Suzaku Discovery of a Hard X-Ray Tail in the Persistent Spectra from the Magnetar 1E 1547.0–5408 during its 2009 Activity

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Abstract

The fastest-rotating magnetar 1E 1547.0–5408 was observed in broad-band X-rays with Suzaku for 33 ks on 2009 January 28–29, 7 d after the onset of its latest bursting activity. After removing burst events, the absorption-corrected 2–10 keV flux of the persistent emission was measured with the XIS as $5.7 \times 10^{-11}$ erg cm$^{-2}$ s$^{-1}$, which is 1–2 orders of magnitude higher than was measured in 2006 and 2007 when the source was less active. This persistent emission was also detected significantly with the HXD in > 10 keV up to at least ~ 110 keV, with an even higher flux of $1.3 \times 10^{-10}$ erg cm$^{-2}$ s$^{-1}$ in 20–100 keV. The pulsation was detected at least up to 70 keV for a period of 2.072135 ± 0.00005 s, with a deeper modulation than was measured in a fainter state. The phase-averaged 0.7–114 keV spectrum was reproduced by an absorbed blackbody emission with a temperature of 0.65 ± 0.02 keV, plus a hard power-law with a photon index of ~ 1.5. At a distance of 9 kpc, the bolometric luminosity of the blackbody and the 2–100 keV luminosity of the hard power-law are estimated to be $(6.2 \pm 1.2) \times 10^{35}$ erg s$^{-1}$ and $1.9 \times 10^{36}$ erg s$^{-1}$, respectively, while the blackbody radius becomes ~ 5 km. Although the source has not been detected significantly in hard X-rays during the past fainter states, a comparison of the present and past spectra at energies below 10 keV suggests that the hard component is more enhanced than the soft X-ray component during the period of persistent activity.

Key words: stars: magnetic fields — X-rays: individual (1E 1547.0–5408) — X-rays: stars

1. Introduction

Luminous neutron stars can be classified into three categories from their dominant energy sources: rotation-powered, accretion-powered, and magnetic-powered objects. The 1st and 2nd groups are represented by radio pulsars and mass-accreting neutron-star binaries, respectively. The last category is comprised of those objects that are called magnetars (Duncan & Thompson 1992; Thompson & Duncan 1995, 1996), mainly observed in X-rays. Magnetars have rotation periods of $P = 2$–12 s and period derivatives of $\dot{P} \sim 10^{-11}$ s$^{-1}$ (Woods & Thompson 2006; Mereghetti 2008). Their slow rotations cannot afford their high soft X-ray luminosities, ~ $10^{35}$ erg s$^{-1}$, nor are they accretion-powered objects, since they lack evidence of companion stars (e.g., Koyama et al. 1989). Further, considering their bursting activity and strong surface magnetic fields (> $4.4 \times 10^{13}$ G), evaluated from their $P$ and $\dot{P}$ values, the energy source of magnetars is considered to be their strong magnetic fields. Their X-ray luminosities, which generally exceed their spin-down energy losses, can be explained by assuming that their magnetic energies are released faster than their rotational energies.

Currently, about 5 Soft Gamma-ray Repeaters (SGR) and about 10 Anomalous X-ray Pulsars (AXP) are known as magnetars.1 The former objects sometimes emit giant flares with peak luminosities of up to $10^{46}$ erg s$^{-1}$, while the latter were discovered by their bright soft X-ray (≤ 10 keV) emission with luminosities of $(0.1$–1$) \times 10^{35}$ erg s$^{-1}$. Recent studies suggest that SGRs and AXPs are essentially the same class of objects, and their distinction is not fundamental (Mereghetti et al. 2009b); i.e., these names reflect mainly their ways of discovery.

One distinguishing property of magnetars, observed not only from SGRs (Israel et al. 2008; Enoto et al. 2009), but also from AXPs (Gavriil et al. 2002; Kaspi et al. 2003), is occasional periods of high activity wherein numerous “bursts” are emitted. These bursts individually have a typical duration of

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1 (http://www.physics.mcgill.ca/pulsar/magnetar/main.html).
a few hundred milliseconds and an energy release of $\gtrsim 10^{37}$ erg. They are thought to represent a sudden release of magnetic energy, leading to the production of hot plasmas and/or energetic particles somewhere in the system.

Bright persistent soft X-rays have long been observed from magnetars at energies below $\sim 10$ keV. Empirically, these spectra have been fitted by a two-blackbody model or a blackbody (of temperature $kT \sim 0.3$–$0.6$ keV) plus a soft power-law (of photon index $\Gamma = 2$–$4$) model, where the power-law is thought to arise via some sort of Compton process (Thompson et al. 2002; Rea et al. 2009).

Recently, INTEGRAL discovered from several magnetars a new emission component (Kuiper et al. 2004, 2006; Götz et al. 2006). Becoming prominent at energies above $\sim 10$ keV, this component exhibits a high pulsed fraction (sometimes $\sim 100\%$ at $\sim 100$ keV), and extends to $\sim 100$ keV or more with a surprisingly hard photon index of $\Gamma \sim 1$. Although this discovery aroused wide interest, the origin of this hard X-ray component is still an open question (e.g., Heyl & Hernquist 2005; Beloborodov & Thompson 2007; Baring & Harding 2007).

So far, the hard tail has been detected from three SGRs (SGR 1900+14, SGR 1806–20, and SGR 0501+4516; e.g., Götz et al. 2006; Esposito et al. 2007; Rea et al. 2009) and three AXPs (4U 0142+61, 1RXS J170849.0–400910, and 1E 1841–045; e.g., Kuiper et al. 2004, 2006). While some detections from SGRs were made in their burst-active states, those from AXPs are limited to their quiescent periods. When attempting to answer these questions, Suzaku (Mitsuda et al. 2007) provides a great advantage, because it allows us to simultaneously detect the two spectral components of these objects in rather short exposures.

