ON THE X-RAY EMISSION MECHANISMS OF THE PERSISTENT SOURCE AND VERY LOW FLUENCE BURSTS OF SGR J0501+4516

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ABSTRACT

We present here a detailed spectral study of the X-ray emission of the persistent source and the low-fluence bursts of SGR J0501+4516 observed during a deep XMM-Newton observation near the peak of its 2008 outburst. For the persistent emission, we employ a physically motivated continuum emission model and spectroscopically determine important source properties such as the surface magnetic field strength and the magnetospheric scattering optical depth. We find that the magnetar surface temperature near the peak of its activity is 0.38 keV, corresponding to an emission area of 131 km² at a distance of 2 kpc. The surface magnetic field strength determined spectroscopically, \( B = 2.2 \times 10^{14} \) G, is consistent with the dipole field strength inferred from the source spin and spin-down rate. We fit the stacked spectra of 129 very faint bursts with a modified blackbody model and find a temperature of 1.16 keV, corresponding to an emission area of 93 km². We also find evidence for cooling during the burst decay phase.

Key words: pulsars: individual (SGR J0501+4516) – stars: neutron – X-rays: bursts

Online-only material: color figure

1 INTRODUCTION

Magnetars are manifestations of isolated neutron stars. Commonly known as soft gamma repeaters (SGRs) and anomalous X-ray pulsars (AXPs), magnetars are generally characterized by relatively slow spin periods (in a narrow range of 2–12 s), rapid spin-down rates \((5 \times 10^{-13}–10^{-10} \text{ s}^{-1})\), and intense X-ray bursts with luminosities anywhere between \(10^{37}\) and \(10^{45}\) erg s\(^{-1}\). Dipole magnetic field strengths of these sources, as inferred from their spin periods and spin-down rates, are of the order of \(\sim 10^{14}\) G (Kouveliotou et al. 1998, 1999), and are in perfect agreement with the predictions of the magnetar model that there exist isolated neutron stars which are powered by their own extremely strong magnetic fields (Duncan & Thompson 1992; Thompson & Duncan 1993).

Magnetars are persistent X-ray emitters in quiescence most of the time at luminosity levels around \(\sim 10^{36}–10^{38}\) erg s\(^{-1}\). As they enter active episodes, they usually exhibit significant variations in their persistent emission spectral and temporal behavior in conjunction with the outburst onset (Rea & Esposito 2011). Transient magnetars are generally undetectable unless they undergo outbursts during which their X-ray fluxes are enhanced by factors of a few tens to hundreds, followed by a gradual decay over timescales of months to years (e.g., Göğüş et al. 2010; Rea & Esposito 2011). Typical magnetar bursts are short, lasting only for \(\sim 100\) ms, with a peak luminosity lower than \(\sim 10^{41}\) erg s\(^{-1}\) (Göğüş et al. 2001; van der Horst et al. 2012). More energetic bursts occur much less frequently and have been observed only from five SGR sources (Mazets et al. 1979, 1999; Hurley et al. 1999, 2005; Watts et al. 2010; Göğüş et al. 2011). For reviews on magnetars, see Woods & Thompson (2006) and Mereghetti (2008).

