BROADBAND STUDY WITH SUZAKU OF THE MAGNETAR CLASS

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ABSTRACT

Broadband (0.8–70 keV) spectra of the persistent X-ray emission from nine magnetars were obtained with Suzaku, including three objects in apparent outburst. The soft X-ray component was detected from all of them, with a typical blackbody temperature of \( kT \sim 0.5 \) keV, while the hard-tail component, dominating above \( \sim 10 \) keV, was detected at \( \sim 1 \) mCrab intensity from seven of them. Therefore, the spectrum composed of a soft emission and a hard-tail component may be considered to be a common property of magnetars, both in their active and quiescent states. Wide-band spectral analyses revealed that the hard-tail component has a \( 1–60 \) keV flux, \( F_{h} \), comparable to or even higher than that carried by the \( 1–60 \) keV soft component, \( F_{s} \). The hardness ratio (HR) of these objects, defined as \( \xi \equiv F_{h}/F_{s} \), was found to be tightly anti-correlated with their characteristic age \( \tau_{c} \) as \( \xi \equiv (3.3 \pm 0.3) \times (\tau_{c}/1 \text{kry})^{-0.67 \pm 0.04} \) with a correlation coefficient of \(-0.989\), over the range from \( \xi \sim 10 \) to \( \xi \sim 0.1\). Magnetars in outburst states were found to lie on the same correlation as relatively quiescent ones. This HR is also positively correlated with their surface magnetic fields with a correlation coefficient of 0.873. In addition, the hard-tail component becomes harder toward sources with older characteristic ages, with the photon index changing from \( \sim 1.7 \) to \( \sim 0.4 \).

Key words: stars: evolution – stars: magnetars – stars: magnetic field – stars: neutron

1. INTRODUCTION

Soft gamma repeaters (SGRs) and anomalous X-ray pulsars (AXPs) are considered to form a distinct class of neutron stars, collectively called “magnetars,” and are thought to have magnetic fields exceeding the critical value of \( B_{\text{QED}} = 4.4 \times 10^{13} \) G (Thompson & Duncan 1995, 1996; for a recent review see, e.g., Mereghetti 2008; Woods & Thompson 2006). Although their radiation, mainly emerging in the X-ray frequency, is considered to be powered by their huge magnetic energies, little is known about how the postulated strong magnetic fields are dissipated and converted into the radiation. It is hence imperative at this stage to examine their emission properties for any empirical relations that provide a more unified characterization of these enigmatic objects.

Through hard X-ray imaging observations with INTEGRAL, some persistently bright magnetars were discovered to emit not only the well-known soft component (with a temperature of \( kT \sim 0.5 \) keV), but also a distinct hard-tail component which emerges above \( \sim 10 \) keV with an extremely hard photon index of \( \Gamma_{h} \sim 1 \) (e.g., Kuiper et al. 2006; Götz et al. 2006). The hard-tail component has also been detected from transient magnetars in outburst states, including SGR 0501+4516 (Naik et al. 2008), CXOU J164710.2−455216 (Nakagawa et al. 2009), SGR1900+14 (Nakagawa et al. 2009), 1E 1841−045 (Morii et al. 2008), CXOU J164710.2−455216 (Naik et al. 2008), SGR 0501+4516 (Enoto et al. 2009, 2010b), and 1E 1547.0−5408 (Enoto et al. 2010a). This unusual new component, though not yet observed from all magnetars, is expected to provide a clue to the emission process and the magnetic dissipation mechanism in magnetars.

To perform wide-band spectroscopy of magnetars covering these two components, multi-satellite observations have generally been employed. However, the hard-tail intensity (\( \lesssim 10 \) mCrab) of these objects requires much longer exposures than are usually spent in observing their soft components. As a result, it has so far been difficult to obtain strictly simultaneous wide-band spectra of these sources which are more or less time variable. In the present Letter, we report on Suzaku (Mitsuda et al. 2007) observations of most of the presently known magnetars, studying for the first time soft and hard X-ray spectra taken simultaneously. We thus found a strong correlation between magnetars’ hardness ratio (HR) and characteristic ages.

