SPATIAL, TEMPORAL, AND SPECTRAL PROPERTIES OF X-RAY EMISSION FROM THE MAGNETAR SGR 0501+4516

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ABSTRACT

SGR 0501+4516 was discovered with the Swift satellite on 2008 August 22 after it emitted a series of very energetic bursts. Since then, the source was extensively monitored with Swift and the Rossi X-ray Timing Explorer (RXTE) and observed with Chandra and XMM-Newton, providing a wealth of information about its outburst behavior and burst-induced changes of its persistent X-ray emission. Here, we report the most accurate location of SGR 0501+4516 (with an accuracy of 0′′.11) derived with Chandra. Using the combined RXTE, Swift/X-ray Telescope, Chandra, and XMM-Newton observations, we construct a phase-connected timing solution with the longest time baseline (∼240 days) to date for the source. We find that the pulse profile of the source is energy dependent and exhibits remarkable variations associated with the SGR 0501+4516 bursting activity. We also find significant spectral evolution (hardening) of the source persistent emission associated with bursts. Finally, we discuss the consequences of the SGR 0501+4516 proximity to the supernova remnant, SNR G160.9+2.6 (HB9).

Key words: pulsars: individual (SGR 0501+4516) – X-rays: bursts

1. INTRODUCTION

Soft gamma repeaters (SGRs) are intriguing manifestations of neutron stars. They are most often discovered in hard X-rays/soft γ-rays, when they (repeatedly) emit clusters of energetic bursts with peculiar properties; these episodes are characterized by a plethora of “short bursts” that usually last only a fraction of a second but emit extremely large energies of $10^{37}–10^{40}$ erg. On rare occasions, SGRs emit relatively more energetic, so-called intermediate events, which are one to two orders of magnitude larger in energy, last longer (∼1–4 s) and often exhibit an extended tail. On extremely rare instances (only three have been detected thus far), SGRs produce “giant flares,” which are even more energetic ($10^{44}–10^{47}$ erg) and have distinctive and similar morphologies: a very bright and spectrally hard initial short spike (<0.5 s) that is followed by a longer (300–600 s) tail clearly modulated at the spin frequency of the originating source (see Woods & Thompson 2006, for a review).

Along with their bursting behavior, SGRs and their close relatives, Anomalous X-ray Pulsars (AXPs), display interesting persistent X-ray emission properties: they pulse with spin periods in the narrow range of 2–12 s. They all slow down at rather large spin-down rates (∼$10^{-11}$ s$^{-1}$), and their inferred dipole magnetic fields are extremely strong ($B_d \sim 10^{14}–10^{15}$ G; Kouveliotou et al. 1998). Moreover, their X-ray intensities vary, usually in the form of a rapid increase associated with the onset of a major bursting episode, followed by a gradual decrease lasting months to years (see, e.g., Woods et al. 2001, 2004; Esposito et al. 2008).

SGRs and AXPs are now classified as magnetars—neutron stars that are powered by their extremely strong magnetic fields ($B \simeq 10^{14}$ G; Duncan & Thompson 1992). The magnetar model attributes the origin of the energetic SGR events to cracking of the solid neutron star crust, when strained by the drifting strong magnetic field: local fractures leading to short bursts (Thompson & Duncan 1995) and cracking at global scales giving rise to giant flares (Thompson & Duncan 1995, 2001). The persistent emission of magnetars likely originates from the stellar surface heated by the decay of the strong magnetic field (Thompson & Duncan 1996; Özel 2001; Ho & Lai 2001) and from resonant Compton scattering of soft photons by magnetospheric currents driven by twists in the evolving magnetic field (Thompson et al. 2002).

SGR 0501+4516 was discovered on 2008 August 22, when four short and soft bursts from the source triggered the Burst Alert Telescope (BAT) onboard NASA’s Swift satellite (Barthelmy et al. 2008). To confirm its magnetar nature, we initiated our target of opportunity (ToO) observations with the Rossi X-ray Timing Explorer (RXTE). The first RXTE/Proportional Counter Array (PCA) observation took place on August 22 for a net exposure of 484 s. Timing analysis of this short stretch of data revealed coherent pulsations with a period of 5.76 s (Göögüs et al. 2008). Subsequent observations of the new source with RXTE and the Swift/X-ray Telescope (XRT; Burrows et al. 2005) allowed us to determine the spin-down rate of SGR 0501+4516, and therefore, to firmly establish it as a magnetar (Woods et al. 2008; Rea et al. 2009).

