Suzaku Studies of the Extremely Hard Emission Components of Magnetars

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Abstract

Recently, extremely hard X-ray tails have been observed in several magnetars, with photon indexes above 10 keV of $\Gamma\sim1$. The emission mechanism of this new enigmatic component has not yet been conclusively unveiled. Last two years, *Suzaku* has performed two target-of-opportunity (ToO) observations: the first one pointing on the newly discovered magnetar SGR 0501+4516, and the second one on the radio transient magnetar 1E 1547.0-5408, both soon after a large X-ray outburst. *Suzaku* successfully detected extremely hard power-law components with Γ =0.79 and 1.54 for SGR 0501+4516 and 1E 1547.0-5408, respectively, as well as their soft X-ray thermal and non-thermal emissions. We found that the hard X-ray fluxes are comparable to or larger than the soft X-rays, and the wide-band spectrum of SGR 0501+4516 looked more like AXPs, while 1E 1547.0-5408 has a spectrum more similar to SGRs. Furthermore, combining these results with published ones, we found that the ratio of hard over soft X-ray flux of magnetars, seems to negatively (or positively) correlate with their characteristic ages (or magnetic fields). This gives a further hint for unifying SGRs and AXPs into one scheme, directly connected to decay of the magnetic activity in the evolution of magnetars. Now a magnetar key project is in progress, where 10 magnetars have already been observed to emit hard X-rays.

Key words: individual (SGR 0501+4516; 1E 1547.0-5408; 4U 0142+61) — X-rays:stars

1. Magnetars in *Suzaku* Era

Strongly magnetized pulsars, namely magnetars, have been recognized in anomalous X-ray pulsars (AXPs) and soft gamma-ray repeaters (SGRs). They form a subgroup of the isolated neutron stars, and have rotation periods in the range of P=5–12 s and spin down rates of $\dot{P}\sim10^{-13}$–10^{-11} s s^{-1}. Given the very high dipolar magnetic field that can be inferred from these timing information, magnetars are believed to be highly magnetized objects, with magnetic fields B of $\sim 10^{14}-10^{15}$ Gauss (Duncan & Thompson 1992; Thompson & Duncan1995, 1996; Woods & Thompson, 2006; Mereghetti, 2008). Figure 1 shows the distribution of the magnetic fields of magnetars compared to normal radio pulsars or accretion-powered pulsars. Furthermore, their emission below 10 keV is characterized by X-ray luminosities of $\sim10^{35}$ erg s^{-1}, which exceed by a few order of magnitudes their spin-down luminosities. Taking into consideration the lack of companion stars, the energy resevoir of magnetars are believed to be of magnetic origin.

In the last 5 years, long-exposure observations by *INGEGRAL* discovered a new emission above 10 keV, with an extremely hard photon index of $\Gamma\sim1$ observed up to $\sim$150 keV (Kuiper et al., 2004, 2006; Gotz et al., 2006). So far, this new component has been detected from $\sim$6 magnetars. This enigmatic radiation attracted a wide attention, and its origin as been extensively discussed, without an overall consensus yet (Thompson et al., 2005; Heyl et al., 2005; Baring et al., 2007).

Magnetars are not only interesting because of their X-ray emission mechanism, but also provide an ideal laboratory of test matter embedded in ultra-strong magnetic field. Current observational issues concerning their hard

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X-ray emission can be listed as follows. First, hard X-ray emissions are common to all the magnetars, or special cases? Second, are they seen in outburst state as well as quiescent state? Third, are there any connection between soft and hard X-ray emissions? The X-ray satellite *Suzaku* (Mitsuda et al., 2007) has the capability to answer these questions, since *Suzaku* can measure both the soft and hard X-ray emission simultaneously, within relatively short exposures, making use of the X-ray Imaging Spectrometer (XIS; Koyama et al., 2007) and the Hard X-ray Detector (HXD; Takahashi et al., 2007).

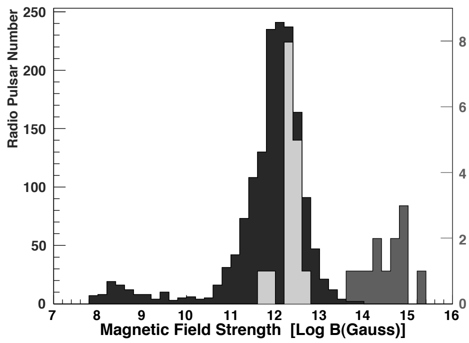

Fig. 1. Magnetic field distribution of radio pulsars (blue; Manchester et al., 2005), accretion-powered pulsars (green; LMXBs, which are accretion powered pulsars too have B fields of 10^{8-9} G, are missing here.) and magnetars (red).