2. OBSERVATION AND ANALYSIS

Since its launch, Suzaku has performed 15 pointed observations of 10 magnetars, including 5 targets in a Suzaku Key Project in 2009. We analyzed all these Suzaku data in a unified way, except for 1E 1048.1−5937, for which the data are not yet public as of 2009 November. This included re-analyses of the data from previously reported observations; i.e., SGR 1806−20 (Esposito et al. 2007; Nakagawa et al. 2009), SGR1900+14 (Nakagawa et al. 2009), 1E 1841−045 (Morii et al. 2008), CXOU J164710.2−455216 (Naik et al. 2008), SGR 0501+4516 (Enoto et al. 2009, 2010b), and 1E 1547.0−5408 (Enoto et al. 2010a). Table 1 summarizes the observations utilized in the present Letter. Among them, three sources, namely, CXOU J164710.2−455216, SGR 0501+4516, and 1E 1547.0−5408, were observed during bursting periods. Our sample, though not complete, covers 9 sources out of the \( \sim 15 \) magnetars known to date.

From each observation, we extracted events for persistent X-ray emission using the X-ray Imaging Spectrometer (XIS; Koyama et al. 2007) and the Hard X-ray Detector (HXD; Takahashi et al. 2007), which cover energy ranges of 0.2–12 keV and 10–600 keV, respectively. The XIS and HXD data were processed with the pipeline processing version 2.0 or later, and events were discarded if they were acquired in the South Atlantic Anomaly or in regions of low cutoff rigidity (<6 GV for the XIS and <8 GV for the HXD), or at low Earth elevation
angles.\(^7\) In addition, a fair number of short bursts, detected from SGR 0501+4516, SGR 1806–20, and SGR 1806–20, were removed by discarding the XIS and HXD events which were detected within a time interval of a few seconds around each of these bursts (e.g., Enoto et al. 2010a). Studies of these burst events are beyond the scope of this Letter.

To create 0.8–10 keV XIS spectra, we accumulated the screened data from a source region typically within a 2.0 radius of the target centroid and derived a background spectrum from adjacent regions on the same CCD chip. Since the background count rates are typically \(\sim 5\%\) of the source rates, systematic uncertainties of the XIS background are negligible. Thanks to the use of appropriate window options, all the observations were free from XIS event pileup.

For each observation, an HXD-PIN spectrum was produced in the 10–70 keV range, after subtracting non-X-ray background (NXB) and cosmic X-ray background (CBXB; typically \(\sim 4\%\) of the NXB). We utilized NXB events which are simulated by the “tuned” model of Fukazawa et al. (2009) and the analytic CBXB model by Moretti et al. (2009). In the case of sources near the Galactic center (i.e., SGR 1806–20 and 1RXS J170849.0–400910), we further subtracted Galactic ridge X-ray emission (GRXE; Krivonos et al. 2007; typically \(\lesssim 3\%\) of the NXB), with a photon index fixed at 2.1 (Valinia & Marshall 1998) and normalizations specified by observations of nearby blank skies at similar Galactic latitudes. Systematic errors in these HXD-PIN spectra are dominated by reproducibility of the NXB model, which is typically \(\lesssim 2\%\) (\(\sigma\)) (Fukazawa et al. 2009), while those of the CXB and GRXE are negligible. This effect is taken into account by changing the PIN-NXB within \(\pm 2\%\). The HXD-PIN field of view was clear of significant contaminating sources in these observations, except for the case of CXOU J164710.2–455216 (Naik et al. 2008), which was confused with GX 340+0. Source confusion was not an issue for the other eight sources, and we hence analyze these eight sources below.

