Spatial Power Spectral Analysis of the Suzaku X-Ray Background

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Abstract

Power spectra of spatial fluctuations of X-ray emission may impose constraints on the origins of the emission independent of that from the energy spectra. We generated spatial power spectrum densities (PSDs) of blank X-ray skies observed with the Suzaku X-ray observatory utilizing the modified Δ-variance method. Using the total measured count rate as the diagnostic tool, we found that a model consisting of the sum of two components, one for the unresolved faint point sources and one for the uniform flat-field emission, can represent well the observed PSD in three different energy bands (0.2–0.5, 0.5–2, and 2–10 keV); only an upper limit is obtained for the latter component in 2–10 keV. X-ray counting rates corresponding to the best-fit PSD model functions and diffuse emission fractions were estimated, and we confirmed that the sum of the counting rates of two model components is consistent with those actually observed with the detector for all energy bands. The ratio of the flat-field counting rate to the total in 0.5–2 keV, however, is significantly larger than the diffuse emission fraction estimated from the model fits of energy spectra. We discussed that this discrepancy can be reconciled by systematic effects in the PSD and energy spectrum analyses. The present study demonstrates that the spatial power spectrum analysis is powerful in constraining the origins of the X-ray emission.

1. Introduction

The origin of the cosmic X-ray background (CXB) has been meticulously studied since its first discovery in the early 1960s (Giacconi et al. 1962). With the deep exposure of ROSAT, Chandra, and XMM-Newton, a substantial fraction, yet not all, of the CXB in soft (0.5–2 keV) and hard (2–10 keV) energy bands has been resolved as discrete source emissions (Moretti et al. 2003; Lehmer et al. 2012). There is consensus that the CXB above 2 keV will be eventually resolved into faint sources in the future with high-spatial-resolution, high-sensitivity observations and that these discrete sources are primarily faint AGNs and soft X-ray galaxies, which have been confirmed with their multiwavelength counterparts (Barger et al. 2001a, 2001b). However, the CXB below about 2 keV is considered to contain hot gas emission from our Galaxy since the first detection in 1968 (Bowyer et al. 1968; McCammon & Sanders 1990). The local emission from the Galaxy is considered to consist of three components: the solar-wind-induced charge exchange (SWCX) emission from the heliosphere (Lisse et al. 1996; Cravens et al. 2001; Snowden et al. 2009; Koutoumpa et al. 2011), the thermal emission from the hot gas (kT ~ 0.1 keV) in the Local Bubble extending to about a few 100 pc scales (McCammon & Sanders 1990; Snowden et al. 1998; Snowden 1998; Galeazzi et al. 2014; Liu et al. 2017), and the emission from the hot gas (kT ~ 0.2 keV) beyond the bulk of the galactic neutral interstellar medium (Kalberla & Kerp 1998; Pietz et al. 1998; Kuntz & Snowden 2000; Yoshino et al. 2009).

All of the aforementioned local emission components are spatially extended and contain emission lines. Some of the strong emission lines have been resolved from the continuum emission with the X-ray microcalorimeter spectrometer on board the XQC sounding rocket experiment and also with the X-ray CCD (charge-coupled device) instruments on board the XMM-Newton, Chandra, and Suzaku observatories. Those spectral features are key to determining the fraction of Galactic components in the CXB. However, the results are highly dependent on the emission model, in particular, the metal abundance of the hot gas assumed in the analysis and spectral model fits.

In addition to the Galactic diffuse emission, the WHIM (warm-hot intergalactic medium; Cen & Ostriker 1999) may contribute to the CXB below 2 keV. The WHIM emission is also spatially extended; however, the length scales of the spatial variation are likely different from those of the Galactic diffuse components.

A few studies attempted to evaluate the WHIM contribution to the diffuse X-ray background using angular clusterings of the WHIM in the unresolved CXB, although no consensus has been reached thus far. Galeazzi et al. (2009) measured the X-ray background in the XMM-Newton satellite and reported that 12% ± 5% of the diffuse emission in the 0.4–0.6 keV energy range is owing to the intergalactic medium (IGM). Forecasting from the hydrodynamic simulation model, Ursino & Galeazzi (2006) estimated the characteristic angular size of the WHIM to be less than a few arcminutes by the autocorrelation function. Cappelluti et al. (2012) investigated the CXB using 4 Ms deep observations of the Chandra Deep Field-South with the power spectral analysis and estimated that ~55% of the unresolved CXB flux, i.e., the CXB flux after removing contributions of all the point sources resolved with the instrument, originates from the IGM in 0.5–2 keV band.
and a third of which is produced by the WHIM ($10^5 < T < 10^7$ K and density contrast $\delta < 1000$).

In this paper, we present the spatial power spectral analysis of Suzaku blank-sky observations. Because the spatial resolution of X-ray telescopes is limited ($\sim 1'$) compared to that of Chandra and XMM-Newton ($\sim 1''-15''$), we will not be able to resolve the clustering of the WHIM. However, we expect that we can distinguish the emission of the unresolved point sources from the spatially extended Galactic emission, and the result is not susceptible to the spectral model that is assumed. We describe our data set and the method in Section 2. The results are presented and discussed in Section 3. We compare our result with the ROSAT R4 band in Section 4. In Section 5, we present the conclusion.

