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Energy Dependent Intensity Variations of Persistent X-ray Emission from Magnetars

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Magnetars, which are highly magnetized neutron stars with field strengths greater than the quantum critical level 4.4×10^{13} G, show persistent X-ray emission as well as sporadic bursts. Using *Suzaku* and HETE-2 data, we discovered that both the persistent X-ray emission and burst spectra consist of thermal ($<$10 keV) and hard X-ray ($>$10 keV) components. Luminosities of these components show a correlation over 5 orders of magnitude. We propose a model that the persistent X-ray emission consists of numerous micro-bursts of various sizes. In our model, intensity RMS variations should be larger than the values expected from the Poisson distribution. We thus calculated the RMS variation for 11 magnetars observed by *Suzaku* in the soft (0.2–12 keV) and hard (10–70 keV) band. As a result, the RMS variations are significantly greater than the values expected from the Poisson distribution in both energy bands, and they are greater in the hard band than those in the soft band.

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1. Introduction

1.1 Highly Magnetized Neutron Star "Magnetar"

Magnetars are unique objects to study physical phenomena under extremely high megnetic field strenghts, because they emit X-ray photons through magnetic field dissipation with field strengths greater than the quantum critical value 4.4×10^{13} G [1].

Phenomenologically, magnetars are known as the soft gamma repeaters (SGRs) and the anomalous X-ray pulsars (AXP). They exhibit persistent X-ray emission and some of them also show sporadic bursts. The persistent X-ray energy spectra are known to consist of thermal ($<$10 keV) and hard X-ray ($>$10 keV) components based on observations by RXTE [2], INTEGRAL [3, 4] and Suzaku [5, 6, 7, 8, 9]. Using *Suzaku* data of SGR 0501+4516 [10] and AXP 1E 1547.0−5408 [11], we discovered that the burst spectra also consist of the same components. Luminosities of those two components are found to exhibit a correlation over five orders of magnitude [10]. These characteristics suggest a common emission mechanism between the persistent X-ray emissions and the bursts. In addition, these results lead a possibility that the persistent X-ray emission consists of numerous micro-bursts of various sizes.

If the persistent X-ray emission consists of numerous micro-bursts of various sizes, dispersion of the micro-burst intensities exceeds that expected from of the Poisson distribution. To measure the dispersion quantitatively, RMS (Root Mean Square) intensity variation in the persistent X-ray emission is estimated to be larger than that expected from the Poisson distribution.

Suzaku data are suitable for estimations of the RMS intensity variations, because on-board narrow field instruments of X-ray imaging spectrometer (XIS; 0.2–12 keV; [12]) and the hard X-ray detector (HXD; 10–700 keV; [13]) have high sensitivities and wide energy bands.

2. Quantitative Estimation of RMS Intensity Variations using *Suzaku* Data

We analyzed 21 observational dataset for 11 magnetars observed by *Suzaku* summarized in table 1. Using 0.2–12 keV light curves obtained by the XIS, bursts with 5 sigma significance are removed from source light curves. Then we subtracted background counts from the source light curves.

First, we calculated RMS intensity variations using 0.2–12 keV XIS and 10–70 keV HXD/PIN light curves. The RMS intensity variations R_V are defined to be

$$R_V = \frac{\left[\frac{1}{N-1}\left\{\sum_i (x_i-\bar{x})^2 - \sum {\delta_{x_i}}^2\right\}\right]^{\frac{1}{2}}}{\bar{x}}, \tag{2.1}$$

where i is bin number, x_i is photons per bin, $\bar{x}$ is an average of x_i, δ_{x_i} is an error of x_i and N is a number of bins. Based on Monte Carlo simulations, we confirmed that variations due to rotations and flux decreasing/increasing do not affect the RMS intensity variations. We also confirmed using *Suzaku* data of Cas A and Coma cluster that variations caused by background fluctuations are found to be negligible. We calculated the RMS intensity variations for each observation using background-subtracted light curves in the 0.2–12 keV and 10–70 keV energy bands. The RMS intensity variations are found to be 1.3–18.8% in the 0.2–12 keV energy band and 17–99% in the

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Table 1: A summary of magnetars used in this study with their RMS intensity variations.