3. RESULTS

Figure 1 shows background-subtracted and pulse-phase-averaged persistent spectra of the eight magnetars. The soft component was clearly observed from all of them, while the hard-tail component was successfully detected from seven of them at a typical intensity of \(\sim 1\) mCrab (at \(\sim 30\) keV). Assuming \(\Gamma_b \sim 1\), any hard-tail flux from 1E 2259+586 was constrained to be less than 8.7 \times 10^{-12} \text{ erg s}^{-1} \text{ cm}^{-2} \text{ in the}}
Figure 1. Background-subtracted νFν spectra of the persistent emission of the magnetars, shown after eliminating the instrumental responses. Interstellar absorption is included. Individual spectra are shown with offsets and are arranged in order of increasing characteristic age from top (young) to bottom (old). Blue horizontal lines indicate a 1 mCrab intensity. Green, red, and blue lines represent the soft component, the hard-tail component, and the SNR contamination (including line emission) in the 1E 1841–045 spectrum, respectively. If a source was observed more than once, one observation is shown. The GSO data of 1E 1547.0−5408 are included after Enoto et al. (2010a). The full names of the sources, which are shown here as abbreviations, are listed in a footnote to Table 1.

Figure 2. Portion of the P–Ṗ diagram of pulsars (Manchester et al. 2005; http://www.atnf.csiro.au/research/pulsar/psrcat/). Sizes of the red circles correspond to the ξ values in the present sample. Blue and green lines represent constant values of the magnetic field strength and the characteristic age, respectively. Small gray circles represent magnetars with upper limits on the hard-tail component, or those not observed with Suzaku. Ordinary radio pulsars are indicated by crosses.

15–60 keV range, which is consistent with the previous result from INTEGRAL (Figure 10 in Kuiper et al. 2006). These Suzaku spectra reconfirm the previous INTEGRAL detections of the hard-tail component from some persistent sources, including 4U 0142+61, 1RXS J170849.0−000910, 1E 1841−045, SGR 1806−20, and SGR 1900+14 (Mereghetti et al. 2005; Kuiper et al. 2006; Götz et al. 2006; den Hartog et al. 2007, 2008). The absorbed 2–10 keV and 15–60 keV X-ray fluxes are summarized in Table 1. Thus, the hard-band flux is comparable to, or sometimes even higher than, that in the softer band.

The unified presentation in Figure 1 yields an intriguing inference that the hard-tail component becomes weaker for older objects. To quantify this property, we simultaneously fitted the XIS and the HXD spectra of each object with a common spectral model. For the hard-tail component, we employed a single power law for all the sources. The soft component of younger magnetars was reproduced by a single blackbody (Model A), but older sources required some modification to this model due to a “soft-tail” excess around 8 keV, which is thought to arise via some sort of Comptonization process (Thompson et al. 2002; Lyutikov & Gavriil 2006; Rea et al. 2008). We therefore introduced an empirical Comptonized blackbody model (Model B; Tiengo et al. 2005; Halpern et al. 2008; Enoto et al. 2010a) and obtained successful fits in most cases. In the case of SGR 0501+4516, neither Model A nor B was acceptable, but a successful fit was obtained by adding a cooler blackbody to Model B (Model C; Enoto et al. 2010b). The XIS spectrum of 1E 1841−045 needed an additional plasma emission component from the surrounding supernova remnant.

From these fit results, we calculated absorption-corrected fluxes for the soft component Fν and the hard-tail component Fνh, both defined in the 1–60 keV range. These values, given in Table 1, are considered physically more meaningful than the raw 2–10 keV and 15–60 keV fluxes, because the two components are separated, and the absorption is corrected. The lower boundary of 1 keV was adopted not only for Fν but also for Fνh, because sources with young characteristic ages have substantial contributions of the hard-tail even in the lowest energy range at ~0.8 keV (e.g., SGR 1806−20 in Figure 1). We may then define the “hardness ratio” (HR), ξ ≡ Fνh/Fν, as shown in Table 1, the values of ξ range over almost 2 orders of magnitude from 0.2 to 10.