Persistent X-ray emission and bursts are both attributed to the decay of extremely strong magnetic fields in the framework of the magnetar model (Thompson & Duncan 1993, 1995; Thompson et al. 2002). However, it is not trivial to describe the observed data with detailed physical models, considering that the radiation ought to emerge from the strong magnetic and gravitational fields. The persistent X-ray spectrum of magnetars is usually fitted with phenomenological models: either the combination of a blackbody and a power law (see Section 14.3.1 of Woods & Thompson 2006) or two blackbody components (Mereghetti 2008). Recently, Güver et al. (2007, 2008) and Göğüş et al. (2011) studied persistent emission spectra with an idealized physical model, the Surface Thermal Emission and Magnetospheric Scattering (STEMS) model. The STEMS model accounts for the transport of radiation in a fully ionized and extremely magnetized atmosphere (Özel 2001, 2003) as well as for resonant cyclotron scattering (RCS; Lyutikov & Gavriil 2006) of photons emerging from the surface in the magnetosphere of the magnetar (see also Section 2). A typical magnetar burst mainly emits radiation up to \(100\) keV. Its spectrum is well described phenomenologically by the sum of two blackbody functions with temperatures of \(\sim 3\) and \(\sim 12\) keV (e.g., Israel et al. 2008; Lin et al. 2012). To physically describe the burst spectra, Lyubarsky (2002) introduced analytically the shape of a thermalized spectrum modified by a strong magnetic field \((\sim 10^{14}\) G). Here we use the latter model in our burst spectral analysis.

SGR J0501+4516 emitted a series of short X-ray/soft \(\gamma\)-ray bursts for almost two weeks starting on 2008 August 22; several tens of events were detected with Swift, Fermi/GBM, Konus-Wind, and Suzaku (Enoto et al. 2009; Aptekar et al. 2009; Kumar et al. 2010; Nakagawa et al. 2011; Lin et al. 2011). A pointing observation with RXTE revealed a spin period of \(5.762\) s. Using long-term monitoring with RXTE and Swift/XRT, a spin-down rate of \(\sim 5.8 \times 10^{-12}\) s s\(^{-1}\) was later obtained, providing an estimate of the inferred dipole magnetic field strength of \(\sim 2 \times 10^{14}\) G (Göğüş et al. 2010). Chandra observations of SGR J0501+4516 located the point source very precisely at R.A. = 05\(^{\circ}\)01\(^{\prime}\)06\(^{\prime\prime}\), decl. = +44\(^{\circ}\)16\(^{\prime}\)33\(^{\prime\prime}\)92 (J2000) with a \(1\sigma\) uncertainty of \(\sim 0.11\) (Göğüş et al. 2010). Unlike many other Galactic magnetars, SGR J0501+4516 is located in the anti-Galactic center direction, most likely at the Perseus arm at \(\sim 2\) kpc (Xu et al. 2006). As a result, the interstellar hydrogen column density, \(N_{\text{HI}}\), toward SGR J0501+4516 is much lower in...
comparison with the values of magnetars located in the Galactic center direction, making SGR J0501+4516 an ideal source for studying its soft X-ray emission characteristics.

In this paper we introduce, for the first time, the RCS process into the modified thermal burst emission in order to study the burst spectra below 10 keV from SGR J0501+4516. We also analyze the persistent emission of SGR J0501+4516 with the STEMS model and investigate whether a link exists between the persistent emission and the dim burst spectra assuming the same scattering process. We describe the physical models used for the persistent emission and burst spectra in Section 2. In Section 3, we describe the analysis of the XMM-Newton data used here, and present the results of our spectral studies in Section 4. Finally, we discuss the interpretation of these results in Section 5.

2. MODELS FOR THE PERSISTENT AND BURST EMISSION

2.1. Persistent Emission

In the magnetar model, the quiescent X-ray emission could originate from the neutron star surface heating by the decay of the strong magnetic field (Thompson & Duncan 1993). Persistent emission photons ought to go through the atmosphere and magnetosphere of the highly magnetized neutron star before they escape. The transport of radiation for different polarization modes was investigated in detail in a series of studies considering the effects of absorption, emission, and scattering by the fully ionized plasma (Zane et al. 2001; Özel 2001, 2003; Ho & Lai 2001, 2003). These studies showed that as photons propagate from the inner to the outer layers of a magnetized atmosphere the spectrum of the emergent emission becomes harder than the original blackbody shape.

