $-3.78 \pm 0.03$| $5.26$            | $0.93$        | SGR 1806–20  | $-8.31$–$7.91$                                | $-3.79 \pm 0.03$| $-3.78 \pm 0.03$| $5.26$            | $0.93$        |
| SGR 1806–20  | $-7.91$–$7.77$                                | $-4.04 \pm 0.03$| $-3.91 \pm 0.04$| $7.54$            | $0.4$         | SGR 1806–20  | $-7.91$–$7.77$                                | $-4.04 \pm 0.03$| $-3.91 \pm 0.04$| $7.54$            | $0.4$         |
| SGR 1806–20  | $-7.77$–$7.26$                                | $-7.59 \pm 0.02$| $-5.57 \pm 0.04$| $8.08$            | $0.87$        | SGR 1806–20  | $-7.77$–$7.26$                                | $-7.59 \pm 0.02$| $-5.57 \pm 0.04$| $8.08$            | $0.87$        |
| SGR 1900+14  | $-8.4$–$7.16$                                 | $-5.44 \pm 0.01$| $-4.00 \pm 0.04$| $6.01$            | $2.12$        | SGR 1900+14  | $-8.4$–$7.16$                                 | $-5.44 \pm 0.01$| $-4.00 \pm 0.04$| $6.01$            | $2.12$        |
| SGR J1550–5418 | $-8.43$–$7.58$                                | $-3.55 \pm 0.03$| $-3.43 \pm 0.03$| $7.58$            | $0.92$        | SGR J1550–5418 | $-8.43$–$7.58$                                | $-3.55 \pm 0.03$| $-3.43 \pm 0.03$| $7.58$            | $0.92$        |
differs between sources or burst episodes. It remains likely that the trend for power-law indices of hot and cool blackbody components show opposite behaviors at different intensity levels. We suggest that the power-law trends of the cool and hot components are the same in the flux regime $\sim 10^{-8}$ erg cm$^{-2}$ s$^{-1}$. Above this flux level, the cooler component shows a greater decrease in emission area with increasing temperature than the hot component (as in the high-intensity case of SGR 1806−20 (Figure 9, upper right panel)). In the much higher flux regime (above $\sim 10^{-7}$ erg cm$^{-2}$ s$^{-1}$), the opposite behavior takes place, as presented by Younes et al. (2014); that is, the emission area of the hot component drops more than that of the cool component with temperature.

7. Concluding Remarks

We presented the results of our time-averaged spectral analysis of a total of 388 bursts from SGR J1550−5418, SGR 1900−14, and SGR 1806−20 as machine-readable tables in this paper and as a database in a companion web-catalog at http://magnets.sabanciuniv.edu. Our spectral analysis shows that BB+BB, BB+PO, LB+LB, and COMPT models all provide acceptable fits at similar levels. We further conducted numerical simulations to constrain the best fitting model. Based on the simulation results, we suggest that COMPT provides significantly better fits with sufficiently constrained parameters. We suggest that the inherent emission mechanism is likely non-thermal or at least not purely thermal for the majority of bursts included in our study within the 2−250 keV range. It is important to note that since our analysis covers time-averaged spectra only, these results may not fully represent instantaneous burst properties. Excluding the results of the COMPT fit, we find that the LB+LB model, which is employed in SGR spectral analysis for the first time here, describes the majority of bursts with well-restricted parameters better than the BB+BB and BB+PO models.

We find that the photon index is positively correlated with fluence and has an increasing lower bound trend with respect to burst flux, suggesting that bursts have a decreasing upper bound limit on hardness with respect to increasing flux. This behavior is similar to the previously reported anticorrelation between hardness and fluence for SGR J1550−5418 bursts, and confirms the anticorrelation between hardness and fluence for SGR 1806−20 and SGR 1900−14 bursts. Since it was shown that AXP 1E 2259+586 bursts show the opposite trend (positive correlation between burst hardness and fluence), we suggest that the relationship between hardness and burst fluence is a distinctive behavior between AXP and SGR bursts.

We confirm a significant anticorrelation between blackbody temperatures (hot and cold) and burst emission areas. Overall, emission area decreases with increasing blackbody temperature in all cases, verifying the model of thermal emission from a hot bubble where emission radiates from a hot ignition point to a colder and wider emission area. Examining the same relation in different flux intervals of SGR 1806−20 bursts, we found that above the flux regime of $\sim 10^{-8}$ erg cm$^{-2}$ s$^{-1}$, the emission area decreases more rapidly with temperature for the cooler blackbody. This is in contrast to what has been reported previously (e.g., Younes et al. 2014). We suggest that the behaviors of area versus $kT$ of the two blackbody components may differ more significantly with increasing flux than previously discussed. It is also possible that the trend between power-law indices for the cool and hot blackbody components shows opposite behaviors at different burst intensities.

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