Enhanced power spectrum analysis of short-term X-ray variability using MAXI/GSC data

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Abstract

Power spectral densities (PSDs) of bright black hole candidates (BHCs) and neutron star X-ray binaries must provide the information about, for instance, state transitions and quasi-periodic oscillations. However, a triangular window function of the effective area of MAXI/GSC affects the light curves of individual sources due to the scanning observation. Suzuki (2015) established the method of evaluating resultant PSDs correctly, and showed its usefulness for some BHCs. We modified his programs to analyze data more efficiently. Scan duration to analyze in the previous method was fixed to the minimum scan duration, 40 s. We extended the duration to use data as long as possible ($\leq$ 200 s). As a result, we could more correctly evaluate a PSD with a break at a lower frequency. In addition, we also improved signal-to-noise ratios of PSDs for not-so-bright sources by cutting the edges of the window function, and evaluated its effects on the PSDs analytically.

Key words: accretion, accretion disks — X-rays: binaries — stars: individual: Cyg X-1

1. Introduction

If very bright new transients appear, MAXI/GSC data must be important. MAXI scans the whole sky every 92 minutes. Therefore, the probability that MAXI/GSC can discover bright new transients is higher than other observatories. Moreover, although observatories focusing X-rays can not observe extremely bright sources due to detector saturation, MAXI can still do that because it does not have mirrors to focus X-rays.

For these reasons, we must prepare the method to analyze short-term variability using MAXI/GSC data for upcoming bright new transients.

2. Power spectral density, PSD, for MAXI

Time duration of a scan transit for a point source is 40-200 s. It depends on the direction of the source orthogonal to the scan direction. In the previous method to obtain a power spectral density (PSD) by Suzuki (2015), the time duration to analyze was fixed to the minimum time duration, 40 s. We modified his programs to use longer time duration data, which enabled us to deal with lower frequencies of the PSD. It is known that the PSD of the black hole candidate (BHC) in the hard state shows breaks at frequencies of 0.01-1 Hz (e.g., Pottschmidt et al. 2003). On the other hand, there is no break in this frequency band when the BHC is in the soft state (e.g., Cui et al. 1997). By this improvement, it becomes easier to find the low frequency breaks, and to notice state transitions not by energy spectra but by PSDs.

We calculate PSDs with reference to van del Klis (1989), and normalize them according to Leahy et al. (1983) and Miyamoto et al. (1994).

3. Effects of a window function on the PSD

3.1. Time variability of the effective area

The effective area of GSC for a point source changes sequentially by a collimator to restrict the direction of incoming X-ray photons (figure 1). Therefore, a triangular window function affects the light curve and its PSD. To analyze the PSD using GSC data, we need to evaluate the effect of the window function correctly.

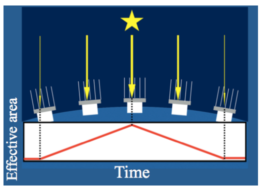

Fig. 1. The movement of GSC in scanning observation and the time variability of the effective area for a point source. When the source is in front of GSC, the effective area reaches the maximum value.

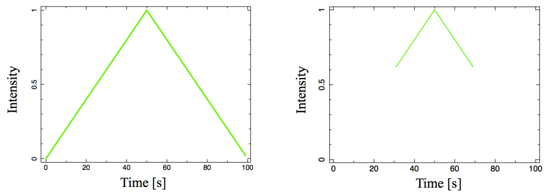

Fig. 2. Left: The previous triangular window function. Right: A new window function for not-so-bright sources.

3.2. New window function for not-so-bright sources

In case of not-so-bright sources, the background counts unaffected by the triangular window function are relatively higher than the source signal at the beginning and the end of the scan. Therefore, we adopt a new window function that cuts the edges of the triangle to remove low signal-to-noise ratio data (figure 2). The cutting ratio should be adjusted by the brightness of the source.