As visualized in Figure 2, ξ exhibits a clear gradient on the P–Ṗ plane. To assess this implication, we show in Figure 3 the values of ξ as a function of the characteristic age τc = P/2Ṗ and the surface magnetic field Bc ≈ 3.2 × 1019(P Ṗ)1/2 G, where the errors associated with ξ include both statistical and systematic errors. The latter is dominated by the 2% uncertainties of PIN-NXB (Section 2), with additional contributions (by ~1% in ξ) from uncertainties in the XIS versus HXD cross.
normalization. The figure indicates that $\xi$ is indeed negatively (or positively) correlated with $\tau_c$ (or $B_s$).

After discarding the two upper limits in Figure 3, $\xi$ is found to be correlated with $\tau_c$ and $B_s$ with Pearson’s linear cross-correlation coefficients of $r = -0.989$ and 0.873, respectively. Thus, $\xi$ is very tightly correlated with $\tau_c$, and to a lesser extent (as evident in Figure 2) with $B_s$. In order to evaluate the correlation in a non-parametric way, we further performed the Spearman’s rank-order test, which gives correlation coefficients of $r_s = -0.963$ and 0.871 for $\tau_c$ and $B_s$, respectively, together with a chance probability in both cases of $<0.001$. Thus, these correlations are indeed significant. Fitting through the least squares method gave the best-fit linear correlation as

$$\xi = \frac{F_h}{F_s} = (3.3 \pm 0.3) \times \left( \frac{\tau_c}{1 \text{ kyr}} \right)^{-0.67 \pm 0.04} \quad (1)$$

$$= (0.09 \pm 0.07) \times \left( \frac{B_s}{B_{QED}} \right)^{1.2 \pm 0.2} \quad (2)$$

with $1\sigma$ uncertainties. Since individual data points have rather small errors, we here added constant systematic errors to them, so as to make the fits acceptable with reduced chi-square values of $\sim 1$. Around the $\xi-\tau_c$ linear fit, the data points scatter by no more than a factor of two in $\xi$.

Now that the $\xi-\tau_c$ and the $\xi-B_s$ correlations were confirmed to be statistically significant, let us examine them for systematic effects. These correlations are unlikely to arise from some selection biases on the $P-$plane, because these magnetars show a two-dimensional scatter in Figure 2 without any particular correlation between $P$ and $P$. These observations are also free from possible uncertainties due to independent variations of $F_s$ and $F_h$, since in all sources these two quantities are based on strictly simultaneous measurements. In addition, multiple observations of the same objects at different epochs gave similar values of $\xi$ (i.e., SGR 1806−20, SGR 1900+14, and 4U 0142+61 in Figure 3). Therefore, the essential features of Figure 2 are not considered to depend strongly on the epochs of observations.

Although the empirical Comptonized blackbody model (Model B) was employed in calculating $F_s$ (and hence $\xi$) of 1RXS J170849.0−400910, SGR 0501+45, and 4U 0142+61, their values of $\xi$ change only by a factor of 1.78, 1.09, and 0.94−1.09, respectively, if their soft component is modeled by two blackbodies that constitute another popular model. Thus, the implication of Figure 3 remains unchanged. The $\xi-\tau_c$ correlation also remains robust, even if we change the lower limit of the energy band from 1 keV to 0.5 keV. For example, this change reduces $\xi$ by only 5% and 26% for the cases of SGR 1806−20 and 4U 0142+61, respectively. Similarly, if we raise the upper-limit energy of the hard-tail flux from 60 keV to 500 keV, the $\xi-\tau_c$ correlation also persists with $r = -0.788$ and $r_s = -0.825$. Therefore, the $\xi-\tau_c$ relation can be considered to represent a model-independent property of our sample of magnetars. Detailed spectral analyses of our sample objects will be described elsewhere, together with separate studies of pulsed and un-pulsed signals.