As the photons reach the magnetosphere, RCS could effectively modify their spectrum (Thompson et al. 2002). This process will again make the spectrum harder, by scattering the low-energy photons to higher energies. Lyutikov & Gavriil (2006) calculated the simplified one-dimensional RCS of a Planck spectrum by a non-relativistic warm plasma in an inhomogeneous magnetic field. Applying the same scattering process to the emission from the atmosphere, Güver et al. (2007, 2008) developed the STEMS model. They then used this model to successfully describe the persistent emission spectra of XTE J1810−197 and 4U 0142+61, and also estimate the surface magnetic fields of these two magnetars. The STEMS model depends on four parameters: the surface magnetic field \( B \), the temperature of the neutron star \( kT_{\star} \), the temperature of the plasma in the magnetosphere \( \beta \), and the optical depth for RCS \( \tau \). Because of the strong gravitational field of the neutron star, the STEMS model also includes a fixed gravitational redshift parameter \( z \), which depends only on the ratio of mass to radius for a neutron star. We fixed \( z = 0.306 \) throughout this paper, corresponding to a typical neutron star with mass of \( 1.4 M_{\odot} \) and radius of 10 km.

2.2. Burst Emission

One of the mechanisms invoked for the origin of the short-duration magnetar bursts is the sudden release of energy by cracking of the magnetically strained neutron star crust (Thompson & Duncan 1995). This sudden energy release creates a hot pair plasma, which then becomes trapped in the magnetosphere forming a bubble with large optical depth (Thompson & Duncan 1995). The photons need to go through multiple scatterings to escape the bubble, thereby thermalizing the burst radiation (Thompson & Duncan 1995). Unlike in the case of persistent surface emission for which absorption, emission, and scattering are important, scattering is the most dominant process in the burst bubble (Lyubarsky 2002). Taking into account the fact that photons with different energies would have different scattering cross-sections, Lyubarsky (2002) calculated the radiation transfer for the magnetar bursts. The resulting spectral shape has a much flatter low-energy distribution compared with the equilibrium blackbody spectrum (hereafter we call the resulting shape the modified blackbody, MBB). The MBB photons are also subject to multiple scatterings as they go through the magnetosphere. We adopted the same RCS process as used in Lyutikov & Gavriil (2006) and Güver et al. (2007) to up-scatter the MBB burst spectrum. The scattered MBB and Planckian functions differ significantly at energies below the bolometric temperature \( T_{b} \). The softer emission is greatly affected by the interstellar absorption, which would make the two models indistinguishable if the source were toward a high interstellar \( N_{H} \) region. The location of SGR J0501+4516 therefore makes it an excellent source to determine the nature of its burst emission mechanism. We generated a numerical grid for the modified blackbody with resonant cyclotron scattering (MBB + RCS) to fit the burst spectral data in XSPEC (Arnaud 1996). The MBB + RCS model has three free parameters: the bolometric temperature of the bubble \( (kT_{b}) \) which was allowed to range between 0.1 and 20 keV, and \( \beta \) and \( \tau \) as defined in Section 2.1. We also used the same gravitational redshift parameter \( z = 0.306 \) while fitting the burst spectra.

3. OBSERVATIONS AND DATA REDUCTION

SGR J0501+4516 was observed with XMM-Newton (Jansen et al. 2001) on seven occasions between 2008 August and September. Here, we select only the first observation performed on 2008 August 23 (Obs. ID: 0560191501), the most burst-active day of the source, to study the spectral properties of the bursts and of the underlying persistent emission at the same time. The observation, lasting for 48.9 ks, was performed in the small window mode of the European Photon Imaging Camera (EPIC) pn instrument (Strüder et al. 2001), allowing a temporal resolution of 6 ms. We processed the data using SAS version 11.0.0 with the latest calibration files generated on 2012 May 18.