Following the onset of its outburst episode, the source flux decayed exponentially with an e-folding time of 23.8 days (Rea et al. 2009). Using a subset of the Swift/XRT observations we also employ here and in addition their XMM-Newton and Suzaku observations, Rea et al. (2009) determined a pulse ephemeris, which showed evidence of strong negative $\dot{P}$. The latter was interpreted as the recovery to a secular spin-down, which might have increased in conjunction with the outburst onset. Rea et al. (2009) also analyzed an archival ROSAT observation of the source and found that the X-ray flux of SGR 0501+4516 in 1992 was about 80 times lower. Recently, using Suzaku observations...
of SGR 0501+4516 obtained 4 days after the outburst onset. Enoto et al. (2010) reported that the persistent emission of the source extends up to about 70 keV. Finally, besides Swift/BAT, SGR 0501+4516 also triggered the Gamma Ray Burst Monitor (GRBM) onboard the Fermi Gamma-ray Space Telescope 26 times. Both instruments recorded burst activity from the source until about 2008 September 3. Detailed analysis of the GBM data is currently underway (L. Lin et al. 2011, in preparation).

We present here spatial and long-term temporal and spectral characteristics of the persistent X-ray emission of SGR 0501+4516 using wideband X-ray observations during three states of the source: (1) its burst active episode, (2) its transition to quiescence, and finally (3) its quiescent phase. In Section 2, we describe the observations and data used in our study. In Section 3, we present the results of our detailed analyses. We discuss the interpretation of our results in Section 4.

2. OBSERVATIONS

2.1. RXTE

We monitored the source with RXTE until 2008 August 30 in densely spaced pointings (consecutive intervals ranging between 0.1 and 0.9 days) followed by longer intervals as the source became fainter (spaced 2–7 days apart). Exposure times of these observations varied between \( \sim 1 \) ks (in two cases) and \( \sim 11.6 \) ks (in one case), while the great majority lasted \( \sim 2.5 \) ks. Overall, we acquired a total exposure of 82.5 ks in 29 RXTE pointings from 2008 August 22 (MJD 54700) to October 14 (MJD 54753). We used data collected with the RXTE/PCA only. The number of operating proportional counter units varied between 1 and 3, with a median value of 2 during our pointings. For each observation, we applied our burst search algorithm (see Gögüş et al. 2000) for its methodology) to the light curve with a 0.125 s time bins to identify short events. We then filtered out the times of short bursts identified to obtain a burst-free event list for timing studies. We finally converted all event arrival times to the solar system barycenter.

2.2. Swift

SGR 0501+4516 was monitored with the Swift/XRT starting 2008 August 26 (MJD 54,704) until 2009 April 19 (MJD 54,940) for a total exposure of 436 ks, providing the longest baseline coverage of the source to date. In Figure 1, we present the long-term X-ray light curve variations of SGR 0501+4516 as seen in the 0.3–10 keV range with Swift/XRT. The solid line is obtained by fitting an exponential function, whose time reference is the time of the first burst observed on August 22 (i.e., 54,700.529 MJD), that yields an \( e \)-folding time of 27.9 \( \pm 2.5 \) days. This value is notably consistent (within 1.6\( \sigma \)) with that reported by Rea et al. (2009) using the first 160 days of data coverage of the source.

We used all XRT observations that were performed in windowed timing (WT) mode. For each pointing we extracted source events from a 15′ segment of the one-dimensional WT image, centered at the pixel with the highest rate. The background events were selected from source-free intervals on both sides of the source extraction interval. We then generated and filtered the light curves of each XRT pointing to ensure that there are no short SGR bursts in the persistent emission data included in our timing analysis. Finally, we transformed the arrival time of each event to the solar system barycenter for timing studies.

We also employed additional Swift/XRT observations in photon counting mode that took place around 2009 October 9, December 6, and 2010 February 20 for 13.2 ks, 13.4 ks, and 11.6 ks, respectively. We performed spectral analysis with these data sets and derived the source flux at late stages of the outburst decay.

2.3. Chandra X-ray Observatory

We initiated our ToO observations with the Chandra/Advanced CCD Imaging Spectrometer (ACIS; Garmire et al. 2003) in continuous clocking (CC) mode on 2008 August 26 (MJD 54,704) for an effective exposure of 36.5 ks. The source was relatively bright at the time of the ACIS observation resulting in a (background subtracted) count rate of \( 4.42 \pm 0.01 \) counts s\(^{-1}\) (0.3–8.5 keV), which is still below the level that would cause pile-up. We extracted source events from an 8′′ segment of the one-dimensional CC mode image centered at the pixel with the highest counts; we extracted background events from a 20′′ long segment with a 10′′ buffer on both sides of the source extraction. We then applied barycentric correction to all event arrival times.

We also observed SGR 0501+4516 with the Chandra/High Resolution Camera (HRC; Murray et al. 2000) in imaging mode for 10 ks on 2008 September 25 (MJD 54,734). We used the superb angular resolution of the HRC to derive the precise X-ray position of the source. The X-ray intensity of the source was considerably lower at the time of the HRC observations with a (background subtracted) count rate of 0.505 \( \pm 0.007 \) counts s\(^{-1}\) in the 0.3–8.5 keV range.