2. Analysis Methods

2.1. Data Reduction

Based on a sample of 187 Suzaku X-ray imaging spectro-meter (XIS) observations of the diffuse X-ray background from 2005 to 2012 (Sekiya et al. 2014), we further screen the CXB data to obtain a robust mask that excludes any distinguishable source-related gradient in the field. First, the images of the Suzaku/XIS observations are produced following the standard full XIS reprocessing and screening routine via the Aepipe-line command integrated in Suzaku FTOOLS in HEASoft (version 6.26.1). With the latest calibration database (last modified on 2018 October 10 for XIS), any illuminated corners caused by calibration sources or hot and flickering pixels have been fully removed in the clean event files. These images are then sent to the manual mask selection to ensure that (1) any resolved point source and vicinity region will be excluded with the masks, (2) any suspicious spots that are systematically brighter than the average fluctuation field will be removed using masks, (3) any observation that has shown a clear large gradient over the image, instead of a background fluctuation, will be discarded, and (4) any observation that has less than a 30% effective area left after being masked will be discarded. Later on, we performed a visual inspection of the blank-sky sample, and no significant features are seen in the

masked images. We show some examples of masked images of Suzaku observations in Figure 1.

For most Suzaku observations, images from detectors XIS0, XIS1, and XIS3 are available, given that XIS2 has not been functioning since 2006. We discarded all XIS2 images and 103 observations after the screening process, remaining 84 images for XIS0, 1, and 3, respectively, for the power spectrum calculation, of which the accumulated observation time equals $\sim 1$ Ms for each detector. As a thinned backside-illuminated (BI) device, XIS1 has a higher sensitivity to X-ray photons at soft energy bands compared with the front-side illuminated (FI) chips, XIS0 and XIS3. We analyzed the images from different detectors separately.

2.2. Method to Estimate the Spatial Power Spectrum Density

To robustly evaluate the fluctuation of the diffuse background at various scales for the images with gaps and holes, we adopt a modified $\Delta$-variance method to calculate the power spectrum of the image using a mask (Arévalo et al. 2012). The masked image is convolved with a Mexican-hat filter, which is equivalent to the difference between two Gaussian functions with smoothing lengths $\sigma_1 = \sigma/\sqrt{1 + \epsilon}$, $\sigma_2 = \sigma\sqrt{1 + \epsilon}$, where $\epsilon \ll 1$. The filter can be described by

$$\hat{F}_k(k) = G_{\sigma_1}(k) - G_{\sigma_2}(k) = e^{-2\pi^2k^2\sigma_1^2} - e^{-2\pi^2k^2\sigma_2^2}$$

(1)

$$\approx 4\pi^2\sigma^2\epsilon k^2 e^{-2\pi^2k^2\sigma_1^2}$$

(2)

where $k$ is the spatial frequency/wavenumber (the angular length scale $\theta = 1/k$). The shape of the filter frequency response does not depend on $\epsilon$ in the limit of $\epsilon \rightarrow 0$ as shown in Equation (2). The filter takes a maximum at $k = k_\epsilon \equiv 1/(\sqrt{2}\pi\sigma) = 0.225/\sigma$, and the response is rather broad (full width is $\sim k_\epsilon$). We adopt $\epsilon = 0.01$ for this study.

The mask, $M$, is defined to be one for the image pixels used for analysis, and to be zero for the pixels discarded. Convolving the masked image with a Gaussian function will produce spurious features. Their amplitudes can be corrected by dividing by the mask that is convolved with the same Gaussian function. Therefore, the difference between two corrected images will be a good estimation for the fluctuation.
of the original image at a frequency scale of $k_r$, thus at a spatial length scale of $\sigma$. The variance of the image at that frequency can be estimated as

$$V_{k_r,\text{obs}} = \frac{N}{N(M=1)} \int \left( \frac{G_{\sigma}^* I}{G_{\sigma}/M} - \frac{G_{\sigma}^* I}{G_{\sigma}^*/M} \right)^2 M^2 d^2 x,$$

(3)

where $N$ and $N(M=1)$ are the total number of original pixels and adopted pixels, respectively, and $I$ denotes the masked image in the unit of counts. The symbol $^*$ represents a convolution, namely,

$$G_{\sigma}^* I = \int G_{\sigma}(y) I(x - y) d^2 y,$$

(4)

where $x$ and $y$ are two-dimensional vectors.