We identified and removed events in the piled-up time intervals (64 s in total), which are the ones with count rates over 50 counts s\(^{-1}\), from the source event list. We then constructed the source light curve with 100 ms bin size as shown in Figure 1. The average count rate of the persistent emission is \( \sim 5.5 \) counts s\(^{-1}\), corresponding to no more than 5.5 counts per bin in the light curve of Figure 1 (or a count rate of 55 counts s\(^{-1}\)). We assumed that a bin contained a burst if it exceeded the persistent X-ray emission level by at least 2\( \sigma \), corresponding to \( \sim 10 \) counts per bin (or a count rate of 100 counts s\(^{-1}\)). We therefore accumulated the persistent emission spectrum using 100 ms time bins with count rates less than 50 counts s\(^{-1}\) and the burst spectra from those bins with over 100 counts s\(^{-1}\). The total exposure time of the persistent emission spectrum was 32.7 ks. There are 129 identified bursts having 100 ms peak count rates between 100 and 500 counts s\(^{-1}\); the total time encompassed by these bursts was 8.7 s. We combined all 129 burst data into one stacked spectrum and regrouped the resulting spectra to have a minimum of 15 counts in each spectral bin, making sure that we kept the bin size within the spectral resolution of the instrument. We then fitted the spectra using XSPEC version 12.7.0.
Figure 1. Light curve of SGR J0501+4516 with 100 ms time resolution. The dashed line marks the count rate (50 counts s\(^{-1}\)) selected for the persistent emission level. The dotted line denotes the count-rate threshold for burst selection.

Table 1
Spectral Fit Results for the Persistent and Burst Emission from SGR J0501+4516

| Spectrum    | Model     | \(N_\text{H}\) \((10^{22} \text{ cm}^{-2})\) | \(B\) \((10^{14} \text{ G})\) | \(kT^a\) \((\text{keV})\) | Index | \(\beta\) | \(\tau\) | \(\chi^2/\text{dof}\) |
|-------------|-----------|---------------------------------|-----------------|-----------------|-----|-----|-----|------------------|
| Persistent  | BB+PL     | 0.91 ± 0.01                      | ...              | 0.70 ± 0.01     | 2.79 ± 0.04 | ... | ... | 0.7657/117       |
| Persistent  | STEMS     | 0.67 ± 0.02                      | 2.21 ± 0.07     | 0.38 ± 0.02     | ... | 0.37 ± 0.01 | 5.0 ± 0.2 | 0.7615/116       |
| Burst all   | BB        | 0.67                            | ...              | 1.08 ± 0.02     | ... | ... | ... | 2.1054/84        |
| Burst all   | MBB       | 0.67                            | ...              | 1.35 ± 0.04     | ... | ... | ... | 1.4944/84        |
| Burst all   | BB+RCS    | 0.67                            | ...              | 0.93 ± 0.03     | ... | 0.37 | 5.0 | 1.4415/84        |
| Burst all   | MBB+RCS   | 0.67                            | ...              | 1.16 ± 0.04     | ... | 0.37 | 5.0 | 1.174/84         |
| Burst rise  | MBB+RCS   | 0.67                            | ...              | 1.12 ± 0.11     | ... | 0.37 | 5.0 | 0.1019/20        |
| Burst peak  | MBB+RCS   | 0.67                            | ...              | 1.35\(^{+0.12}_{-0.10}\) | 0.37 | 5.0 | 0.9632/25        |
| Burst decay | MBB+RCS   | 0.67                            | ...              | 0.92\(^{+0.06}_{-0.07}\) | 0.37 | 5.0 | 1.169/36         |
| Burst rise+peak | MBB+RCS | 0.67                            | ...              | 1.25\(^{+0.09}_{-0.07}\) | 0.37 | 5.0 | 1.015/46         |

Note. \(^a\) For all burst fits this parameter is the \(kT\) of the modified blackbody model.