The X-ray source 1E 1547.0–5408 was discovered by the Einstein Observatory in 1980 (Lamb & Markert 1981), and was suggested by recent X-ray observations to be a magnetar candidate associated with a young supernova remnant G327.24–0.13 (Gelfand & Gaensler 2007). Subsequent radio observations discovered pulsations with $P = 2.069$ s and $\dot{P} = (2.318 \pm 0.005) \times 10^{-11}$. This established 1E 1547.0–5408 as the fastest rotating magnetar to date, with a surface field strength of $2.2 \times 10^{14}$ G, a characteristic age of 1.4 kyr, and a spin-down luminosity of $1.0 \times 10^{35}$ erg s$^{-1}$, all estimated from the measured $P$ and $\dot{P}$ (Camilo et al. 2007). The radio observation also gave a distance estimate of 9 kpc from its dispersion measure, and identified 1E 1547.0–5408 as the second example of transient radio magnetars after XTE J1810–197 (Camilo et al. 2006). Since then, X-ray monitoring observations detected a possible X-ray outburst in 2007 (Halpern et al. 2008). The X-ray pulsation, which was not confirmed in quiescence (Gelfand & Gaensler 2007), was first detected with XMM-Newton during the period of this enhanced activity (Halpern et al. 2008).

Following a possible precursor phase in 2008 October (Krimm et al. 2008a, 2008b), the Swift Burst Alert Telescope detected bursting activity from 1E 1547.0–5408 on 2009 January 22 (Gronwall et al. 2009). Large numbers of short bursts were recorded by several X-ray satellites, including INTEGRAL (Savchenko et al. 2009; Mereghetti et al. 2009a), Fermi (Connaughton & Briggs 2009), Konus-Wind (Golenetskii et al. 2009), and RHESSI (Bellm et al. 2009). The Wide-band All-sky Monitor (WAM) on board Suzaku also recorded $\sim 250$ short bursts on January 22 (Terada et al. 2009). Based on this information, a Suzaku Target-of-Opportunity (ToO) observation was conducted on January 28. In the present paper, we report on the result of this observation, focussing on wide-band spectra of the persistent emission. Analysis of short bursts will be reported elsewhere.

2. Observation

The present ToO observation of 1E 1547.0–5408 was carried out with Suzaku from 2009 January 28 21:34 (UT), to January 29 21:32 (UT), with a gross duration of $\sim 86$ ks. This was 7 d after the onset of its latest strong bursting activity on January 22 (Gronwall et al. 2009). The Suzaku observation overlapped with those by INTEGRAL, RXTE, Swift, and Chandra.

Two out of the three operating cameras of the X-ray Imaging Spectrometer (XIS: Koyama et al. 2007), XIS 1 (a back-illuminated or BI CCD) and XIS 3 (a front-illuminated or FI CCD), were operated incorporating a 1/4 window option to ensure a time resolution of 2 s. A burst option was also employed to avoid possible photon pile-up problems, with its exposure being reduced to 1/4 (i.e., 0.5 s exposure and 1.5 s artificial dead-time), although the actual persistent flux of 1E 1547.0–5408 was not enough to allow operation without this option. The other one, XIS 0, was operated in the timing mode (P-sum mode), which provided a $\sim 7.8$ ms time resolution, together with only one-dimensionally projected position information.

The Hard X-ray Detector (HXD: Takahashi et al. 2007) was operated in the standard mode, wherein individual events were recorded with a time resolution of 61 $\mu$s. The target was placed at the “HXD nominal” position.

3. Data Reduction

Using version 6.6.2 HEADAS software, we analyzed the Suzaku data of 1E 1547.0–5408 (OBSID = 903006010) prepared through version 2.3.12.5 processing. Events were discarded if they were acquired in the South Atlantic Anomaly (SAA) or in regions of low-cutoff rigidity ($\leq 6$ GV for the XIS and $\leq 8$ GV for the HXD), or with low Earth elevation angles (ELV $< 5^\circ$). The net exposures for XIS 0, XIS 1, XIS 3, and the HXD were 42.6 ks, 10.6 ks, 10.7 ks, and 33.5 ks, respectively. The reduced exposures of XIS 1 and XIS 3 are due to the burst option (section 2).

3.1. XIS Data Reduction

For our spectroscopic studies, we used the data from XIS 1 and XIS 3, which were acquired in the normal imaging mode. The source was detected clearly in the XIS images. On-source XIS 1 and XIS 3 events were extracted from a region of 2$^\prime$ in radius, centered on the source centroid. Background events were derived from a similar region where is as far away from the source as possible. After subtracting this background, we detected 1E 1547.0–5408 at a burst-inclusive 2–10 keV
average count rate as given in table 1. The higher XIS 3 rate is due to a relatively hard spectrum and a strong absorption (subsection 4.2), coupled with a more high-band-enhanced efficiency of FI CCDs than that of a BI chip.

The data from XIS 0, taken in the timing mode, were used in our timing analyses. We applied some additional corrections to the XIS 0 data. Namely, we further filtered the cleaned event file using a selection criteria as \((\text{GRADE}==0) \lor (\text{GRADE}==1) \lor (\text{GRADE}==2)\), and eliminated hot pixels and flickering ones. In addition, we shifted nominal time assignments of the XIS 0 events by \(-60\) ms (i.e., \(\text{TIME} - 0.06\) s), to take into account the following two effects. One is the read-out time lag when a target is placed at the HXD nominal position (Koyama et al. 2007). The other is a \(30 \pm 16\) ms offset of the absolute timing of the XIS data acquired in the P-sum mode (Matsuda et al. 2009). This offset was measured by observing the Crab pulsar and Her X-1, and comparing the results with simultaneous HXD data of which the relative and absolute timing accuracies had already been verified (Terada et al. 2008). These observations of the two pulsars also confirmed the relative timing accuracy of the XIS.