Object[a]	OBSID[b]	Date[c] (UTC)	$R_{V(\mathrm{XIS})}$[d] (%)	$R_{V(\mathrm{HXD/PIN})}$[e]
SGR 0501+4516	404078010	2009-08-17	9.2±1.1	50 ± 6
	405075010	2010-09-20	7.2±2.5	99 ± 86
	903002010	2008-08-26	7.37±0.07	–
SGR 1833−0832	904006010	2010-03-27	18.8±1.1	–
SGR 1900+14	401022010	2006-04-01	6.8±2.7	–
	404077010	2009-04-26	9.6±3.5	–
SGR 1806−20	401021010	2007-03-30	6.4±4.8	31 ± 19
	401092010	2006-09-09	6.5±0.8	17 ± 13
	402094010	2007-10-14	4.2±0.5	< 55
	406069010	2012-03-24	16.4±0.4	–
AXP 1E 1547.0−5408	405024010	2010-08-07	8.4±0.6	20 ± 12
	903006010	2009-01-28	14.7±0.2	22 ± 5
AXP 4U 0142+614	402013010	2007-08-13	2.0±0.1	< 40
	404079010	2009-08-10	1.3±0.3	33 ± 20
	406031010	2011-09-07	1.8±0.3	< 42
AXP 1E 1048.1−5937	403005010	2008-11-30	3.0±1.0	–
AXP Swift J1822.3−1606	906002010	2011-09-13	6.0±0.3	–
AXP CXOU J164710.2−455216	901002010	2006-09-23	3.3±0.7	–
AXP 1RXS J170849.0−400910	404080010	2009-08-23	7.85±0.07	23 ± 16
	405076010	2010-09-27	9.25±0.06	< 36
AXP 1E 2259+586	404076010	2009-05-25	4.1±0.1	–

(a) Object name of the SGRs and AXPs.
(b) *Suzaku* observation ID.
(c) Date of the observation start.
(d) The RMS intensity variations in 0.2–12 keV.
(e) The RMS intensity variations in 10–70 keV.

10–70 keV energy band summarized in table 1, after subtracting the variance expected from the Poisson distribution.

Next, We investigated an energy dependency of the RMS intensity variations using the data of XIS and HXD-PIN. We found that the RMS intensity variations clearly increase in higher energy band for 4 magnetars (6 observations) as shown in panels (a), (b), (c), (g), (l) and (n) in figure 1. Figure 1 shows an energy dependency of the RMS intensity variations for each observation.

3. Summary

We quantitatively estimated RMS intensity variations using *Suzaku* data archives for 11 mag-

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netars (21 observations). The intensity RMS variations are significantly greater than the values expected from the Poisson distribution for 21 observations in the 0.2–12 keV energy band (XIS) and 8 observations in the 10–70 keV energy band (HXD/PIN). This result supports our idea that the persistent X-ray emission consists of numerous micro-bursts. We also discovered an energy dependency of the RMS intensity variations for 4 magnetars (6 observations), that the RMS intensity variations clearly increase in higher energy band. Among these 6 observations, the RMS intensity variations are highly increased above $\sim$8 keV and $\sim$4 keV for SGR 0501+4516 (OBSID=404078010; figure 1a) and AXP 1E 1547.0$-$5408 (OBSID=903006010; figure 1l), respectively. These energies are crossing points of the soft thermal components and the hard X-ray components. The positive energy dependency of the RMS intensity variations implies that the hard X-ray components vary much significantly than the soft thermal component.