4. SPECTRAL ANALYSIS RESULTS

4.1. The Persistent Emission Spectrum

We first fitted the spectrum of the persistent emission with a single blackbody and a power law (BB + PL). The best-fit parameters listed in Table 1 are consistent with the results reported in Rea et al. (2009) and Göğü et al. (2010). We then fitted the spectrum with STEMS (see also Figure 2). The STEMS and BB+PL models fit the persistent spectrum equally well; the STEMS model provides well-constrained model parameters (see Table 1). We find an unabsorbed source flux of \((5.88 ± 0.02) \times 10^{-11} \text{ erg s}^{-1} \text{ cm}^{-2}\) in the 0.5–6.5 keV range and a temperature \(kT = 0.38 ± 0.02 \text{ keV}\) corresponding to a hot-spot surface area of 131 ± 27 km\(^2\) (assuming a source distance of 2 kpc).

Using the STEMS fit, we obtained a hydrogen column density of \(N_\text{H} = (6.7 ± 0.2) \times 10^{21} \text{ cm}^{-2}\), much lower than the value obtained with the BB + PL fit \((N_\text{H} = 9.1 \times 10^{21} \text{ cm}^{-2})\). The weighted average values of \(N_\text{H}\) toward the direction\(^3\) of

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3 As obtained with the HEASARC \(N_\text{H}\) tool: http://heasarc.gsfc.nasa.gov/cgi-bin/Tools/w3nh/w3nh.pl
Lin et al.

Figure 3. Time-integrated stacked spectrum of 129 dim SGR J0501+4516 bursts overplotted with the best-fit MBB+RCS model and the residuals for the MBB+RCS, BB+RCS, MBB, and BB models (from top to bottom).

SGR J0501+4516 are $6.2 \times 10^{21} \text{ cm}^{-2}$ and $5.2 \times 10^{21} \text{ cm}^{-2}$ using the Dickey & Lockman (1990) and Kalberla et al. (2005) surveys, respectively. The value of $N_{\text{H}}$ from the STEMS fit agrees well with the Galactic value but the BB + PL model fit overestimates the absorption.

4.2. The Time-integrated Burst Spectrum

To remove the contribution of the persistent emission from the burst emission, we used the persistent spectrum as the background for the burst spectrum. We fitted the burst spectrum with several continuum models: blackbody, modified blackbody, blackbody with RCS, and MBB + RCS. In all our fits, we fixed $N_{\text{H}}$ at $6.7 \times 10^{21} \text{ cm}^{-2}$, the value obtained from the persistent spectrum fit with the STEMS model. Previous studies revealed that the magnetospheric parameters do not vary significantly over timescales of months (Güver et al. 2007, 2008; Göğüş et al. 2011). We also assumed that the RCS by the non-relativistic warm plasma in the magnetosphere of SGR J0501+4516 does not vary over the course of the XMM-Newton observation and adopted the magnetospheric electron velocity ($\beta$) and the optical depth ($\tau$) from the persistent spectrum fit. We list all the fit results in Table 1. Figure 3 exhibits the burst spectrum with the MBB + RCS fit (top panel) and the residuals for all models (next four panels). We find that MBB + RCS gives the best fit of the four models. Note the apparent deviation above 7 keV in all spectral fits; this may be due to an additional component in the spectra of SGR bursts as shown by Lin et al. (2012).

We calculated the average unabsorbed flux of the bursts in the 0.5–10 keV range as $(1.80 \pm 0.05) \times 10^{-9} \text{ erg s}^{-1} \text{ cm}^{-2}$. The total energy released by all 129 very dim bursts is $\sim 7.5 \times 10^{36} \text{ erg}$.

4.3. The Time-resolved Burst Spectrum

We studied the time evolution of the spectral properties of the brightest bursts in our set of 129 events, using their stacked time-resolved spectra. We selected all the bursts with peak count rate greater than 300 counts s$^{-1}$ on a 25 ms bin size. Note the fact that we reduced the time resolution in order to accommodate SGR bursts with finer temporal structures. This selection resulted in a set of 47 bursts. Then, we separated each selected burst into three parts: rise, peak, and decay. The peak bin is defined as the 25 ms time bin with the highest count rate during the burst, the rise part is the time interval from the onset of the burst to the start of the peak bin, and the decay part starts from the end of the peak bin and ends when the emission returns back to the background level. Figure 4 shows an example of the three parts of a relatively bright burst. We generated stacked spectra for the rise, peak, and decay parts and fitted these spectra with the MBB + RCS model.