2. *Suzaku* ToO Observations

Last year *Suzkau* performed two successful target-of-opportunity (ToO) observations of the magnetars SGR 0501+4516 and 1E 1547.0-5408. These observations were performed following the outburst activation of these two sources, as can be seen by the large bursts shown in Figures 3 and the burst spectrum in Figure 2 .

2.1. SGR 0501+4516

A new Soft Gamma-ray Repeater, SGR 0501+4516, was discovered on 2008 August 22nd by the Swift Burst Alert Telescope (Holland & Sato, 2008; Barthelmy et al., 2008). Just four days after the onset of the outburst activity, *Suzaku* ToO observation was performed for ∼51 ks, which recorded both of the soft and hard X-ray emission components of the source, as well as 32 short bursts (Enoto et al., 2009a).

The largest burst had a intensity of ∼23 Crab at ∼40 keV. Figure 2 shows the νF_ν spectrum of this burst, recorded over the 0.2–200 keV energy range using the XIS, HXD-PIN and HXD-GSO instruments. The burst spectrum was well fit by a two-blackbody radiation model with temperatures of $3.3^{+0.5}_{-0.4}$ keV and $15.1^{+2.5}_{-1.9}$ keV. These two blackbody temperatures stay on the scaling reported by Nakagawa et al. (2009a), and accumulated spectra of other short bursts are discussed by Nakagawa et al.(2009b).

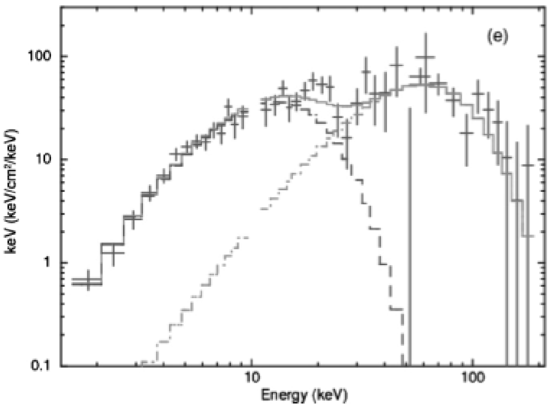

Fig. 2. The νF_ν spectrum of the largest burst of SGR 0501+4516 modeled by two blackbody components (Enoto et al., 2009a).

Suzaku also observed the persistent X-ray emission over the 0.8–200 keV band, as shown in Figure 4b. A hard X-ray emission was detected up to 70 keV by the HXD-PIN with a 3σ significance, while HXD-GSO data stays within 1% level of the X-ray background (a typical uncertainty level of GSO). Therefore we used only data from the XIS and PIN cameras for spectral fittings.

The pulse profiles have a sinusoidal shapes below 5 keV, while a second peak appears at a phase opposite to the main peak above 12 keV (Enoto et al., 2009b). The 0.5–70 keV spectrum consists clearly of two components, crossing over at ∼7 keV. The hard component has a very hard photon index of $\Gamma = 0.79^{+0.20}_{-0.18}$(stat.)$^{+0.01}_{-0.06}$(sys.). The persistent soft and hard X-ray fluxes are $8.7 \pm 0.8 \times 10^{-11}$ and $4.8^{+0.8}_{-0.6}$(stat.)$^{+0.8}_{-0.4}$(sys.) $\times 10^{-11}$ erg s^{-1} cm^{-2} in the 0.5–10 keV and 20–100 keV, respectively. The latter is consistent with that measured by the almost simultaneous *INTEGRAL* observation (Rea et al., 2009).

2.2. 1E 1547.0-5408

On 2009 January 22nd, an intensive bursting activity (∼250 short bursts in one day) was detected by the Wide-band All-sky Monitor (WAM) on board of it Suzaku, from the direction of the magnetar 1E 1547.0-5408. Figure 3a and 3b show short burst forests detected by one shielding counter of HXD-WAM in a day time (Terada et al., 2009). Figure 3c zooms on one of these short burst, occurred at 17:02:56 on January 22, which was detected up to ∼600 keV.

Suzaku performed a ToO observation on 2009 January 28–29 for 33 ks (Enoto et al., 2009d), seven days after the on-set of its strong bursting activity. The object remained in an outburst state with an absorbed fluxes of $5.71^{+0.15}_{-0.18} \times 10^{-11}$ and $1.25^{+0.08}_{-0.11}$(stat.) $\pm$ 0.10(sys.) $\times 10^{-10}$ erg cm^{-2} s^{-1} in the 2–10 and the 20–100 keV energy ranges, respectively.