### 3.2. HXD-PIN Data Reduction

From the HXD-PIN data, we subtracted an estimated non-X-ray background (NXB), which was produced by the “tuned” (LCFITDT) NXB model (Fukazawa et al. 2009). In order to assess the accuracy of the background modeling, we compared its prediction with an Earth-occulted portion of the data with 14 ks exposure, because these data are considered to consist solely of the NXB. Two of these spectra are compared in figure 1. On average, the simulated background was found to fall below the actual Earth-occultation data by 2.3% in the 15–70 keV range. The discrepancy is relatively large (13.0%) in the 40–50 keV range, presumably because this band is affected by instrumental Gd-K lines (42.3 keV, 43.0 keV, 48.6 keV, and 50 keV). However, if the 40–50 keV range is ignored, the data versus model difference reduces to only 1.0%. Therefore, we consider the HXD-PIN NXB modeling to be appropriate, and assign it a systematic error of 2.0% after Fukazawa et al. (2009).

From the HXD-PIN data, we also subtracted an unexpected contribution from the Cosmic X-ray Background (CXB). This was calculated by using a recent result from Moretti et al. (2009), which describes the CXB photon number spectrum as

\[
\frac{C \cdot \Omega}{(E/E_0)^{\Gamma_1} + (E/E_0)^{\Gamma_2}} \text{ photons s}^{-1} \text{ cm}^{-2} \text{ keV}^{-1}.
\]

Here, \(C = 1.33 \times 10^{-4}\) a normalization, \(E_0 = 29\) keV a characteristic energy, \(\Gamma_1 = 1.40\) and \(\Gamma_2 = 2.88\) photon indices, and \(\Omega = 1.2 \times 10^{-3}\) ster the solid angle of an assumed \(2^\circ \times 2^\circ\) emission region with uniform brightness, corresponding to the HXD-PIN “flat” response. The CXB counts are subject to \(\sim 11\%\) sky-to-sky fluctuations (Fukazawa et al. 2009). The average CXB flux corresponds to \(\sim 5\%\) of PIN-NXB.

Since 1E 1547.0–5408 is located on the Galactic plane at Galactic coordinates of \((l,b) = (−32.8^\circ, −0.1^\circ)\), Galactic Ridge X-ray Emission (GRXE) may contaminate the data as well. INTEGRAL mapping observations showed that the typical 17–60 keV GRXE flux is less than \(1 \times 10^{-9}\) erg s\(^{-1}\) cm\(^{-2}\) within an IBIS FOV, on the Galactic plane at \(|l| > 20^\circ\) (figure 13 of Krivonos et al. 2007). Within the HXD-PIN FOV, we then expect a flux of \(\lesssim 2 \times 10^{-11}\) erg s\(^{-1}\) cm\(^{-2}\), which is less than \(\sim 1\%\) of NXB or \(\sim 20\%\) of CXB. This estimate is also supported by a near-by blank sky observation (OBSID = 501043010) at \((l,b) = (−29.6^\circ, −0.38^\circ)\), 3^\circ/2

| Detector          | Energy (keV) | Background-inclusive | Background-subtracted | Burst-removed |
|-------------------|--------------|----------------------|-----------------------|--------------|
| XIS 1*            | 2–10         | 1.44 ± 0.01          | 1.40 ± 0.01           | 1.34 ± 0.01  |
| XIS 3*            | 2–10         | 1.64 ± 0.01          | 1.61 ± 0.01           | 1.53 ± 0.01  |
| HXD-PIN*          | 15–70        | 0.528 ± 0.004        | 0.174 ± 0.004         | 0.168 ± 0.004|
| HXD-GSO†          | 50–114       | 9.40 ± 0.06          | 0.151 ± 0.064         | 0.148 ± 0.064|
| HXD-GSO‡          | 114–578      | 27.01 ± 0.19         | 0.030 ± 0.192         | 0.028 ± 0.192|

* Counts s\(^{-1}\) with statistical (1σ) errors.
† Counts s\(^{-1}\), with statistical (1σ) and systematic errors.
off 1E 1547.0–5408; after subtracting the nominal NXB and CXB, the GRXE contribution in the 12–70 keV band was \( \sim 30\% \) of the average CXB. Therefore, the GRXE contribution in the HXD-PIN data is negligible.

As summarized in table 1, we were left with positive signals of \( \sim 0.174 \pm 0.004 \text{cts s}^{-1} \) in the 15–70 keV HXD-PIN band, when both the NXB and CXB were subtracted. Thus, the signal detection is highly significant in the HXD-PIN data, because the systematic error (2.0\%) is estimated to be \( \sim 7 \times 10^{-3} \text{cts s}^{-1} \) in the same band.

### 3.3. HXD-GSO Data Reduction

The simulated background of HXD-GSO, also produced by the “tuned” model, was evaluated again by the Earth-occulted data. As shown in figure 1, the simulated background systematically underpredicted the actual Earth-occulted HXD-GSO data by 0.53\% in the 50–114 keV band and 1.4\% in the 115–578 keV band. Conservatively, we hence subtracted the HXD-GSO background after increasing it by 0.53\% and 1.4\% over the above ranges, and added systematic uncertainties of 0.60\% and 0.59\% therein (Fukazawa et al. 2009).

After we subtracted the NXB and took into account the above systematic errors, the HXD-GSO signal count rate became as given in table 1. Therefore, the signal has an overall significance of \( \sim 2.3 \sigma \) in the 50–114 keV range, but is insignificant in higher energies.