2.4. XMM-Newton

We observed SGR 0501+4516 with XMM-Newton on 2008 August 23 (MJD 54,701) for 48.5 ks. Here, we used data

5 Note that uncertainties reported throughout the paper are 1\( \sigma \) unless otherwise indicated.
collected with the European Photon Imaging Camera (EPIC; Pfeffermann et al. 1999) PN camera operated in imaging with prime small window mode. We selected source events from a circular region with a radius of 20′ small window mode. We selected source events from a circular region with a radius of 20′ centered at the source and background events from a source-free region on the same chip. The background subtracted source count rate is 5.62 ± 0.01 counts s⁻¹ in the 0.3–8.5 keV range. Inspection of the source light curve revealed many short SGR events, as expected since the observation took place during the burst active episode of the source. We adopted our burst finding algorithm to search in the 0.3–10 keV band of the EPIC-PN data and identified 642 short bursts over a wide range of X-ray intensities. After removing the time intervals corresponding to all bursts, the exposure time was reduced to 47.5 ks. Finally, we applied a barycentric correction to the event arrival times for our timing studies.

3. DATA ANALYSES AND RESULTS

3.1. Source Location

We generated an image of the entire Chandra/HRC-I field in the 0.5–7.0 keV range and used wavdetect⁸ to identify all X-ray sources in our frame. We found two point sources: SGR 0501+4516 at the aim point of the image and a previously uncataloged X-ray source (CXOU J050111.3 + 451525) that is separated by 1.4 from the SGR location. Their locations are R.A. = 05°01′06″.76, decl. = +45°16′33″.92 (J2000), and R.A. = 05°01′11″.33, decl. = +45°15′25″.28 (J2000) for SGR 0501+4516 and CXOU J050111.3 + 451525, respectively.

The statistical uncertainty of the X-ray location of the latter source is 0′.09 (22 source counts). To derive a precise positional uncertainty, we searched the 2MASS catalog and found an IR source (2MASS 05011132 + 4515252) at R.A. = 05°01′11″.33, decl. = +45°15′25″.25 with an uncertainty of 0′.06. This location is consistent within the uncertainties, with the Chandra location of CXOU J050111.3 + 451525, so we concluded that the latter is very likely the X-ray counterpart to 2MASS 05011132 + 4515252. Given the excellent alignment between these two localizations, we estimate the absolute positional uncertainty of SGR 0501+4516 to be 0′.11 (1σ).

3.2. Pulse Properties

3.2.1. Pulse Timing Analysis

For this analysis, we used the pulse timing technique described in detail in Woods et al. (2002). In summary, we use an epoch folding algorithm to determine the pulse frequency and its higher order time derivatives as follows. We first group all available observations (RXTE/PCA, Swift/XRT, Chandra/ACIS, XMM-Newton/EPIC-PN) into discrete time segments. We then generate a (high signal-to-noise ratio) pulse profile template using the data in the 2–10 keV energy band by accumulating multiple, closely spaced pointings. Next we cross-correlate the pulse profile obtained by each group of pointings with the template profile and measure the phase drifts with respect to the template (see Figure 2, top panel). We obtained a good fit to the phase residuals by modeling with a fifth-order polynomial (χ²/degrees of freedom = 139.5/110). In Table 1, we provide the best-fit parameters of the spin ephemeris of SGR 0501+4516. The fit residuals are presented in the middle panel of Figure 2. We also employed a quadratic spline fit to all available phase residuals in seven segments. In Table 2, we list the spin frequencies and their time derivatives as determined with the quadratic spline method; the bottom panel of Figure 2 shows the phase residuals obtained with the spline fit. It is important to note that in the pulse timing technique we employ a systematic pulse profile change in which the profile drifts in phase cannot be distinguished from phase drift due to timing noise.

| Table 1 | Pulse Ephemeris of SGR 0501+4516 Obtained using the Combined RXTE/PCA, Swift/XRT, CXO/ACIS-S, and XMM-Newton/EPIC-PN Observations |
| Parameter | Value |
|------------|-------|
| Epoch (MJD) | 54700.794–54940.953 |
| ν (Hz) | 0.173547943(1) |
| ν (10⁻¹⁵ Hz s⁻¹) | -1.752(8) |
| ν (10⁻²¹ Hz s⁻²) | 6.9(3) |
| ν (10⁻²⁷ Hz s⁻³) | -2.7(3) |
| ν (10⁻³⁴ Hz s⁻⁴) | 3.5(6) |

| Table 2 | Pulse Frequency and Frequency Derivative of SGR 0501+4516 Obtained with a Quadratic Spline Fit to the RXTE/PCA, Swift/XRT, Chandra/ACIS-S, and XMM-Newton/EPIC-PN Data |
| Epoch (MJD) | Range (MJD) | ν (Hz) | (10⁻¹⁵ Hz s⁻¹) |
|------------|-------------|--------|----------------|
| 54707.5 | 54700.0 – 54715.0 | 0.173548659(2) | -2.03(8) |
| 54722.5 | 54715.0 – 54730.0 | 0.173548384(3) | -2.2(8) |
| 54740.0 | 54730.0 – 54750.0 | 0.173548100(3) | -1.62(8) |
| 54765.0 | 54750.0 – 54780.0 | 0.173547721(4) | -1.85(6) |
| 54805.0 | 54780.0 – 54830.0 | 0.173547146(3) | -1.55(4) |
| 54855.0 | 54830.0 – 54880.0 | 0.173546954(4) | -1.93(4) |
| 54915.0 | 54890.0 – 54950.0 | 0.17354554(2) | -1.75(6) |