Figure 5 exhibits the spectra of the rise, peak, and decay parts of the bursts together with their best-fit model curves. We list all spectral fit results in Table 1. We find that, of the three parts, the burst bubble temperature is the highest at the peak. However, the temperatures of the rise and peak parts differ only by $\sim 2\sigma$. Therefore, we fit these two parts simul-
and decay parts of the 47 brightest bursts of SGR J0501+4516. The error bars in the time axis represent the total exposure time of each accumulated part.

Figure 5. Count spectra and their best fit with the MBB + RCS model curves for the rise (dots), peak (circles), and decay (triangles) parts of the stacked bursts. (A color version of this figure is available in the online journal.)

Figure 6. Time evolution of the temperature of the modified blackbody (squares) and the unabsorbed flux (filled circles) in the 0.5–10 keV range for the rise, peak, and decay parts of the 47 brightest bursts of SGR J0501+4516. The error bars in the time axis represent the total exposure time of each accumulated part.

5. DISCUSSION

We investigated the persistent X-ray and very dim burst emission properties of SGR J0501+4516 during the day after the onset of its 2008 outburst, using the deepest XMM-Newton observations of the source that included a large number of bursts. We analyzed the persistent X-ray emission with the STEMS magnetar emission model and found a magnetar average surface temperature of $kT = 0.38$ keV, much lower than the temperature of $\sim 1$ keV obtained with the phenomenological BB + PL model fit. The persistent emission of almost all other sources modeled with BB + PL yields a blackbody temperature of $\sim 0.5$ keV. Note that this value is much lower than that of our SGR J0501+4516 fit with BB + PL, but closer to or slightly higher than our value estimated with the STEMS model fit. We also found that, for SGR J0501+4516, the BB + PL model gives a larger $N_H = 10^{22}$ cm$^{-2}$ than the Galactic value ($5–6 \times 10^{22}$ cm$^{-2}$) in the direction toward SGR J0501+4516, while the STEMS $N_H = 6.7 \times 10^{23}$ cm$^{-2}$ agrees well with the latter value.

Enoto et al. (2010) investigated the Suzaku observations of SGR J0501+4516 on 2008 August 26–27 in the energy range 1–70 keV. They used thermal emission with an RCS model (see Lyutikov & Gavriil 2006) to describe the persistent soft X-ray spectrum plus a simple power law for the hard X-ray component. This model did not provide a good fit (reduced $\chi^2 = 1.73$). They reported a value for $N_H = 6.2 \times 10^{21}$ cm$^{-2}$, a surface temperature of $kT = 0.39$ keV, and magnetospheric scattering parameters, $\tau = 5.1$ and $\beta = 0.3$, which are quite similar to our results. However, the uniqueness of the STEMS model is the fact that it takes into account the presence of the strong surface magnetic field and its possible effect on the emergent spectrum via atmospheric processes. Using STEMS we obtain, for the first time, the surface magnetic field strength of SGR J0501+4516 via X-ray spectroscopy as $B = 2.2 \times 10^{15}$ G, a value which agrees well with the inferred equatorial dipole field strength of $2 \times 10^{15}$ G (Rea et al. 2009; Göğüş et al. 2010).