The power spectrum density (PSD) can be estimated by normalizing $V_{k_r,\text{obs}}$ by the two-dimensional frequency bandwidths of the filter. Thus,

$$P(k_r) = \frac{V_{k_r,\text{obs}}}{\int |\mathcal{F}_c(k)|^2 d^2 k},$$

(5)

We further renormalized $P(k)$ so that it represents the PSD of the surface brightness:

$$P_{s}(k) = \frac{P(k)}{ST^2},$$

(6)

where $S$ and $T$ are, respectively, the solid angle of the sky selected by the mask (where $M = 1$) and the exposure time of the observation. In this equation and hereafter, we replace $k_r$ with $k$ for convenience. The characteristic angular length scales range from $37^\prime\prime$ to $930^\prime\prime$ to sample the PSD of the Suzaku observations, which are limited by the image pixel size and the field of view of the telescope, respectively. The sampling rate is chosen such that at each frequency the Mexican-hat filter function of the next point decays to $1/\sqrt{2}$ of its maximum value.

2.3. Non-X-Ray Background Subtraction

The non-X-ray background (NXB) originates from cosmic rays and solar protons in space going through the spacecraft, interacting with materials inside, and depositing energy on the CCD detectors. Owing to the low-orbit altitude of the Suzaku satellite, the NXB level of Suzaku is significantly less influenced by solar flares and is more stable than Chandra and XMM-Newton (Yamauchi et al. 2006). Moreover, the predicted counts of the NXB for each observation can be reliably estimated based on the satellite orbital period, given that the NXB is anticorrelated with the cutoff rigidity and correlated with the count rate of the PIN upper discriminator on board Suzaku (Tawa et al. 2008).

The spectra and image of the NXB are available from the observation of night-Earth events for Earth elevation angles less than $-5^\circ$ (Tawa et al. 2008). From the database, we can construct an NXB event list suited for a particular observation of each of the four XIS sensors separately. The event lists contain night-Earth events within $\pm$ half a year of the observation and with the same cutoff rigidity time distribution as the observation. From the events, we can construct NXB images, subtract the NXB images from the observational images, and then calculate the spatial PSD for the subtracted images. Alternatively, we may first calculate the PSDs of the observations and NXB images respectively and calculate the difference. We tried two methods and found that the difference is negligibly small between the two PSDs. However, we decided to adopt the first method for the following two reasons. First, the PSD of the raw image may contain the cross-terms of the observed and NXB images, which cannot be subtracted by NXB PSD subtraction. Second, the NXB PSD consists of the Poisson-noise component and the spatial gradient component. The spatial gradient component can be subtracted by the first method using the NXB image with a much longer accumulation time than the observation, thus the Poisson noise itself is negligible for those NXB images constructed for spatial gradient PSD subtraction, and the Poisson-noise PSD of the NXB in the observations can be subtracted independently by the A-B technique (see the next subsection). $I$ in Equation (3) is now given by

$$I(x) = I_{\text{obs}}(x) - \frac{T_{\text{obs}}}{T_{\text{NXB}}} I_{\text{NXB}}(x),$$

(7)

where $I_{\text{obs}}$ and $I_{\text{NXB}}$ are, respectively, the masked-observation and NXB images, and $T_{\text{obs}}$ and $T_{\text{NXB}}$ are their exposure times.

2.4. Poisson-noise Subtraction

Spatial fluctuation due to the Poisson counting statistics is significant for both the observation and the NXB images, in particular, at high frequencies. We estimated the PSD of the Poisson fluctuation using the A-B technique (Kashlinsky 2005) and subtracted it from the PSD. We divide the observation, which contains the NXB events, into even and odd events in time sequence, construct even and odd images (A and B images) for each observation, calculate PSD for the (A-B)/2 images, and subtract them from the PSDs of the NXB-subtracted observation images.

2.5. Ensemble Average and Standard Deviation of PSD

Our data consist of in total 252 images of Suzaku observations from three XIS(0,1,3) CCD detectors. We average all the Poisson-noise-subtracted PSDs for each corresponding XIS chip independently as

$$\bar{P}_{s}(k) = \frac{1}{n} \sum_{i=1}^{n} P_{s,i}(k),$$

(8)

where $P_{s,i}(k)$ is the Poisson-noise-subtracted PSD of the $i$th observation, and $n$ is the total number of PSDs averaged. Then we estimate the standard deviation of the PSD from the variance of $P_{s,i}(k)$,

$$\sigma_{P_{s}}(k) = \sqrt{\frac{\sum_{i=1}^{n} (P_{s,i}(k) - \bar{P}_{s}(k))^2}{n(n - 1)}}.$$

(9)

In the next section, we will perform $\chi^2$ model fitting to $\bar{P}_{s}(k)$ using $\sigma_{P_{s}}(k)$ as the standard deviation. Strictly, it is not correct because the NXB events used to estimate spatial power, which is later subtracted in $P_{s,i}(k)$, partly overlap with each other. However, because the contribution of the NXB spatial gradient to the power spectrum is at most 10% beyond 150", we still use $\sigma_{P_{s}}(k)$ as the error of $\chi^2$ fitting.
2.6 Nonuniformity of Effective Area