Figure 2. Top panel: plot of pulse phase drifts of each SGR 0501+4516 observation with respect to the pulse template (see also the text); middle panel: the fit residuals when the pulse phase evolution is modeled with a fifth-order polynomial; bottom panel: the fit residuals when a quadratic spline fit is applied.

⁸ A CIAO tool, http://cxc.harvard.edu/ciao/.
3.2.2. Pulse Profile Evolution

To investigate the pulse morphology and its evolution in energy and time, we generated pulse profiles in the 0.3–2 keV, 2–4.5 keV, and 4.5–8.5 keV energy intervals for the Chandra/ACIS-S, XMM-Newton/EPIC-PN and Swift/XRT data, and in the 2–4.5 keV, 4.5–8.5 keV, 8.5–14 keV, and 14–40 keV intervals for the RXTE/PCA data. We used the phase-connected spin ephemeris presented in Table 1 for determining the phases of all event arrival times in each specified energy interval.

Figure 3 shows the pulse profile evolution with energy as observed with XMM-Newton/EPIC-PN on the day after the onset of activation and during an episode of continued bursting. We find that the pulse profile in the 0.3–2 keV band is dominated by a broad peak ($\phi \sim 0.25–0.75$) and a broad valley ($\phi \sim 0.75–1.25$), with overlying sub-pulses. The most significant sub-pulse appears at $\phi \sim 0.34$. The significance of these sub-pulses decreases at higher energies and the profile becomes almost sinusoidal in the 4.5–8.5 keV range. The bottom panel in Figure 3 demonstrates that the lowest energy interval emission is the most dominant component of the overall profile.

The rms pulsed fraction\(^9\) is energy dependent and increases with energy: (24.2 ± 0.2)%, (30.6 ± 0.3)%, and (32.9 ± 0.8)% in 0.3–2 keV, 2–4.5 keV, and 4.5–8.5 keV, respectively. The rms pulsed fraction in the entire energy range (0.3–8.5 keV) is (27.1 ± 0.2)%.

\(^9\) The rms pulsed fraction is defined as $P_{\text{RMS}} = (\sum_{i=1}^{N}(R_i - R_{\text{ave}})^2 - \Delta R_i^2)/R_{\text{ave}}$, where $N$ is the number of phase bins ($N = 24$), $R_i$ is the rate in each phase bin, $\Delta R_i$ is the associated uncertainty in the rate, and $R_{\text{ave}}$ is the average rate of the pulse profile.

In Figure 4, we show the pulse profiles of SGR 0501+4516 seen with Chandra/ACIS-S near the end of the burst active episode of the source. We find that the morphology of these profiles closely resembles in all energy ranges those obtained with the XMM-Newton, despite important differences in the source state: (1) the intensities (count rates) in all energy ranges are lower, (2) the sub-pulse that peaks around $\phi \sim 0.03$ becomes more prominent, and (3) some pulsed fractions are significantly different. Most prominently, the Chandra 0.3–2 keV rms pulse fraction is (21.6 ± 0.3)%, which is 7.2$\sigma$ lower than that seen with XMM-Newton. The 2–4.5 keV range pulse fraction is (29.7 ± 0.4)% (consistent with the XMM-Newton data within error). Finally, the 4.5–8.5 keV band has an rms pulsed fraction of (38 ± 1)%, which is 4$\sigma$ higher than that in the XMM-Newton data. The energy-averaged rms pulsed fraction (0.3–8.5 keV) is (25.2 ± 0.3)%.

We present in Figure 5 the RXTE/PCA energy-resolved pulse profiles and their evolution in time. For this analysis, we have split the PCA observations into four groups of nearly equal exposures and obtained pulse profiles for each in the instrument energy range of 2–40 keV. As the PCA is not an imaging instrument, its background determination relies on model based estimates and most likely does not reflect the true background; for that reason, we plot the pulse profiles in arbitrary units.

The leftmost column of Figure 5 corresponds to pulse profiles obtained during the most burst active episode of the source (~75% of bursts were emitted in the two days following the episode onset). The pulse profile in the 2–4.5 keV range is characterized by a single, smooth pulse with a large duty cycle (~60%). In the 4.5–8.5 keV band, the pulse structure is still broad and peaks around $\phi \sim 0.5$, as in the lower energy interval,
but it is asymmetric. Note that there is also evidence of weaker structures around $\phi \sim 1.0$. The pulse profile in the 8.5–14 keV band is multi-peaked: the structure around $\phi \sim 1.0$ becomes more prominent and almost as significant as the other pulse in the profile at about half the spin cycle. However, only the structure around $\phi \sim 1.0$ remains in the 14–40 keV energy band.