### 3.4. Elimination of Burst Events

Figure 2 shows a dead-time corrected and background-subtracted XIS 1 + XIS 3 light curve in the 2–10 keV range. There, a number of short burst events can be noticed as sharp spikes. By visually inspecting this XIS 1 + XIS 3 light curve and that of HXD-PIN (15–70 keV), produced with a bin width of 2 s (one frame) and with 1 s, respectively, we identified 13 prominent burst candidates. Some of them were detected by both instruments, while the others by either of them. Then, the XIS and HXD data acquired within 3 s time intervals both before and after each of these bursts were discarded.

After this burst elimination, the background-subtracted average count rates of XIS, XIS 3, and HXD-PIN became as given in table 1. Although the remaining data must still contain smaller bursts, their summed contribution is estimated to be not more than 0.1\%.

### 3.5. Contaminating Sources

During the Suzaku observation, the 10–30 keV HXD-PIN signal intensity, after subtracting the NXB and CXB, was \( \sim 10 \text{mCrab} \). According to the INTEGRAL General Reference Catalog (gref_cat_0030.fits), the HXD-PIN full FOV (\( \sim 34' \times 34' \)) contained 4 contaminating source candidates detected with ASCA (Sugizaki et al. 2001). Their 10–30 keV intensities (using JEM-X) — 0.01 mCrab of AX J1550.5–5408, 0.26 mCrab of AX J1549.8–5416, 0.01 mCrab of AX J1553.5–5347, and 0.41 mCrab of AX J1549.0–5420 — sum up to \( < 10\% \) of the signal from the 1E 1547.0–5408 field. Although these may be variable X-ray sources, AX J1550.5–5408 was not detected either with the XIS, nor in a 3–10 keV Swift/XRT image obtained on 2009 January 29. The Swift/XRT count rate of AX J1549.8–5416 was \( \leq 0.01 \) times that of 1E 1547.0–5408 on that occasion. In addition, AX J1553.5–5347 and AX J1549.0–5420 were located outside the FWHM FOV of HXD-PIN, with their aperture transmissions of \( \leq 10\% \) and \( \leq 50\% \), respectively. Further considering the lack of reports on X-ray brightening from none of these sources, we regard their contamination as negligible. This assumption is further confirmed in subsection 4.2.

As summarized in table 2, the 4° × 4° HXD-GSO FOV (and outside that of HXD-PIN) contains 5 sources with 20–60 keV intensities of \( > 3 \text{mCrab} \). Since they are also variable X-ray sources, we examined the RXTE/ASM(All Sky Monitor) quick-look data (Jahoda et al. 1996) for their intensities over a 10 d period around our Suzaku observation. All of them were found, during this period, to be \( < 20 \text{mCrab} \) in the 2–10 keV range. When we assume spectral shapes from the INTEGRAL General Reference Catalog and normalizations of the ASM monitoring, their 50–200 keV intensities are estimated to be less than \( \sim 0.01\% \) level of the HXD-GSO NXB. Therefore, we can also ignore the source confusion within the HXD-GSO FOV. From these examinations, we regard the burst-removed signals detected with HXD-GSO (below 114 keV), given in the last column of table 1, as coming also from 1E 1547.0–5408, itself.
Table 2. Contaminating source candidates.*

| Name       | Type   | Intensity | Flux   |
|------------|--------|-----------|--------|
| 1H 1538–522| HMXB   | 9.8 mCrab | $\sim 1 \times 10^{-5}$ |
| H 1608–522 | LMXB   | 19 mCrab  | $\sim 8 \times 10^{-5}$ |
| XTE J1550–564| LMXB | 12 mCrab  | $\sim 2 \times 10^{-4}$ |
| XTE J1543–568| HMXB | 0.23 mCrab | $\sim 4 \times 10^{-4}$ |
| Cir X-1    | LMXB   | < 0.1 mCrab | $< 5 \times 10^{-7}$ |

* Source within the FOV of HXD-GSO with > 1 mCrab in the 20–60 keV range, from the INTEGRAL General Reference Catalog.
† Average 2–10 keV intensity, measured by the RXTE/ASM, over a 10 d period around the Suzaku observation.
‡ Predicted flux (photons s$^{-1}$ cm$^{-2}$) of HXD-GSO, using spectral parameters in the INTEGRAL General Reference Catalog, and normalized by the ASM intensities. The angular transmission of the HXD-GSO FOV is not considered.

**Fig. 3.** Periodograms derived with an epoch-folding analysis from the 2–10 keV XIS P-sum mode data (panel a) and the background-inclusive 12–70 keV HXD-PIN data (panel b). The number of phase bins per period is indicated by 13 for the XIS and 15 for the HXD-PIN. Typical chance probabilities are horizontal lines. Subpeaks at 2.0717 s and 2.0725 s in the upper panel correspond to beats with half of the spacecraft orbital period (≈ 45 min).

4. Data Analysis and Result

4.1. Pulsation

After eliminating the 13 burst candidates, we converted all of the XIS 0 and HXD event arrival times to those measured at the solar-system barycenter, using a source position of ($\alpha, \delta)_{2000.0} = (15^h50^m54^s11, -54^\circ18'23.7")$ and the spacecraft orbital information. Then, via the standard epoch-folding technique, we searched the 2–10 keV XIS P-sum data and the 12–70 keV HXD-PIN data for the known 2.0 s X-ray period (Halpern et al. 2008). The analysis was performed over a trial period ranging from 2.0713 to 2.0730 s, with a step of $4 \times 10^{-6}$ s, which corresponds to a change of 0.08 cycle over a span of $\sim 86$ ks. The derived periodograms are shown in figure 3. A significant ($\chi^2/\nu = 141.1/14$ for the XIS P-sum data, and $\chi^2/\nu = 41.8/12$ for the HXD-PIN data) periodicity was found at a consistent period of

$$P = 2.072135 \pm 0.00005 \, s,$$

as of epoch 54859 (MJD). The analysis employed a period derivate of $\dot{P} = 2.35 \times 10^{-11} \, s^{-1}$, from multisatellite timing observations of 1E 1547.0–5408 (G. L. Israel, private communication) which covers our Suzaku observation epoch. We use equation (2) and $\dot{P} = 2.35 \times 10^{-11} \, s^{-1}$ for our subsequent timing analyses.