The effective area of the observed images is not spatially uniform because of two reasons: the vignetting of the telescope (Serlemitsos et al. 2007) and the nonuniform thickness of the contaminants stuck on the optical blocking filter of the XIS detectors, which create extra absorption in soft X-ray bands. The nonuniformity works as a window function of the Fourier analysis. Thus, the true Fourier transform of the sky image will be convolved with the Fourier transform of the nonuniformity function so that the obtained PSD is smoothed by this transfer function. Figure 2 shows the exposure maps for the flat field in different energy ranges, illustrating the spatial nonuniformity caused by the vignetting effect and contamination. Given the small gradient in the exposure map image, the frequency bandwidth of this window function filter due to the nonuniformity is in general narrower than that of the Mexican-hat filter. Both filters smooth the PSD but have different influences on the power at zero frequency because the nonuniformity of the effective area convolves the PSD at zero frequency, but the Mexican-hat filter only maximizes the power at its own smoothing length scale, as shown in Equation (2). The power at zero frequency spreads out to the PSDs at nonzero frequencies by the nonuniformity of the effective area first and then gets further smoothed with the Mexican-hat filter. We took these effects into account when modeling and fitting for the observed PSD (see Section 2.8).

In order to create model PSD functions, we first constructed a simulation event list using the ray-tracing Monte Carlo simulator xissim in which both the vignetting and contamination are considered as functions of photon energy (Ishisaki et al. 2007). In the present analysis, we extend our energy range down to 0.2 keV, which is not supported in the standard analysis package. To extend the energy range, we adopted the latest update of the contamination calibration. The contamination source is considered to be the outgassed plastic material from the antivibration rubber protecting the inertial reference unit during the launch of the spacecraft. The effect of the contamination on the Suzaku X-ray spectra below 0.5 keV was recently extensively studied by Nagayoshi (2019), and the calibration database was revised. According to this study, the contaminant contains S in addition to the elements C, H, and O, which were previously considered. This study successfully reproduced the 15 X-ray spectra of the calibration source, RX J1856.5–3754, in the 0.2–1 keV band observed from 2005 to 2014. It was also shown that the new calibration database better reproduces an improved energy spectrum of the other calibration source, 1E0102.2–7219, which is subject to a larger Galactic absorption than RX J1856.5–3754 in the range of 0.3–3 keV. We used the new calibration database in the ray-tracing simulation.

2.7 Point-spread Function of the Telescope

The sky image is convolved with the point-spread function (PSF) of the telescope before being detected by the X-ray CCD cameras. Consequently, the Fourier transform of the sky image is multiplied with the Fourier transform of the PSF and consequently attenuated significantly in the high-frequency range. We also take this effect into account in the PSD modeling by creating the power spectrum for the point source using the xissim ray-tracing simulation. The shape of PSF varies across the field of view of the XIS detectors, and the response is averaged over the detector plane given the wide and random distribution of X-ray sources in the field of view.

2.8 Model PSDs for Unresolved Point Sources and a Uniform Flat Field

We constructed two model functions, one for the unresolved point sources (UPS) and the other for the uniform flat-field emission (UFF) using Monte Carlo simulations. The latter model is used to represent the diffuse X-ray background.

To construct a realistic UPS model, we need a spatially random point-source sample whose brightness distribution obeys the log N–log S relation of the sky. Because we average the PSDs from different Suzaku observations with different exposure times, the detection threshold of the point sources varies from field to field. We, however, represent the detection threshold with a single model parameter, $S_{\text{max}}$, the flux of the point source in the corresponding energy band. We adopt the log N–log S relation from Moretti et al. (2003). We generate simulation point sources whose energy flux is between $S_{\text{min}}$ to $S_{\text{max}}$ in a circular sky region of a 20' diameter. The value of $S_{\text{min}}$ was $1 \times 10^{-17}$ erg s$^{-1}$ cm$^{-2}$ and $1 \times 10^{-16}$ erg s$^{-1}$ cm$^{-2}$ for the 0.5–2 keV band and for the 2–10 keV band, respectively. We do not have an observed log N–log S for the 0.2–0.5 keV band. We thus scaled the point-source energy flux in the 0.5–2 keV band to that of the 0.2–0.5 keV band to obtain a reference log N–log S for this band, assuming an energy spectrum of an absorbed power-law spectral shape, modeled by tbabs*po in XSPEC with the hydrogen column density $N_H = 2.5 \times 10^{20}$ cm$^{-2}$ and the photon index $\Gamma = 2$. The flux lower limit $S_{\text{min}}$ is chosen to be $1 \times 10^{-17}$ erg s$^{-1}$ cm$^{-2}$ for the 0.2–0.5 keV band, below which the detector is no longer sensitive to receive any photons given the simulation time. The X-ray emission of the point sources in the chosen field of view is generated via the Monte Carlo simulator xissim.

To generate a photon list in the simulation, we need to specify an energy spectrum for each source. We adopted a

![Figure 2](image-url)
power-law function absorbed by the galactic cold interstellar medium. The photon index is 2.0 for the sources simulated in all energy bands, and we assumed a galactic HI column density of $N_{\text{H}} = 2.5 \times 10^{20} \text{ cm}^{-2}$ for all sources.