In the time interval from 2009 August 25 to 30, (the second column from the left in Figure 5), the source was at a very low level of bursting activity. Here, we see again the structure at around $\phi \sim 1.0$ and the sub-pulse near $\phi \sim 0.34$ that was also seen in the 2–4.5 keV band profiles of XMM-Newton and Chandra. In the higher energy bands, there are no remarkable changes in pulse shapes compared to the earlier interval, except for the fact that the structure near $\phi \sim 1.0$ is now less significant.

The last short burst from SGR 0501+4516 was observed on 2009 September 3, therefore, the profiles corresponding to the time intervals from September 6 to 24 (third column from the left in Figure 5), and from September 27 to October 14 (the rightmost column in Figure 5), are characteristic of the source’s descent to the quiescent phase. In the 2–4.5 keV band of the third column, we find a sub-pulse around $\phi \sim 0.7$ that was significantly seen in the 0.3–2 keV Chandra profile. The structures peaking at $\phi \sim 0.5$ and $\phi \sim 1.0$ are clearly seen in the 4.5–8.5 keV band, while they are marginally seen in the 8.5–14 keV range. The pulse profile of the highest energy interval only shows marginal evidence of the structure near $\phi \sim 1.0$. The 2–4.5 keV pulse profile of the rightmost column contains a single structure with a large duty cycle, broadly resembling profiles in the same band of earlier intervals. We find that the duty cycle of this pulse is significantly lower ($\sim 0.35$ of the spin phase) in the 4.5–8.5 keV energy band. The pulse profiles of the higher energy bands of this episode are consistent with random fluctuations.

Finally, we also studied the SGR 0501+4516 energy and time-resolved pulse profile evolution using the Swift/XRT observations which span a much longer time. We grouped the XRT pointings into four segments, each of which is comprised of nearly equal exposure time. The first interval corresponds to the burst active episode of the source (the leftmost column in Figure 6), the second interval starts immediately after bursting ceased (the second column from left in Figure 6), while the third and fourth intervals correspond to the quiescent state (long after the burst active phase; the observation end date is 2009 February 4). Unlike the RXTE/PCA pulse profiles in Figure 5, we plot the Swift/XRT profiles in real units since proper background subtraction is possible with the XRT data. We find that the sub-pulses seen in the low energy bands of the XMM-Newton and Chandra observations persist during the burst active episode and in the interval immediately after, but disappear during quiescence. Interestingly, the sub-pulse near $\phi \sim 0.7$ becomes remarkably prominent in the 0.3–2 keV and 2–4.5 keV ranges within days as the bursting stops. The pulse profiles of the interval of 40–65 days after the outburst onset reveal that the pulsed amplitudes in all energy ranges were significantly reduced (the third column from left in Figure 6) and sub-pulses seen in the lower energies have disappeared. During the quiescent phase (the rightmost column in Figure 6), we find further gradual decline in pulsed intensity, while similar to the previous time interval, we see only one significant pulse with duty cycle decreasing with energy.
Figure 6. Pulse profile history of SGR 0501+4516 in the energy intervals shown on the right of each horizontal panel, obtained with Swift/XRT. The labels on top of columns are the time ranges (in MM/DD format) within which the data used to construct these profiles were accumulated. Note that the year changes to 2009 at the rightmost column.

We plot in Figure 7, the energy resolved variations of the rms pulsed fractions during the burst active episode and immediately afterward in the 0.3–2 keV, 2–4.5 keV, and 4.5–8.5 keV intervals with XMM-Newton, Chandra, and Swift/XRT. In the 0.3–4.5 keV band the pulsed fraction drops to its minimum value during ongoing source bursting. The lowest energy band rms increases with time, while in the other two bands the deviation from a constant trend is less than 2.4σ.

3.2.3. Pulsed Intensity Properties

To investigate the pulsed intensity variations of SGR 0501+4516 in time and energy, we employed the rms pulsed count rate, which is not affected by background, therefore provides a measure of the pulsed intensity. We used the PCA observations since its exclusive coverage starts from soon after the onset of the source activation, continues throughout the active episode and extends well into the burst quiescent phase, while the Swift/XRT observations start after the end of the major bursting activity. We present in Figure 8 the evolution of the rms pulsed intensity in three energy intervals. We find that the pulsed intensity in the 2–4.5 keV band gradually declines while the source is actively emitting bursts, while the pulsed intensities in the 4.5–8.5 keV and 8.5–14 keV bands increase at the same time. The pulsed intensities remained constant in all energy bands for about a week following the active bursting phase and then declined. The steepness of the decline is inversely proportional to the energy range.