The persistent X-ray emission was detected from ∼0.8 keV to 114 keV, and its pulse period was detected

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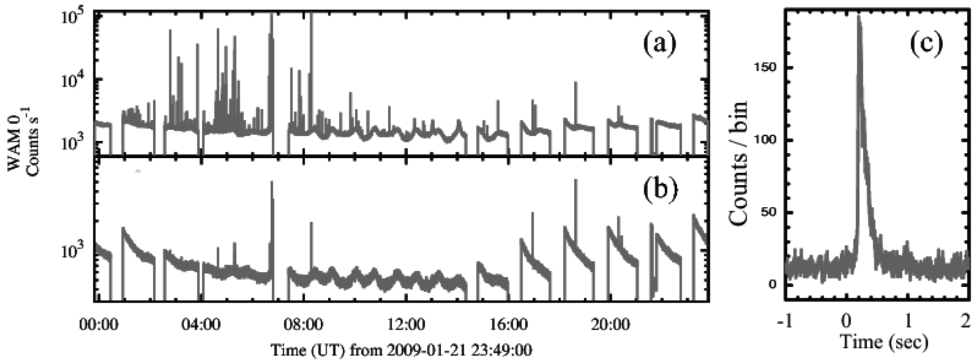

Fig. 3. (a) Short burst forests of 1E 1547.0-5408 detected by HXD-WAM on January 22 in the 71–324 keV energy band. (b) same as panel (a), but in the 324–534 keV energy range. (c) One short burst zoom up.

at 2.072135 ± 0.00005 s. The wide-band and phase-averaged spectrum was well fit by a blackbody emission with a temperature of 0.65 ± 0.02 keV and a strong hard X-ray tail having a power-law photon slope of $1.54^{+0.06}_{-0.05}$(stat.) $\pm$ 0.02(sys.) (Figure 4a). In addition to the persistent emission, 12 short bursts were detected in a range of 10^{-9}–10^{-7} erg s^{-1} cm^{-2} in the 10–70 keV energy range.

3. Spectral Evolution of Magnetars

Figure 4 compares the persistent soft plus hard X-ray spectra of three magnetars, 1E 1547.0-5408 and the newly discovered SGR 0501+4516 during their outbursts, and a famous AXP 4U 0142+61 (the latter was observed by *Suzaku* on 2007 August 15th for 102 ks; Enoto et al., 2009c). Their characteristic ages are 1.4 kyr, 18 kyr, and 70 kyr for 1E 1547.0-5408, SGR 0501+4516, and 4U 0142+61, respectively. The spectral shapes of magnetars have the tendency to become flatter/brighter in the hard X-ray band for younger magnetars, while become harder/dimmer above 10 keV. In addition to the above three magnetars, *Suzaku* has already observed other 7 magnetars, as shown in Figure 5. These spectral changes are also suggested from all 10 magnetars observed. A comprehensive study of magnetars by *Suzaku* will be reported elsewhere.

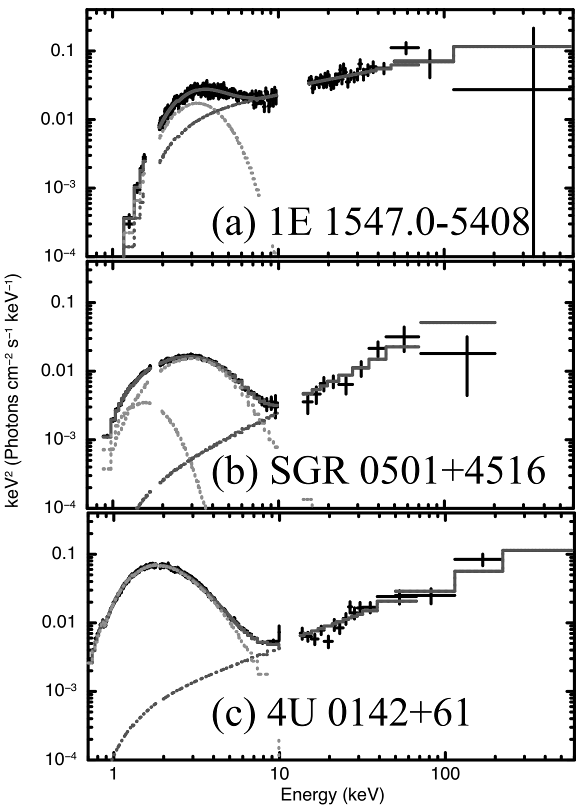

Fig. 4. Persistent spectra of (a) 1E 1547.0-5408 in outburst, (b) SGR 0501+4516 in outburst, and (c) 4U 0142+61.