We generated a photon list for 66.5 ks of observation (the average exposure time of the Suzaku samples) and calculated the PSD according to the method described in Sections 2.2 and 2.4. The photon lists for sources over a sky area of $3 \text{ deg}^2$ are generated assuming the log-$N$-log-$S$ relation in each energy band. The total numbers of the photon lists are 21,085 for the 0.2–0.5 keV, 38,289 for the 0.5–2 keV, 23,375 for the 2–10 keV energy bands. We selected 14 subsets of the photon list in a circular sky region of a 20′ diameter to mimic different pointings of the observations and calculated the ensemble average and standard deviation of PSDs as described in Section 2.5.

To fit for the observed PSD spectrum, we generated the average PSD models with a series value of $S_{\text{max}}$. Figure 3 shows the PSD model functions simulated with various $S_{\text{max}}$ for the 0.2–0.5 keV, 0.5–2 keV, and 2–10 keV energy bands. The free parameter of the UPS model is $S_{\text{max}}$ during the fitting procedure. The fitted PSD $S_{\text{max}}$ is interpolated linearly from the $S_{\text{max}}$ of the PSD models based on the model and the observed PSD spectrum amplitude.

We assumed a simple power-law energy spectrum for all point sources in the simulations. In reality, the spectral shapes are different for different point sources, and as a result, the average spectrum may be described with double broken-power-law functions as described in Section 4.1. In order to check the dependence of the analysis results on the assumed spectral shapes of point sources, we also created the UPS PSD assuming double broken-power-law functions for the energy spectrum with model parameters determined in the section. We found the difference of all the results described below is well within the statistical errors. Thus, we will only adopt and discuss the results utilizing the simple power-law model for the energy spectrum hereafter.

We also constructed a model UFF PSD function with the xissim ray-tracing simulator, assuming a power-law function with a photon index $\Gamma = 2.0$ without Galactic absorption for the energy spectrum. The size of the flat field is $20'$ as the default setting of xissim, and the XIS was pointed to the center of the flat field in the simulation. The power-law energy spectrum assumption might be too simple for the diffuse emission, but it is confirmed that the UFF model count rate and PSD do not depend on the energy spectrum of the input source. That is, to check the energy dependence, we assumed an alternative spectral model consisting of the sum of an absorbed and an unabsorbed thermal emission as described in Section 4.1 and modeled the PSD with the spectral parameters fixed to the best-fit values for Suzaku observations. Then we compared the PSD amplitude and count rate with the ones simulated assuming the simple power-law function. As a result, we found that the two UFF PSD models with different energy spectra are identical to each other. We thus adopt the PSD model based on the simple power-law spectrum in the following analysis.

UFF emission intrinsically contains power only at zero frequency. However, we see nonzero power at nonzero frequencies owing to the nonuniformity of the effective area (see Section 2.6). The surface brightness of the UFF model can be arbitrary because the PSD amplitude of the UFF model is proportional to the square of the model surface brightness, or the count rate. The uniform diffuse emission component in the observed PSD will be represented by the UFF model that is scaled with a normalization factor, which is the actual free parameter of the PSD fitting.

3. Results

3.1. Sky-averaged PSD in Three Energy Bands

The spatial PSDs averaged over 252 observation fields were obtained in three different energy bands for XIS1 (back-illuminated CCD) and in two bands for XIS0 and XIS3. The PSDs of three different detectors are consistent with each other after correcting for the difference in the effective area. We concentrate on the XIS1 results to study the energy dependence of the PSD. The Poisson-noise-subtracted PSD is shown in Figure 4 with 1σ error bars, where the $x$-axis of the plot is the length scale $\theta$ (the quantity denoted by $k$ in Section 2.2).

3.2. PSD Model Fitting

In order to find out whether the observed PSD can be explained by a sum of spatial fluctuations due to the unresolved point sources and due to the flat field, we fitted them with the...
model function:

$$PSD(\theta) = PSD_{UPS}(\theta, S_{\text{max}}) + B \ PSD_{UFF}(\theta),$$

where $PSD_{UPS}$ and $PSD_{UFF}$ are, respectively, the PSD models for UPS and UFF of the relevant energy band, and both are functions of the angular length scale, $\theta$. $S_{\text{max}}$ and $B$ are free parameters of the fit. We minimized the $\chi^2$ and obtained the results shown in Table 1.

The best-fit model functions and the residuals are shown in Figure 4. The model function represents the observed PSD generally well. The minimum $\chi^2$ values for 0.2–0.5 and 2–10 keV are large: The upper tail probabilities are, respectively, 0.36% and 2.3%. We see in Figure 4 a systematic deviation of the data points over the model at length scales below $\approx 200$″ affecting the fit results. This deviation extends down to the shortest length-scale bin, thus the length scale of the fluctuation is shorter than that of the PSF of the telescope. The large error bars of these bins suggest large field-to-field variations. We thus consider that some flickering pixels of the X-ray CCD camera that could not be removed in the 0.2–0.5 keV band are the reason causing the deviation on the short length scale. Flickering pixels are the CCD pixels that intermittently generate output pulse heights higher than the hot-pixel threshold even without input signals, which are not usable for observations and have to be disregarded in scientific analysis. The hot-pixel rejection is processed well above 0.5 keV but might not be as clean for 0.2–0.5 keV because the calibration was only recently updated for this energy band.