In Figure 9, we show the evolution of the pulsed hardness ratios, which are the ratios of the pulsed intensity in the two

\[ \text{PCR}_{\text{rms}} = \frac{1}{N} \left( \sum_{i=1}^{N} (R_i - R_{\text{ave}})^2 - \Delta R^2 \right)^{\frac{1}{2}} \] with propagated errors

\[ \delta \text{PCR}_{\text{rms}} = \frac{1}{\text{PCR}_{\text{rms}}} \left( \sum_{i=1}^{N} \left[ (R_i - R_{\text{ave}})\Delta R_i \right]^2 \right)^{\frac{1}{2}}. \]
3.3. Spectral Properties

We analyzed the X-ray spectra of SGR 0501+4516 using the XMM-Newton, Chandra/ACIS-S, and the Swift/XRT observations during and immediately after the burst active episode of the source. With respect to the longest extending observations of the Swift/XRT, we generated seven combined spectra using multiple pointings to provide statistically significant spectral parameters and close in time, to avoid blending different spectral shapes (in case of spectral evolution). We fit all spectra simultaneously with an absorbed blackbody plus power-law model by linking the interstellar absorption parameter in the 0.5–10 keV energy range. We obtained an acceptable fit to all spectra ($\chi^2$/degrees of freedom = 5086.2/4470 = 1.14) with a hydrogen column density, $N_H = (0.95 \pm 0.08) \times 10^{22}$ cm$^{-2}$. In Figure 10, we present the evolution in time of our best-fit blackbody temperature and power-law index. We find that the blackbody temperature declined very rapidly while the source was burst active, increased to a maximum value of $kT = 0.77$ keV soon after the intense bursting ceased, and then gradually decreased. The power-law component, on the other hand, became less steep during the burst active phase, and then steeper as the source went into burst quiescence.

Motivated by the rapid spectral variations (as well as by the change in rms pulsed fraction) seen in the Chandra/ACIS-S observations, we performed a phase-resolved spectral analysis of the data. As a reminder, the Chandra data cover the fourth day after the onset of the source burst activity. We divided the spin phase into 10 bins and extracted spectra for each bin. We then simultaneously fit all 10 spectra with the attenuated blackbody plus the power-law model, again by linking the interstellar absorption. We obtained a good fit to all spectra ($\chi^2$/degrees of freedom = 1909.7/1785 = 1.06) with $N_H = \ldots$

Figure 8. Time history of pulsed count rates in the 2–4.5 keV (filled circles), 4.5–8.5 keV (squares), and 8.5–14 keV (diamonds). Note that the tick mark values on the left axis correspond to the 2–4.5 keV band data, while the values on the right axis to the higher two energy bands. The vertical dashed line indicates the end of the active bursting episode of the source.

Figure 9. Time history of hardness ratios of rms pulsed intensities in the 4.5–8.5 keV to that in the 2–4.5 keV (filled circles) and in the 8.5–14 keV to that in the 2–4.5 keV (diamonds). The vertical dashed line indicates the end of active bursting episode of the source.

Figure 10. Evolution of the X-ray spectral parameters of SGR 0501+4516: blackbody temperature (diamonds) and power-law index (squares). The vertical dashed lines indicate the interval during which intense short SGR bursts were detected. Letters at the bottom of the figure indicate the instrument with which the plotted data above were obtained; X: XMM-Newton, C: Chandra, and S: Swift/XRT.
to exhibit torque noise (Woods et al. 2002); similarly, AXP 1E

1048.1

three

flux as the source entered the quiescent phase, we generated

the phase maximum.

becomes softer during the phase minimum and harder during

within errors over the whole spin phase, while the power-

law model and with the hydrogen column density linked.

We find that all three power-law indices are consistent with

the spin ephemeris of the source can be described well with a

the longest time baseline available (≈ 200 days). We find that

the spin ephemeris of the source can be described well with a

fifth-order polynomial (see Table 1) or by employing a quadratic

strain the blackbody component. We obtained a very good fit

one another, therefore, we linked them as well to better con-

straining the blackbody component. We obtained a very good fit

(χ²/degrees of freedom = 123.8/114 = 1.09) with an \( N_H =

(1.19 ± 0.22) \times 10^{22} \text{ cm}^{-2} \), a common power-law index of

5.04 ± 0.21 and blackbody temperatures of 0.78 ± 0.07 keV,

0.59 ± 0.07 keV, and 0.56 ± 0.06 keV, for the above-mentioned

two epochs, respectively. The corresponding 1–10 keV unab-

sorbed flux values were (7.0 ± 0.3) \times 10^{-12}, (6.4 ± 0.2) \times 10^{-12},

and (5.8 ± 0.2) \times 10^{-12} \text{ erg cm}^{-2} \text{ s}^{-1}.

4. DISCUSSION

4.1. Persistent Emission Properties

We determined the pulse ephemeris of SGR 0501+4516 using

the longest time baseline available (≈ 240 days). We find that

the spin ephemeris of the source can be described well with a

fifth-order polynomial (see Table 1) or by employing a quadratic

spline method including only the spin frequency and frequency

derivative (Table 2). We, therefore, argue that the recent report

of \( \dot{P} \) being the recovery of the secular spin-down (Rea et al.