4. DISCUSSION AND CONCLUSION

Including most of the known SGRs and AXPs, the present data set provides the first simultaneous coverage of their soft and hard X-ray spectra (Figure 1). This has led to a discovery of the $\xi-\tau_c$ and $\xi-B_s$ correlations in Figure 3. These tight correlations suggest that the values of $\xi$ in the present objects approximately behave as a one parameter family (a single valued function) determined uniquely by $P$ and $P$. Among possible physical quantities expressed as simple combinations of $P$ and $P$, the characteristic age $\tau_c$ may be regarded as a likely determinant of $\xi$ (see Figure 2). Then, by regarding $\tau_c$ as an indicator of the age in assuming a self-similar spin-down, and further noting that our sample covers a significant ($\sim 50\%$) fraction of the presently cataloged objects of these two classes, the $\xi-\tau_c$ correlation is considered to represent a common spectral evolution of them. Since both SGRs and AXPs follow the same correlations, the present result provides another support to the increasing evidence that these subsets are intrinsically considered the same kinds of object, namely, “magnetars.”

Figure 3. Left: correlation between the HR $\xi$ and the characteristic age $\tau_c$. Quoted errors are statistical plus systematic 1$\sigma$ (Table 1). Upper limits are also shown for SGR 0501+4516 (second observation) and 1F 2259+586. Green solid and dashed lines represent the best fit of Equation (1) and their boundaries shifted by a factor of two, respectively. SGRs and AXPs are shown in red and blue, respectively, while burst-active sources are shown with star symbols. Right: same as the left panel, but plotted as a function of the surface magnetic field.
From the burst-active magnetars SGR 0501+4516 and 1E 1547.0–5408, we successfully detected the hard-tail components. On the \( \xi - \tau_c \) correlation, their \( \xi \) values generally agree with data points of the other magnetars, which mainly refer to quiescent or less active states. Therefore, the bursting activity of a magnetar is thought to cause a significant enhancement in the hard component, roughly to the same intensity as the soft component, which is known to increase by 1–2 orders of magnitude with data points of the other magnetars, which mainly refer to quiescent or less active states. Therefore, the bursting activity of a magnetar is thought to cause a significant enhancement in the hard component, roughly to the same intensity as the soft component, which is known to increase by 1–2 orders of magnitude (Tam et al. 2008; Rea et al. 2009; Enoto et al. 2010a). The upper limit on the second observation of SGR 0501+4516 is consistent with this picture. These results further suggest that the basic mechanism of quiescent wide-band emission is retained during increased activity.

In addition to the above interpretation invoking \( \tau_c \), the same magnetar \( \xi - \tau_c \) correlation may be interpreted in an alternative way. The strong magnetic field \( B \), combined with the rotation, would induce an electric field up to

\[
|\vec{E}| \sim R_\Omega B \approx 2.6 \times 10^{12} \frac{V}{cm} \sqrt{\frac{6}{P} \frac{s}{10^{11} s^{-1}} \left(\frac{R}{10 km}\right)} \\sim \left(\frac{1}{\tau_c}\right)_c \quad (3)
\]

where \( R \) and \( \Omega \) are the distance from the center of the star and the angular frequency, respectively. Thus, \( \tau_c \) can be uniquely converted to \( |\vec{E}| \), as shown at the top of Figure 3 (left). Thus, the magnetar \( \xi - \tau_c \) correlation can also be regarded as a correlation between \( \xi \) and \( |\vec{E}| \). If so, the hard-tail component, which should require the presence of particles more energetic than \( \sim 100 \) keV, might be related to particle acceleration by this induced electric field.

A closer inspection of Figure 1 suggests a hardening of the hard-tail component for objects with larger \( \tau_c \). This is more clearly shown in Figure 4(a), where \( \Gamma_h \) is observed to evolve from \( \sim 1.7 \) to \( \sim 0.4 \). Such a correlation was first pointed out in the \( 1-10 \) keV band by Marsden & White (2001) and recently extended into hard X-rays by Kaspi & Boydstun (2010). The latter authors found a correlation of \( \Gamma_h \) with \( B_s \) or \( P \), with implications similar to those of our Figure 4(a). In contrast, they did not find any correlations that can be compared with our

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