### Table 1

| Energy Band (keV) | 0.2–0.5 | 0.5–2 | 2–10 |
|------------------|---------|-------|------|
| $S_{\text{max}}$ | 1.2$^{+0.2}_{-0.1}$ | 0.82$^{+0.04}_{-0.04}$ | 2.9$^{+0.2}_{-0.2}$ |
| $B$              | 0.077$^{+0.074}_{-0.075}$ | 0.14$^{+0.05}_{-0.05}$ | 0.15 |
| $\chi^2$        | 22.8 | 3.88 | 17.8 |
| d.o.f.           | 8 | 8 | 8 |

**Note.**

$^a$ In units of $10^{-14}$ erg s$^{-1}$ cm$^{-2}$. Quoted errors are single-parameter 1σ errors.

The best-fit values of $S_{\text{max}}$ seem to be reasonable when we compare the energy flux distribution of point sources detected in the observation and removed from the PSD analysis. The cutoff of the flux distribution is around $5 \times 10^{-15}$, $2 \times 10^{-14}$, and $6 \times 10^{-14}$ erg s$^{-1}$ cm$^{-2}$ for the 0.2–0.5 keV, 0.5–2 keV, and 2–10 keV bands, respectively.

We can estimate the counting rates of the best-fit PSD models of respective energy bands from the photon lists created by xissim. For the UPS model, this can be readily done by interpolating the counting rates from simulations of nearby $S_{\text{max}}$ values. For the UFF model, the counting rate of the model component scales with $B$. We thus obtain the counting rates of both UPS and UFF emission that produces the observed PSD. The total counting rate of each energy band is just the sum of the counting rates of two components. The 1σ error intervals for the fitting parameters, $S_{\text{max}}$ and $B$, are determined using the $\chi^2$ contour map shown in Figure 4, where the minimum and maximum values of $S_{\text{max}}$ and $B$ are picked.
among all their combinations satisfying $\chi^2 \leq \chi_{\text{min}}^2 + 1$. We also estimated the counting rate from the energy spectra of the same observations (see Section 4.1) and show the results in Table 2. We find that the total counting rates from the PSD fitting and the energy spectrum are consistent with each other within the $1\sigma$ statistical errors. According to the PSD fit results in the table, we further estimate the fractions of the flat-field diffuse emission to the total for the three energy bands, which are $60^{+4+2}_{-4-2}$%, $56^{+2\%}_{-2\%}$, and $<23\%$ in 0.2–0.5, 0.5–2, and 2–10 keV, respectively. The $1\sigma$ error intervals are again estimated by the $\chi^2$ contours in Figure 4.

We obtained only an upper limit for the diffuse emission in the 2–10 keV bands, which means that the PSD can be explained with merely unresolved faint point sources. For the 2–10 keV band, this is consistent with the present understanding of the cosmic X-ray Background above 2 keV (Moretti et al. 2003; Gilli et al. 2007; Lehmer et al. 2012). For the 0.2–0.5 keV band, the uncertainty of the fitted diffuse fraction is large. However, at a $1\sigma$ confidence limit, at least 18% diffuse emission is supposed to exist in this band. For the 0.5–2 keV band, the PSD cannot be explained with only unresolved point sources and an additional component representing a flat diffuse emission is needed.

### 4. Discussion

#### 4.1. Diffuse Fraction in 0.5–2 keV: Comparison with the Energy Spectra

We have derived the spatial PSD of the X-ray background in a length scale around $50^\circ$–$100^\circ$ for three different energy bands. The PSD in 2–10 keV can be well described with a model representing the UPS. This result is consistent with previous results that about 90% of the 2–10 keV X-ray background was resolved into point sources and that the rest of the emission is likely from fainter sources. On the other hand, the PSD of the 0.5–2 keV band requires an additional PSD model representing the UFF emission. We estimated the counting rate of the two PSD components, and the results inferred that $56^{\pm3\%}$ of the total count rate in this energy band is associated with the diffuse flat-field emission. For 2–10 keV, we obtained an upper limit of 23% for the diffuse emission. For the lowest-energy band, 0.2–0.5 keV, the diffuse emission fraction of the total background is $60^{+42\%}_{-39\%}$.

In this subsection, we will compare those results with the energy spectra obtained with the same Suzaku observation.