Figure 4 shows energy-sorted pulse profiles derived from XIS 0, HXD-PIN, and HXD-GSO, folded at equation (2). The null hypothesis probabilities of the pulse detection in the 1–3 keV (XIS 0), 3–10 keV (XIS 0), 10–25 (HXD-PIN), 25–70 (HXD-PIN), and 50–114 keV (HXD-GSO) energy bands are $< 1 \times 10^{-4}$, $< 1 \times 10^{-4}$, $3 \times 10^{-4}$, 0.06, and 0.47, respectively. Therefore, the pulsations are significant in the XIS and the low-energy ($\lesssim 25$ keV) HXD-PIN data with $> 3$ sigma, although they are inconclusive in the high-energy HXD-PIN band and...
insignificant in the HXD-GSO data. The HXD-PIN data were further analyzed with the Z-squared tests (Buccheri et al. 1983; Brazier 1994). Then, the 10–25 keV and 25–70 keV HXD-PIN data yielded $Z_{N}^{2} = 19.7$ (the total event number being $N \approx 1.7 \times 10^5$) and $12.7$ ($N \approx 6.5 \times 10^5$), which correspond to null hypothesis probabilities of $6 \times 10^{-4}$ and 0.013, respectively. In other words, the high-energy (25–70 keV) HXD-PIN data are modulated, with the $\sim 99\%$ confidence, at the same period as the lower-energy photons, even though the $\chi^2$ significance is not high enough. Therefore, we discuss the 25–70 keV pulse profile as well.

As shown in figure 4 and reported before (Halpern et al. 2008), the pulse profiles of this object are relatively shallow. The peak-to-peak pulsed fraction, defined as $(F_{\text{max}} - F_{\text{min}})/(F_{\text{max}} + F_{\text{min}})$, is presented in figure 5 as a function of the photon energy. Here, $F_{\text{max}}$ and $F_{\text{min}}$ are the maximum and minimum background-subtracted count rates across the pulse phase, respectively. Error bars include Poisson fluctuations and the systematic uncertainties of the NXB. Although the pulsed fraction tends to increase with energy as observed in some magnetars (Kuiper et al. 2006), the dependence is insignificant, judging from the errors.

4.2. Persistent Phase-Averaged Spectrum

Figure 6a shows time-averaged and dead-time-corrected spectra of the persistent emission from 1E 1547.0–5408, derived over a broad energy band with XIS 1, XIS 3, HXD-PIN, and HXD-GSO. The data accumulation and the background subtraction were carried out as described in subsections 3.1, 3.2, and 3.3. The 13 burst events were excluded (subsection 3.4). In addition, as described in subsections 3.3, the 0.6% systematic errors were assigned to the HXD-GSO data, while the 2.0% systematic error in the HXD-PIN NXB (subsection 3.2) is separately considered later. From the fact that figure 4e is in agreement with the results in subsection 3.3, the hard X-ray signals were detected with HXD-GSO at least up to 114 keV with a $2.3\sigma$ level. This significance increases to a level of $>3\sigma$ when the upper bound energy is lowered to 70 keV of HXD-PIN.

Since the small pulsed fractions (figure 5) and the short exposure (33 ks with the HXD) make it difficult to perform detailed phase-resolved spectroscopy, hereafter we analyze only these phase-averaged spectra. The analysis utilized xspec version 12.5, with the HXD response matrices version 2009-04-03, and the XIS response matrices created by using xissimarfgen and xismfgen.

As clearly revealed in figure 6c in an unfolded source spectrum ($\nu F_{\nu}$ form), the detected HXD-PIN and HXD-GSO signals show a prominent hard component above 10 keV, just like in some other magnetars (e.g., Kuiper et al. 2006). This provides the first detection of such a hard spectral component from this magnetar. In deriving figure 6c, the cross-normalization factor of HXD-PIN relative to the XIS was fixed at 1.181 after Y. Maeda et al. (2008). Since the XIS and the HXD-PIN spectra thus are connected smoothly with each other, the HXD-PIN signals are unlikely to be contaminated by other sources that are inside the HXD-PIN FOV and outside that of the XIS. Any signal from such contaminants is estimated to be $\lesssim 24\%$ at 15 keV of the HXD-PIN spectrum. This level would be much lower in harder energies, if we consider that such sources, as most likely low-mass neutron-star binaries (Sugizaki et al. 2001), should exhibit softer spectra than the observed spectrum.

In order to approximately characterize this hard component, we fitted the 15–70 keV HXD-PIN data (figure 6a) with a single power-law model. The fit was successful with $\chi^2/\text{d.o.f} = 30.4/31 = 0.98$, and yielded a photon index of $\Gamma = 1.41_{-0.16}^{+0.17}$ (statistical) $\pm 0.04$ (systematic), and a 15–70 keV flux of $F_{\nu} = [1.38_{-0.12}^{+0.22} (\text{statistical}) \pm 0.09 (\text{systematic})] \times 10^{-10} \text{erg s}^{-1} \text{cm}^{-2}$. Here, the systematic errors were estimated by increasing or decreasing the PIN-NXB by 2% (subsection 3.2). The result implies that the hard component is rather featureless.