2009) suggested that untwisting of the magnetic field through

the magnetosphere due to sudden crustal motion may account

for the variable or noisy spin-down behavior of these sources.

The variations seen in SGR 0501+4516 may then well be due

to a noisy spin-down of the source.

We estimate the inferred dipole magnetic field strength of

SGR 0501+4516 as \( B_0 \approx 2 \times 10^{14} \text{ G} \), assuming that the

neutron star slows down via magnetic braking. This value is very

similar to the inferred field strength of the recently discovered

SGR J1833−0832 (Göğüş et al. 2010) and lies near the lower end

of the inferred magnetic fields of SGRs. The characteristic

age (\( P/2 \dot{P} \)) of SGR 0501+4516 is estimated to be 15.7 kyr.

We find the energy and time dependence of the pulse

profiles of SGR 0501+4516, during its burst active episode and

soon afterward, intriguing. During the burst active phase, the

∼ 4.5 keV pulse profiles are smooth while those in the lower

energy bands show significant sub-pulses. In particular, there

are at least four sub-pulses between 0.3 and 2 keV, indicating

that there are significant intensity variations over the spin

phase. The most significant sub-pulse peaks near \( \phi \sim 0.34

\) and lasts about 0.72 s, which corresponds to \( \sim 1/8 \) of the spin

period.

The energy dependence of the pulse profile extends to the

higher energies; the pulsations are clearly seen up to 40 keV

following the onset of the outburst. The significant peak in the

14–40 keV band near \( \phi \sim 1.0 \) is weaker in the 8.5–14 keV range

and not seen in the lower energy bands. This hard component

fades away within a few weeks after the burst activity onset.

Rea et al. (2009) and Enoto et al. (2010) deduce the same decay

behavior using INTEGRAL and Suzaku/HXD observations,

respectively. A similar trend is also seen in the post-outburst

pulse profiles of SGR J0418+5716 (P. M. Woods et al. 2011, in

preparation). This fact may (indirectly) indicate the existence of

heating of the neutron star crust as a result of crustal fracturing

(Thompson & Duncan 1996).

We find that the pulsed fraction significantly increases with

energy after a large drop in the 2–4.5 keV band near the end of

the bursting episode. This trend is noteworthy but should be

taken with caution since inter-instrument calibration may play

a role as we discuss below.
SGR 0501+4516 went through significant spectral variations both during the bursting phase and throughout the quiescent phase, when no more SGR events were seen. We find that the spectrum of the source was hardening during the active period (see also Rea et al. 2009). According to the magnetar scenario, this is a natural outcome of surface fracturing at a wide range of scales: sufficiently large-scale crustal fracturing would lead to highly energetic short bursts (Thompson & Duncan 1996) while smaller scale fracturing may contribute to the persistent X-ray emission of the source (Thompson & Duncan 1995). During the post-outburst episode, the spectrum of SGR 0501+4516 remained constant for about a week and softened thereafter. This is also expected in the magnetar model as the heated stellar crust cools down (Güver et al. 2007).

The significant phase-resolved spectral variations near the end of the burst active phase seen with Chandra are very interesting. We showed that the blackbody temperature remains constant over the spin phase, while the power-law component gets shallower (harder) with increasing X-ray intensity. Since the peak interval of the pulse phase would dominate the phase-averaged spectrum, it is possible to “hide” a shallow power-law trend. On the other hand, the sharp drop in the blackbody temperature during the burst active phase and then its rapid rise in a day is indeed puzzling. Since this behavior was only seen with the Chandra data, there is no way to confirm these results with other contemporaneous observations.

Finally, we find that the flux in the 1–10 keV range measured with Swift/XRT between 412 and 546 days after the onset of the 2008 outburst, follows a marginal decline from \(7 \times 10^{-12}\) erg cm\(^{-2}\) s\(^{-1}\) to about \(6 \times 10^{-12}\) erg cm\(^{-2}\) s\(^{-1}\). It is interesting to note that the source flux in the same energy range at about 100 days after the onset was around \(6–7 \times 10^{-12}\) erg cm\(^{-2}\) s\(^{-1}\) (see Figure 11 of Rea et al. 2009). Therefore, the source flux likely remained constant over a year following a steady decrease over the first 100 days after activation.