We first derived energy spectra of 84 images described in Section 2.1 and fitted the 84 XIS1 energy spectra in 0.2–10 keV separately. With respect to the spectral model, we followed the same strategy introduced in Yoshino et al. (2009). They fitted the energy spectrum of the X-ray background in ~0.5–10 keV with a spectral model consisting of two thin thermal emission components and a double broken-power-law component (e.g., Yoshino et al. 2009). One of the thin thermal components is considered to represent a sum of the SWCX emission and the emission from the Local Bubble, modeled by APEC in XSPEC, which is not subject to Galactic absorption. The other thin thermal component is considered to arise from the hot gas in the halo of our Galaxy, thus it is subject to Galactic absorption. The double broken-power-law component is considered to represent the emission from extragalactic faint point sources and is subject to Galactic absorption. This component is a sum of the two broken-power-law functions. The two power-law photon indices are fixed at 1.96 and 1.54, respectively, below 1.2 keV, while both indices are fixed at 1.4 above 1.2 keV. The normalization factor of the power-law function with an index of 1.54 below 1.2 keV is fixed at 5.7 photon s$^{-1}$ cm$^{-2}$ keV$^{-1}$ sr$^{-1}$ at 1 keV, and only the normalization factor of the other power-law component is set free for spectrum fitting. We fixed the absorption column density to the value estimated from 21 cm observations (HI4PI Collaboration et al. 2016). There were five free parameters of the spectrum fitting: three normalization factors and the temperatures of the absorbed and the unabsorbed thin thermal components. The resultant reduced $\chi^2$ values were in the range of 0.95 to 3.99 for the d.o.f. of 99 to 640 and were primarily smaller than 2 for more than 95% of the spectrum fitting results. We then estimated the counting rates for each spectral model component that are convolved with the response functions of the instrument in all three energy bands and calculated the averages and the standard deviations.

The counting rate of the double broken-power-law component is considered to correspond to that of the UPS component of the PSD. On the other hand, the sum of the counting rates of the two thin thermal components corresponds to that of the UFF. As shown in Table 2, total counting rates from the energy spectra and the PSD are consistent with each other. The fraction of the diffuse emission to the total was estimated to be $82\%\pm 10\%$, $15\%\pm 10\%$, and $1%\pm 5\%$ for 0.2–0.5, 0.5–2, and 2–10 keV, respectively. The diffuse emission fraction for the 0.5–2 keV band, 15%, is significantly smaller than the value obtained from the PSD fit.

McCammon et al. (2002) tried to constrain the fraction of thermal emission by combining line emission intensities of the X-ray background observed by the X-ray microcalorimeter array on board the XQC sounding rocket and the ROSAT R4 band intensity. They estimated that O VII and O VIII emission lines account for 32% of the X-ray background in the ROSAT R4 band. Adding possible thermal continuum emission associated with the oxygen lines, they estimated that at least 42% of the total rate is of thermal origin, which is spatially diffuse. They also claimed that 38% of the R4 band is accounted for by the AGNs, leaving 20% for possible diffuse extragalactic contribution. Thus, the diffuse fraction can be as large as 62%.

In order to compare our result with McCammon et al. (2002), we need to convert the counting rate of the ROSAT R4 band to that of the Suzaku 0.5–2 keV band assuming the energy spectrum described above, i.e., double broken-power-law functions for the unresolved faint point sources, and a sum of

### Table 2

| Energy Band (keV) | 0.2–0.5 | 0.5–2 | 2–10 |
|------------------|---------|------|------|
| From PSD UPS     | 0.19 ± 0.01 | 0.36 ± 0.01 | 0.404 ± 0.007 |
|                 | 0.29±0.12 | 0.46±0.08 | 0.00±0.10 |
|                  | 0.33±0.11 | 0.68±0.09 | 0.404±0.007 |
| Total UPS        | 0.48±0.11 | 0.83±0.09 | 0.404±0.007 |
| From the energy spectrum UPS | 0.06 ± 0.02 | 0.6 ± 0.2 | 0.4 ± 0.1 |
|                 | 0.3 ± 0.2 | 0.1 ± 0.1 | 0.01 ± 0.03 |
|                  | 0.4 ± 0.2 | 0.7 ± 0.2 | 0.4 ± 0.1 |
| Total            | 0.41 ± 0.20 | 0.72 ± 0.19 | 0.53 ± 0.23 |

Note. Counting rates are in units of counts s$^{-1}$ cm$^{-2}$ deg$^{-2}$ in terms of the Suzaku PI energy band.
absorbed and unabsorbed thin thermal emission for the diffuse emission. The spectral parameters are fixed to the average value from the aforementioned Suzaku spectral analysis. We found that the diffuse fractions of 42% and 62% in the ROSAT R4 band are respectively converted to 16% and 30% for the Suzaku 0.5–2 keV band. The previous value, i.e., the fraction of thermal emission, is consistent with that from the spectral fitting of Suzaku spectra (15 ± 10%).

We conclude that the present analysis of the spatial PSD measures a larger diffuse fraction compared to the values estimated from the energy spectra of both XQC and Suzaku. Systematic effects in both or either of the PSD and energy spectrum analyses may explain this discrepancy.