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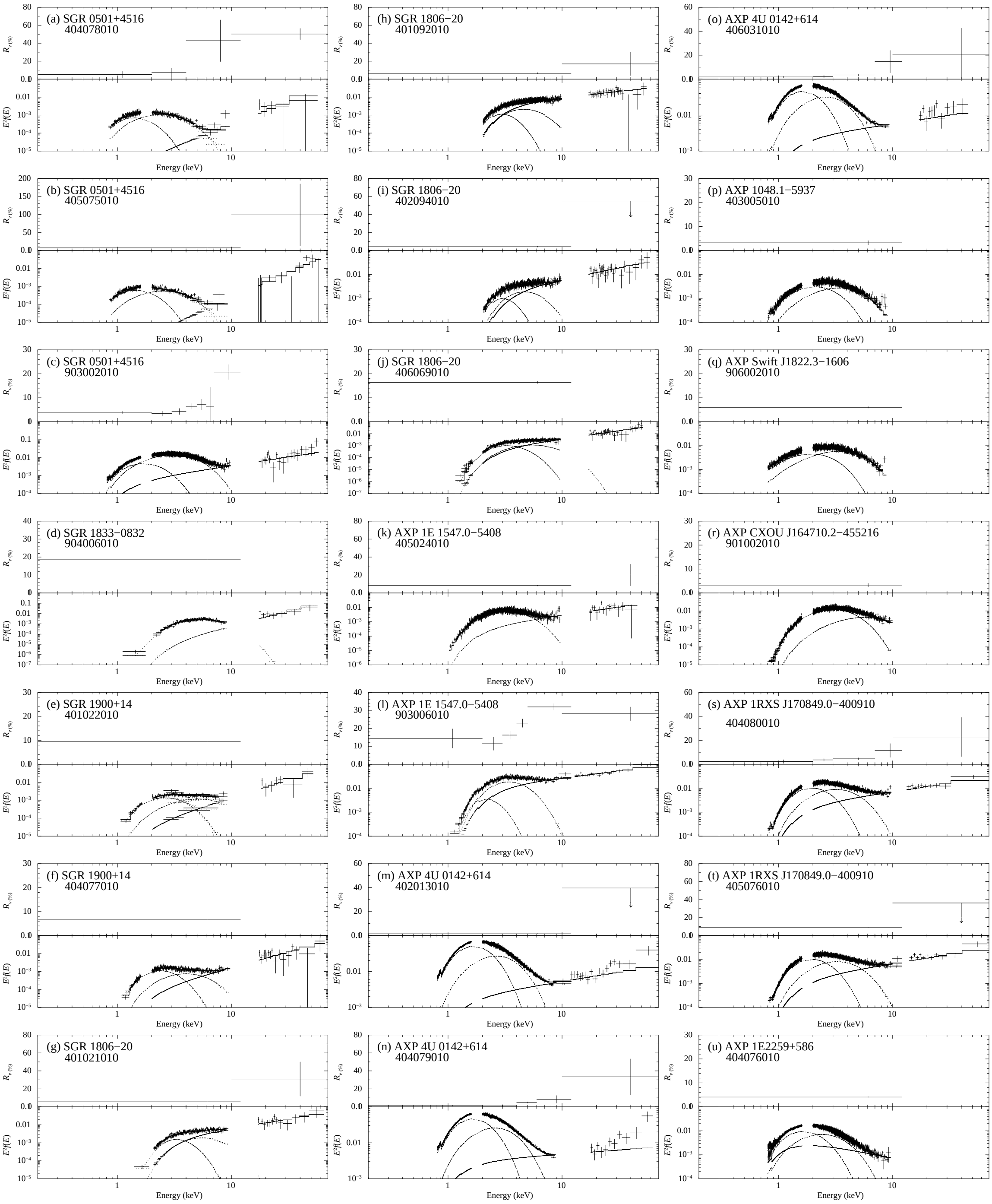

Figure 1: Spectra of the RMS intensity variations and $E^2 f(E)$ spectra.

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