4.2. Archival Outburst Episodes of SGR 0501+4516

On 1993 July 25, the Burst And Transient Source Experiment (BATSE) onboard the Compton Gamma Ray Observatory triggered on two peculiar events: at 17:45:21 UT (BATSE trigger number 2463) and at 23:32:37 UT (BATSE trigger number 2464). In Figure 12, we present BATSE Large Area Detector (LAD) light curves of these two events in the four LAD discriminator energy intervals. These two bursts were both short (\(T_0 = 0.064\) s and \(0.048\) s, respectively), had soft spectra, and their locations were consistent with one another (R.A., decl. = \(05^h09^m12^s\), \(43^\circ48’00”\), error radius of \(5’\), and \(04^h42’00”\), \(44^\circ12’00”\), error radius of \(6’2\), respectively). Note that the Chandra position of SGR 0501+4516 falls well within the overlap of these two error circles. Given the soft nature of these events, their short durations and the fact that they originated from the same region of the sky within about 5.8 hr apart, it is strongly suggestive that these events are from SGR 0501+4516. Our search for untriggered events using the continuous BATSE DISCLA data (see Göğüş et al. 1999 for the methodology) for 10 days starting on 1993 July 20, resulted in no additional events from the source. Therefore, we conclude that SGR 0501+4516 was indeed burst active back in July 1993 for a very brief period.

Furthermore, the GRBM onboard the BeppoSAX satellite recorded a short burst (\(T_0 = 0.77\) s) on 2000 October 11 at 10:06:49 UT (GRB 001011A) from R.A. = \(04^h28^m\), decl. = \(53^\circ\) (with a positional uncertainty of \(34^\circ\)) that includes the position of SGR 0501+4516 (Frontera et al. 2009). Even though the spectrum of the GRBM burst is not very soft, there is another short duration event from the same direction about 95 s after the GRBM trigger. It is, therefore, suggestive that the source of these bursts is SGR 0501+4516 since they were positionally coincident, they were short and they repeated. Note, however, that the large error circle of GRBM also included another recently discovered magnetar source, SGR J0418+5729 (van der Horst et al. 2010).

With the definite active episodes in 1993 and 2008, and a third possible one in 2000 we can infer that SGR 0501+4516 is going through burst active phases on a timescale of \(\sim 10\) years. This timescale is similar to that of SGR 1627–41 which was discovered in 1998 during about a week-long burst active episode (Kouveliotou et al. 1998; Woods et al. 1999) and exhibited a burst active epoch again in 2008 (Esposito et al. 2008). The two recently discovered SGRs (SGR J0418+5729 and SGR J1833–0832) have emitted only a few bursts during their very brief active episodes (van der Horst et al. 2010; Göğüş et al. 2010) and their outburst recurrence behaviors may characteristically be different from SGR 0501+4516 and SGR 1627–41.

4.3. On the Association with Supernova Remnant, G160.9+2.6

Gaensler & Chatterjee (2008) compared the position of SGR 0501+4516 with the locations (Green 2009) of known Galactic supernova remnants (SNRs), and reported that the magnetar sits just outside the south-eastern rim of the well-known SNR G160.9+2.6 (also known as HB9; Hanbury & Hazard 1953; Leahy & Tian 2007).

All of the four initially identified SGRs (1806–20, 0526–66, 1900+14, 1627–41) were originally claimed to sit near but outside SNRs (Cline et al. 1982; Atteia et al. 1987; Hurley et al. 1999, 2000). If the SNR and neutron star in these...
cases are physically associated and hence formed in the same supernova explosion, the large angular offsets of the SGR positions from the respective SNRs require high space velocities of thousands of km s\(^{-1}\). Indeed, it was hypothesized that magnetars received large kicks through magnetic field-driven mechanisms that were ineffective for ordinary pulsars (Duncan & Thompson 1992). However, in three of the four cases the density of SNRs on the sky in that region is sufficiently high that a chance projection between SGR and SNR cannot be ruled out, while for SGR 1806–20, the classification of the extended nebula as an SNR is now thought to have been erroneous (Gaensler et al. 2001). Recently, Esposito et al. (2008) reported the detection of diffuse soft X-ray emission around SGR 1627–41 and interpreted it as emission from the SNR G337.00.1. Meanwhile, direct measurements of magnetar proper motions imply much lower velocities than inferred by these offsets (Helfand et al. 2007; Kaplan et al. 2009), compatible with the velocities observed for radio pulsars (Arzoumanian et al. 2002; Hobbs et al. 2005; Chatterjee et al. 2009).

Assuming that the progenitor supernova explosion occurred at the geometric center of the SNR, the SGR has traveled approximately 80 arcmin from its birthplace over its lifetime. For a distance to the SNR of 800 ± 400 pc and an estimated age of 4000–7000 years (Leahy & Tian 2007), the implied projected space velocity for the SGR is 1300–6800 km s\(^{-1}\). As for the previous claimed SGR/SNR associations mentioned above, this is at or beyond the highest directly observed velocity observed for any other neutron star (cf. Chatterjee et al. 2005; Winkler & Petre 2007). However, the proximity of this SNR allows a direct test: independent of distance or projection angle, if the SNR and SGR are physically associated, then the predicted proper motion of the SGR will be approximately 0′.7–1′2 yr\(^{-1}\) to the south, which should be measurable with the Chandra X-ray Observatory over even a relatively short time baseline. Confirming more associations would force a reconsideration of currently disfavored SGR–SNR associations and of the highest velocities that neutron stars can attain.

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