Next, we included the XIS 1, XIS 3, and HXD-GSO spectra in the HXD-PIN. The absorbing column density, $N_{\text{H}}$, is allowed to vary. Then, as shown in figure 6 and table 3, the entire 0.7–114 keV spectra were successfully fitted by adding a blackbody with a temperature $kT = 0.65$ keV to the flat power-law which was found with the HXD-PIN data. Hereafter, we call this “blackbody+power-law” modeling Model A. While the errors in table 3 are statistical only, the inclusion of the HXD-PIN systematic errors affected $\Gamma$ by $\pm 0.02$, and the 20–100 keV flux by $\pm 8\%$. The fit is reproduced in figure 6c in an unfolded source spectrum ($\nu F_{\nu}$ form).

Although Model A gave an acceptable result, we tried to replace the backbody component, accounting for the soft signals, with a Comptonized blackbody model. This is because a soft power-law tail with $\Gamma = 2–4$, that is suggestive of Comptonization, often emerges in the soft X-ray ($< 10$ keV) spectra of magnetars (Meremeghi 2008). In order to take into account this effect, we constructed a simple formalism of the Comptonized blackbody radiation model (Rybicki & Lightman 1979; Tiengo et al. 2005; Halpern et al. 2008), which is thoroughly described in the Appendix. At high energies this model approaches a power-law form with a steep photon index, $\Gamma_{\text{comp}}$, but it is free from an infrared divergence.

\begin{figure}[htp]
\centering
\includegraphics[width=0.5\textwidth]{fig5.png}
\caption{Pulsed fraction shown as a function of energy.}
\end{figure}
Fig. 6. (a) Persistent phase-averaged X-ray spectra of 1E 1547.0–5408, fitted simultaneously with a model consisting of a blackbody (green) and a hard power-law (red). Related background spectra are also shown. (b) Fit residuals. The XIS 1 and XIS 3 data are shown in gray and black. (c) An unfolded source spectrum ($eF_{\nu}$ form) of panel (a) using Model (A).

Fig. 7. Same as figure 6c, but using Model B (left panel) and Model C (right panel).
that plagues a more conventional modeling of a blackbody plus steeper power-law. As presented in figure 7 (left panel) and table 3, this Comptonized blackbody plus harder power-law model, hereafter called Model B, also gave an acceptable (and slightly better) fit to the data. The photon index of the soft tail was obtained at $\Gamma_{\text{comp}} \sim 4.9$ (table 3); that of the hard power-law remained unchanged from that of Model A within errors; and the blackbody temperature decreased to $kT = 0.48 \pm 0.05$ keV.

Alternatively, to represent the above soft power-law component, we may also employ the 1D semianalytical resonant Compton blackbody and resonant cyclotron scattering, respectively. ND represents “not determined.” All the quoted errors are only statistical at the 90% confidence level. Table 3 gives the phase averaged spectral parameters for each model. We found that Model A and B employing Model A, and multiplied its hard power-law component, we may also employ the 1D semianalytical resonant cyclotron scattering model after Rea et al. (2009) using xspec12 local model “RCS.mod”. This local model assumes repeated resonant cyclotron scatterings of the thermal radiation from the surface by hot electrons in the neutron-star magnetosphere. The model, hereafter Model C, also gave an acceptable fit (figure 7 right), although it requires a large optical depth (table 3).

The hard-tail slope, $\Gamma \sim 1.5$, must steepen at some energies, in order for the hard-component luminosity not to diverge. To obtain a constraint on such a high-energy steepening, we employed Model A, and multiplied its hard power-law with an exponential cutoff factor of the form $\exp(-E/E_{\text{cut}})$, where $E$ is the photon energy and $E_{\text{cut}}$ is a parameter. Then, the data gave a constraint as $E_{\text{cut}} > 200$ keV at the 90% confidence limit.

5. Discussion

5.1. Broad-Band Information

The present Suzaku ToO observation of 1E 1547.0–5408, carried out 7 d after the onset of the 2009 January bursting activity, have allowed the first study of the fastest-rotating magnetar in an extremely broad band ranging over two orders of magnitude in energy. The most important finding is the first discovery from this source of the very hard component, which was so far observed from some (though not all) other magnetars. This component dominates the burst-removed persistent emission spectra of 1E 1547.0–5408 in $\geq$ 7 keV, and extends at least up to $\sim$ 100 keV with $\Gamma \sim 1.5$ without any evidence of prominent spectral features or steepening ($E_{\text{cut}} > 200$ keV).

We discovered that the hard X-rays are pulsed at the same period as the soft X-rays, although the pulsed fractions are considerably smaller (figure 5) than those of typical magnetars.

As summarized in table 3, the measured 20–100 keV flux ($1.3 \times 10^{-11}$ erg s$^{-1}$ cm$^{-2}$) exceeds the unabsorbed 2–10 keV flux ($8.0 \times 10^{-11}$ erg s$^{-1}$ cm$^{-2}$) by a factor of $R = 1.57 \pm 0.15$. (This factor becomes 2.1 if we use the absorption-uncorrected 2–10 keV flux in table 3 instead.) Therefore, at least during this active period, the emission appeared mainly in hard X-ray energies. If we separate the soft and hard components while referring to Model A for the sake of simplicity, and employ a distance of $d = 9$ kpc as a fiducial value, the absorption-corrected bolometric luminosity of the soft component (blackbody) becomes $L_{\text{BB}} = (6.2 \pm 1.2) \times 10^{35}$ (d/9 kpc)$^{2}$ erg s$^{-1}$, whereas that of the hard component in the 2–100 keV band becomes $1.9 \times 10^{36}$ (d/9 kpc)$^{2}$ erg s$^{-1}$.