In order to quantify these spectral changes we used the hardness ratio between the 20-100 keV and 2-10 keV unabsorbed fluxes. These hardness ratios do not dependent on the fine-structure of the spectral fitting. The hardness ratios are 1.64±0.40, 1.6±0.4, and 0.71±0.08, for 1E 1547.0-5408, SGR 0501+4516, and 4U 0142+61, respectively. Figure 6 shows possible correlations between these spectral hardness ratios to fundamental pulsar properties, such as (a) characteristic ages and (b) surface magnetic field strengths. Here we also plotted the previous results of XMM-*Newton* and *INTEGRAL* from Gotz et al. (2006), Rea et al. (2009), and the McGill SGR/AXP online catalog[1] . These correlations suggest the hard X-ray tail intensity (relative to the soft component) appears to correlate negatively with characteristic ages.

These new correlations may be key to investigate the origin of the emission mechanisms both of the soft and hard X-ray components of magnetars.

*1 http://www.physics.mcgill.ca/ pulsar/magnetar/main.html

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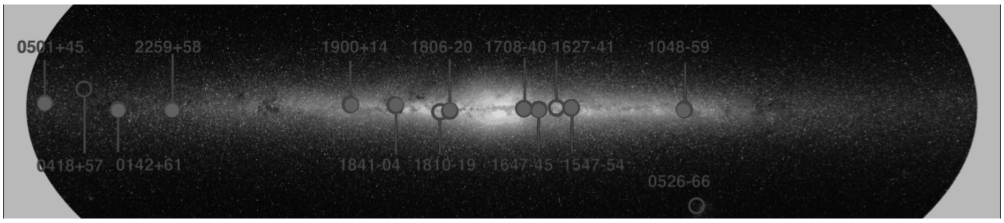

Fig. 5. Magnetar location on the Galactic plane. Red filled circles represent those targets which were already observed by *Suzaku*.

4. Summary and Conclusion

- The hard X-rays above 10 keV were observed in most of the magnetars by *Suzaku*. During large outbursts, both the soft X-ray and hard X-ray components become brighter.
- Photon index is extremely flat in AXPs ($\sim$1) while slightly less in SGRs. Ordinary acceleration and emission mechanism fails to explain these very hard emission.
- The intensity of the hard X-ray tail relative to the soft component appears to be negatively correlated with the characteristic age, although hardness ratios may change between different emission states, as e.g. during outbursts.
- Key project of magnetars (AO-4) is now going on, and these magnetars are good targets both for *MAXI* and *ASTRO-H*.

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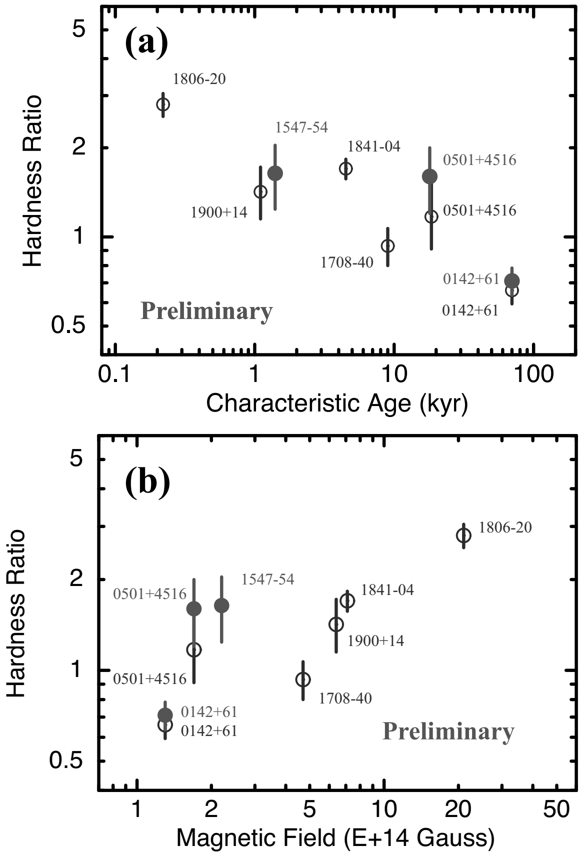

Fig. 6. Hardness ratios between the 20–100 keV and 2-10 keV unabsorbed fluxes of magnetars, versus (a) characteristic ages or (b) magnetic field strengths. Red points represents *Suzaku* data, while blue points are data of *INTEGRAL* and XMM-*Newton*.

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