In the energy spectrum analysis, the intensities of the O VII and O VIII lines are determined directly from the energy spectrum. Those lines are likely to arise from three different origins, the SWCX, the Local Bubble, and the hot gas in the halo of our Galaxy. The fractions of three origins in line intensities cannot be determined from spectral analysis alone, which requires some assumptions (e.g., Yoshino et al. 2009). The continuum intensity of thermal emission is very sensitive to the plasma temperature. For example at $kT \sim 0.2$ keV, the O VII emissivity of a CIE plasma decreases rapidly with increasing temperature, as a function of $T^{-3.8}$, while the continuum decreases only slowly. Because the O VIII to O VII intensity ratio mainly constrains the plasma temperature, the continuum intensity is very dependent on the component fraction of the lines in the model we assume. Furthermore, we have almost no constraint on the metal abundance of the plasma. In the Suzaku spectral fit, the double broken-power-law model also contributes a substantial fraction of the background in 0.5–2 keV where thermal emission starts to dominate. As a result, the intensity of the continuum of the thermal emission must be strongly coupled with the double broken-power-law model. Changing the second power-law index of the double broken-power-law model from 1.96 to 1.0 and setting both the abundance and the temperature of the ~0.2 keV APEC free in the spectral fitting, we found the diffuse fraction was boosted to 27% ± 14%.

The other uncertainty of spectral analysis is the possible existence of extragalactic diffuse emission, which is not included in the spectral analysis. If it exists, it will not only increase the diffuse fraction but also modify, likely flatten, the spectral shape of emission underneath the Galactic emission.

The PSD analysis also contains systematic errors. We adopted a single value of $S_{\text{max}}$ in the model, while we averaged PSDs of different images, which should have different values of $S_{\text{max}}$. This is likely to introduce a systematic error in the counting rate of the UPS model. Because the sum of the counting rates of the UPS and UFF models is consistent with that of the energy spectrum within the error, the total counts need to be kept within the statistical uncertainty even when the counting rate of the UPS model is modified because of the systematic error. Then, the lower limit of the diffuse fraction is estimated to be 40%, using the maximum total count rate from the energy spectrum and the minimum UFF counting rate from the PSD analysis. This is marginally consistent with the upper bound of the diffuse fraction, 41%, from the spectral analysis with a modified power-law index above.

In summary, by taking possible systematic effects of both PSD and energy spectrum analyses into account, we consider that we can reconcile the discrepancy, and we conjecture that the value is around 40%.

4.2. Diffuse Fraction in 0.2–0.5 keV

We are also able to compare the diffuse fraction from the spatial PSD with that from the spectral analysis in 0.2–0.5 keV. From the model fits of the Suzaku spectra, we estimate that the diffuse fraction is $82% \pm 10%$ for the soft energy band of 0.2–0.5 keV. This value is consistent with the value from the present PSD analysis within the statistical errors. Our lower limit of the faint point-source contribution is 30%. It suggests that extragalactic point sources with a steep power-law index of ~2 are still contributing to the X-ray background in this energy band in spite of the large Galactic absorption.

5. Summary and Conclusion

We studied the spatial PSDs for blank X-ray skies observed with Suzaku in three energy bands separately utilizing the modified $\Delta$-variance method. We constructed two types of model PSD functions. One model represents the PSD of the UPS, which follows the log $N$–log $S$ relations estimated from the Chandra and XMM-Newton deep-field observations. The other model is to account for a UFF, which we consider to represent truly diffuse emission. The observed PSDs were fitted with a model function consisting of a sum of the two model components. We can estimate the counting rates of the UPS and UFF components that best fit the observation. The main conclusions of the fit results are summarized as follows:

1. The observed PSDs can be fitted well with the model function.
2. In the two lower-energy bands, 0.2–0.5 and 0.5–2 keV, both the UPS and UFF components are necessary to reproduce the observed PSD. However, for 2–10 keV, only an upper limit was obtained for the UFF.
3. The sums of the UPS and UFF counting rates are consistent with the counting rates actually observed by the X-ray detector in all three energy bands.
4. The fractions of the UFF counting rates to the total, namely the diffuse emission fraction of the unresolved X-ray background, are estimated to be $60^{+9}_{-42}\%$, $56^{+5}_{-3}\%$, and $<23\%$ in 0.2–0.5 keV, 0.5–2, and 2–10 keV, respectively.
5. The diffuse emission fraction can also be estimated from the energy spectra, where the emission lines and their associated continuum counterpart assuming a thermal plasma in the collisional ionization equilibrium state are considered to represent the truly diffuse component. For 0.5–2 keV, the diffuse fraction estimated by the present PSD analysis is significantly larger than that from the energy spectra, whereas for 0.2–0.5 keV, they are consistent with each other within the large statistical errors.
6. Systematic effects in the energy spectrum model and in the PSD analysis were investigated as the cause of the discrepancy in the 0.5–2 keV band. We conjecture that these effects can reconcile the discrepancy.

In conclusion, we have demonstrated that even with the limited spatial resolution of the Suzaku X-ray telescope, the spatial power spectrum is a powerful tool to constrain the origins of the X-ray emission. Future observations with a wider
field of view and/or better spatial resolution will elucidate the origins in more detail and more conclusively.

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