Enoto et al. (2010) pointed out that the flux ratio $R$ of a magnetar between the 20–100 keV and the 2–10 keV, as introduced above, negatively correlates with their characteristic age $\tau_c$. During the present activity 1E 1547.0–5408 exhibited $R = 1.57$, as derived above. This ratio is higher than those of magnetars with older characteristic ages (typical AXPs, e.g., $R \sim 0.7$ for 4U 0142+61 with $\tau_c = 70$ kyr), while lower than those of objects with younger characteristic ages (typical SGRs, e.g., $R \sim 2.8$ for SGR 1806–20 with $\tau_c = 0.2$ kyr). Furthermore, the hard-tail slope of 1E 1547.0–5408 ($\Gamma \sim 1.5$) is in between those of typical AXPs ($\Gamma \sim 1.0$) and of typical SGRs ($\Gamma = 1.8–3.1$: G"otz et al. 2006). This is reinforced when we plot the photon index of 1E 1547.0–5408 on figure 3 of Kaspi and Boydston (2010), which reports a correlation between the hard-band photon index and the magnetic field strength. These properties, together with $\tau_c = 1.4$ kyr, make the activated 1E 1547.0–5408 an object in between the typical SGRs with young characteristic ages and the typical AXPs with older ones.

5.2. Modeling of the Soft Component

Taking into account the hard-tail component, the broad-band Suzaku spectra have been reproduced successfully by the three alternative modelings (Models A, B, and C) of the soft component. In all cases, the hydrogen column density was obtained as $N_H = (3.2–4.0) \times 10^{22}$ cm$^{-2}$ (table 3), which is consistent with the past XMM-Newton and Swift measurements in a much fainter state in 2006–2007 (Halpern et al. 2008). Although this $N_H$ is 1.5–1.8 times higher than the Galactic H1 column density in the direction of 1E 1547.0–5408, 2.2 $\times 10^{22}$ cm$^{-2}$ (Dickey & Lockman 1990), the difference can be explained away by including the H$_2$ gas contribution, as judged from CO observations (Halpern et al. 2008).

Although the three models all proved to be successful,
Model B and Model C give better chi-squares than Model A (figure 7, table 3). According to $F$-tests, chance probabilities of the fit improvement from Model A to Model B, and Model A to Model C, are $1.2 \times 10^{-3}$ and $8.3 \times 10^{-2}$, respectively. Therefore, the hardest end of the soft component is suggested to exhibit a power-law like extension, as found in the quiescent spectrum of this object (Halpern et al. 2008), rather than turning over exponentially.

5.3. Effects of the Enhanced Activity

While 1E 1547.0–5408 showed AXP-like soft X-ray spectra in quiescence (Gelfand & Gaensler 2007; Halpern et al. 2008), its burst properties recorded in the present activity are very similar to those of typical SGRs (Mereghetti et al. 2009). Therefore, this object is considered to exhibit properties typical of both SGRs and AXPs, depending on its activity states. It is hence expected to provide us a unique opportunity for comparing magnetars of different activity levels.

Past Swift and XMM-Newton observations of this object reported on a historical minimum 1–8 keV flux (absorption uncorrected) of $3.3 \times 10^{-13}$ erg cm$^{-2}$ s$^{-1}$ in 2006 August, while a much enhanced value of $4.6 \times 10^{-12}$ erg cm$^{-2}$ s$^{-1}$ during the previous outburst in 2007 January (Halpern et al. 2008). The same quantity measured in the present observation, $(5.2 \pm 0.2) \times 10^{-11}$ erg cm$^{-2}$ s$^{-1}$ (using Model A for the sake of simplicity), is even $\sim 158$ times higher than that in 2006 August, and $\sim 11$ times higher than in 2007 January. These large soft X-ray variations are similar to those of the transient magnetars XTE J1810–197 and CXOU J164710.2–455216 (Halpern et al. 2008).

In evaluating how the activity affected the soft component, let us for the sake of simplicity refer to Model A, even though the soft component may not be a pure blackbody (subsection 5.2). In terms of Model A, we measured a blackbody temperature of $0.65 \pm 0.02$ keV (table 3), which is $\sim 1.5$ times higher than the value of $0.43^{+0.03}_{-0.04}$ keV measured in 2006 during quiescence (Gelfand & Gaensler 2007). Likewise, the blackbody radius of $5.2^{+0.4}_{-0.3} (d/10$ kpc)$^2$ km from Model A (table 3), which implies a sizable fraction of a neutron-star surface, is larger than the values of $1.7–3.7$ km measured in 2006 August to 2007 August (Gelfand & Gaensler 2007; Halpern et al. 2008). Therefore, the enhanced activity caused the increase, in both the area and the temperature, of the blackbody source located presumably on the neutron-star surface. A qualitatively similar result was obtained by Halpern et al. (2008), who made use of the result that the 1–8 keV flux increases the factor by 14 times during the period from 2006 August to 2007 June.

Since the present Suzaku observation has allowed the first detection of 1E 1547.0–5408 at energies above $\sim 10$ keV, it is not trivial to evaluate how the hard tail was enhanced by the bursting activity. Let us then use spectra below 10 keV, and define a fractional luminosity carried by any “nonblackbody” component, as $\eta = (L_{\text{tot}} - L_{\text{BB}})/L_{\text{tot}}$, where $L_{\text{tot}}$ is the absorbed 1–10 keV total luminosity at 9 kpc, and $L_{\text{BB}}$ is the bolometric luminosity of the soft blackbody. In the present case, we have $L_{\text{BB}} = (6.2 \pm 1.2) \times 10^{35}$ erg s$^{-1}$ (subsection 5.1), together with $L_{\text{tot}} = 1.1 \times 10^{36}$ erg s$^{-1}$, and hence $\eta \sim 0.44$. Thus, even at energies below 10 keV, nearly half of the persistent X-ray flux in the present activity is considered to be carried by the hard component, unless it steeply cuts off toward lower energies.