The STEMS model has already been used to study the persistent emission spectra of four AXPs, XTE J1810–197, 4U 0142 + 61, 1E 1048.1–5937, and 1RXS J170849.0–400910 (Güver et al. 2007, 2008; Özel et al. 2008), and four SGRs, SGR 1900+14, SGR 0418+5729, SGR 0526+66, and SGR J1550–5418 (Göğüş et al. 2011; Güver et al. 2011, 2012; Ng et al. 2011). In most cases, including SGR J0501+4516, the surface magnetic field obtained from X-ray spectroscopy is consistent with the dipole magnetic field inferred from the spin period and the spin-down rate, as shown in Figure 7. Because magnetars emit energetic bursts, their surface magnetic field strengths are expected to be in the $10^{14}$–$10^{15}$ G domain. Some sources, however, may have lower inferred dipole magnetic field strengths (Rea et al. 2010), although higher-order magnetic structures (multipolar fields) may be present (Güver et al. 2011). The similarity between the surface
magnetic field strengths of SGR J0501+4516 as obtained via X-ray spectroscopy and as inferred from the spin properties suggests that its surface magnetic field topology is close to a dipole.

We also studied here, for the first time, the dimmest bursts and their physical link to the persistent X-ray emission as both kinds of emission are redistributed by the RCS process in the magnetosphere. The burst spectrum can be described as a warm bubble trapped by the magnetosphere, emitting thermal radiation modified by a strong magnetic field. The bolometric radiation flux as

\[ F = \frac{1}{2} \sigma T_b f, \]

(1)

where \( D \) is the distance to SGR J0501+4516, \( f \) is the unabsorbed flux, \( \sigma \) is the Stefan–Boltzmann constant, and \( T_b \) is the bolometric temperature. Assuming a distance to the source of ~2 kpc, we estimate the average emission area of the burst as 93 ± 10 km², which is ~7.4% of the magnetar surface (\( R_{NS} = 10 \text{ km} \)).

Enoto et al. (2010) and Nakagawa et al. (2011) studied spectra of the persistent emission and the dim short bursts (average flux \( \sim 10^{-8} \text{ erg s}^{-1} \text{ cm}^{-2} \)) from SGR J0501+4516 with *Suzaku*. They fitted both spectra with two blackbody functions and a power-law model. Comparing the parameters of these fits, Nakagawa et al. (2011) concluded that the persistent emission and the dim bursts have the same emission mechanism. They further suggested that the persistent emission of magnetars may be composed of numerous microbursts. We find that both kinds of emission are forms of modified thermal emission redistributed by RCS in the magnetosphere. However, the spectral shapes of the thermally dominated portions (\( \leq 4 \text{ keV} \)) of the STEMS and MBB+RCS models are remarkably different and yield significantly different temperatures. We therefore argue against the idea that the persistent and burst emissions have a common origin. The main difference between the two is that the scattering is the dominant process in the burst bubble, while for the persistent emission, one needs to consider not only the scattering but also the emission and absorption processes as photons travel through the magnetar atmosphere. We investigated the dependence of burst peak times on the rotational phases of the source and found that bursts occur quite uniformly over the entire spin phase, showing no significant concentration during any phase. This result supports our argument that short bursts and persistent emission do not have a common origin.

Finally we investigated the stacked time-resolved spectra of the brighter bursts from SGR J0501+4516. We found that their temperature traces their flux behavior and has a lower value in the decaying part compared to the rise and peak parts. We note here that these results do not contradict the earlier results of Lin et al. (2011), who found that the burst hardness evolves from hard to soft to hard with flux over a very broad burst flux range, since the bursts studied here correspond to a very narrow flux range in a softer energy band. From Equation (1) above, we calculate the emission areas for the rise, peak, and decay parts as

\[ A \sim 19 \text{ km}^2, 160 \pm 29 \text{ km}^2, \text{ and } 160 \pm 29 \text{ km}^2, \text{ respectively.} \]

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Figure 7. Comparison of the inferred dipole magnetic fields with the surface magnetic field obtained with X-ray spectroscopy for nine magnetars. The dashed line marks the line on which the two axes are equal. SGR J0501+4516 is shown as a five-point star. All other values in this figure are taken from Güver et al. (2011). SGR J0418 + 5729 has an upper limit for the inferred dipole magnetic field and a measurement with STEMS spectroscopy.

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