In contrast, the results by Halpern et al. (2008), obtained in the less active periods in 2006–2007, imply $\eta = 0.26–0.32$. We therefore infer that the hard-tail component is more strongly affected by the activity variation than the soft emission is done. This inference is reinforced if we notice that the “nonblackbody” fraction in 2006–2007 could be at least partially attributed, e.g., to the Comptonization tail of the soft component itself, rather than to the genuine hard tail component. In common with this inference, Enoto et al. (2010) suggest that the hard component of SGR 0501+4156 decayed, after its 2008 August emergence, more rapidly than the soft component.

However, another effect of the enhanced activity is a marked increase in the pulsed fraction. In the less-active state in 2007, the pulsed fraction obtained with XMM-Newton measured $\sim 7\%$ (Halpern et al. 2008). This value was defined, differently from our definition (subsection 4.1), as a fraction of counts above a minimum of the folded pulse profile. Even if we use this definition, the 1–3 and 3–10 keV pulsed fractions of the present XIS 0 data are obtained as $\sim 17\%$ and $\sim 20\%$, respectively, which are not much different from these given in figure 5. Thus, the pulsed fraction in the present active state is 2–3 times higher than that in the less active one. Such a change of the pulse fraction between the outburst and quiescence has also been reported in the cases of XTE J1810–197 and CXOU J164710.2–455216 (Israel et al. 2007). A possible scenario is that these objects are observed relatively parallel to their rotational axes, and a blackbody emitter localized on the neutron-star surface (may or may not be at a magnetic pole) is always visible from us normally. As the activity becomes higher, the blackbody emitter, gradually increasing in area as we found above, may start to exhibit self-eclipse as the star rotates.

6. Summary

On 2009 January 28–29, we performed a Suzaku ToO observation of the fastest-rotating magnetar 1E 1547.0–5408 in its burst-active state.

1. In addition to short bursts, the persistent X-ray emission was detected over a broad energy band, from $\sim 0.8$ keV at least up to $\sim 100$ keV. The 20–100 keV flux of $1.3 \times 10^{-10}$ erg cm$^{-2}$ s$^{-1}$, measured for the first time from this source, exceeds by a factor of 1.6 (or 2.1) the absorption-corrected (or uncorrected) 2–10 keV flux.

2. The pulsation was detected up to $\sim 70$ keV at a period of 2.072135 s. Although the pulsed fraction (16%–28%) is lower than those of most of other magnetars, it is considerably higher than was observed previously from this object in quiescence.

3. The broad band X-ray spectra were fitted successfully by a soft blackbody of $kT = 0.65$ keV plus an extremely hard power-law component of $\Gamma \sim 1.5$. At 9 kpc distance, the bolometric luminosity of the former becomes $(6.2 \pm 1.2) \times 10^{35}$ erg s$^{-1}$, while the 2–100 keV luminosity of the latter does $1.9 \times 10^{36}$ erg s$^{-1}$. 


4. Compared to the quiescence, the blackbody temperature increased by a factor of \(~1.5\), and the blackbody radius (\(~5\) km at 9 kpc) also increased. As a result, the 2–10 keV flux increased by 1–2 order of magnitude compared to the previous fainter states in 2006 and 2007.

5. Replacing the blackbody with a Comptonized blackbody or an RCS model improved the fit, suggesting that the soft component deviates from a pure blackbody.

6. The hard X-ray flux, though not measured previously, is inferred to have increased during the activity by a larger factor than the soft X-ray flux. In the present data, the hard component still carries nearly half of the flux in energies below 10 keV.

7. These results can be understood by considering that 1E 1547.0—5408, during the activity, became a magnetar that has properties in between the most active SGRs and the least active AXPs.

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Appendix. Comptonized Blackbody Model

When an X-ray photon with an energy \(\epsilon'\) is upscattered in a single Compton process to an energy \(\epsilon\), its energy becomes \(\epsilon_k \sim \epsilon' A^k\) after \(k\) scatterings, where \(A \equiv \epsilon/\epsilon'\) denotes an amplification factor. When the scatterer has an optical depth \(\tau\) and is optically thin, a probability that a photon experiences \(k\) scatterings is given as \(\tau^k\). These scatterings change the original photon number flux \(I(E')\) to

\[
I(E) \sim I(E') \epsilon^k = I(E') \left(\frac{E'}{E}\right)^{-\alpha},
\]

(A1)

where \(\alpha \equiv -\ln\epsilon/\ln A\). If the original radiation is a blackbody radiation (in photon number flux),

\[
I(E') = \frac{E'^2}{\exp(E'/kT) - 1} \text{photons s}^{-1} \text{cm}^{-2} \text{keV}^{-1}
\]

(A2)

with a temperature \(kT\) and a normalization factor \(C\), then the modified spectrum after multiple scatterings becomes

\[
I(E) dE = \int_0^E I(E') \left(\frac{E'}{E}\right)^{-\alpha} dE' \text{photons s}^{-1} \text{cm}^{-2} (A3)
\]

\[
I(E) = CE^{-1-\alpha} \int_0^E \frac{E'^{2+\alpha}}{\exp(E'/kT) - 1} dE' = CE^{-\Gamma_{\text{comp}}} \int_0^E \frac{E'^{\Gamma_{\text{comp}}+1}}{\exp(E'/kT) - 1} dE'.
\]

(A4)

Here, a photon index in the high-energy range is defined as \(\Gamma_{\text{comp}} = 1 + \alpha\), because it has a form of \(I(E) \propto E^{-(1+\alpha)} = E^{-\Gamma_{\text{comp}}}\) at \(E/kT \gg 1\). This also has the Rayleigh–Jeans form in the low-energy region \((E/kT \ll 1)\), \(I(E) \propto E\) photons s\(^{-1}\) cm\(^{-2}\) keV\(^{-1}\). We implemented this integration in xspec12 with the GNU Scientific Library (GSL) codes, where the integration has a relative accuracy of \(10^{-4}\).

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