Eq (1) shows the relation of a source signal $x(t)$, a window function $w(t)$, and their Fourier transforms $X(\omega)$ and $W(\omega)$. The Fourier transform of the product of $x(t)$ and $w(t)$ is the convolution of $X(\omega)$ and $W(\omega)$, $X * W$.

$$\int_{-\infty}^{\infty} x(t)w(t)e^{i\omega t}dt = X(\omega) * W(\omega) \tag{1}$$

Eq (2) is the Fourier transform of the window functions in figure 2. T is the scan duration for a point source, and α is the cutting ratio for a new window function ($0 < \alpha \leq 1$). If $\alpha = 1$, this equation corresponds to the window function of the left panel of figure 2.

$$W(\omega) = \frac{2}{\alpha\omega^2 T^2} e^{\frac{i\omega T}{2}} \left\{ 4\sin^2\frac{\alpha\omega T}{4} + \omega T(1-\alpha)\sin\frac{\alpha\omega T}{2} \right\} \tag{2}$$

4. PSD of random shot-noise data

4.1. Break at a lower frequency

We performed simulations using random shot-noise data to confirm whether it is possible to evaluate a break of PSD at a lower frequency. A time constant of the shots was assumed to be, for instance, 4 s. The lowest frequency of the PSD obtained by 40 s data was at 0.025 Hz. On the other hand, if we set the time duration for 100 s using our new programs, the lowest frequency was at 0.01 Hz. We produced 48 light curves, which were a typical number of data sets for 3 days data of GSC. The count rate of them corresponded to 400 mCrab.

Fitting the PSD by a Lorentzian model gives a break frequency at 0.0210 ± 0.0343 Hz. This does not tightly constrain a break frequency because of the large error. On the other hand, a break frequency of the PSD for the longer time duration data was obtained at 0.0370 ± 0.0029 Hz. This frequency is in good agreement with the analytical break frequency of 0.0398 Hz for the time constant of 4 s.

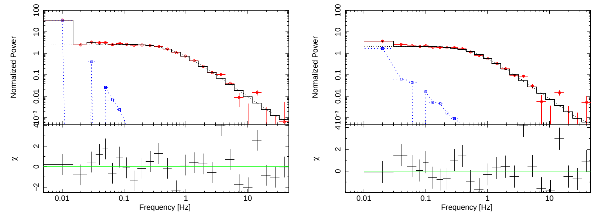

Fig. 3. A PSD of random shot-noise affected by a triangular window function (Left), and a new window function (Right, $\alpha = 0.5$ in Eq.2). Red plots are data, and blue plots are the effect of the window function. The PSDs are fitted by a Lorentzian.

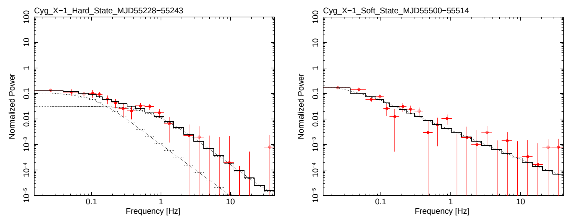

Fig. 4. PSDs of Cyg X-1 in the hard state (Left, MJD 55228-55243, 2-20 keV), and the soft state (Right, MJD 55500-55514, 2-20 keV).

4.2. PSD using a new window function

Next, we confirm that the PSD is correctly evaluated by a new window function. We prepared 100 light curves of random shot-noise data for 100 s. The count rate of them corresponded to 400 mCrab. A time constant of the shots was 0.2 s. We also prepared light curves removing both edges of them, and made a PSD (figure 3). Since α was 0.5, the time duration of them was 50 s.

We could confirm that a large effect of the window function appeared in the lowest frequency bin on both PSDs, and evaluate both of them correctly.

5. PSD of Cyg X-1

We made PSDs of the BHC, Cyg X-1, for 15 days (figure 4). We used only one camera data. A PSD of the hard state was fitted by the sum of two Lorentzians model, and a PSD of the soft state was fitted by a power-law model. We confirmed these results were consistent with previous results (e.g., Pottschmidt et al. 2003).

6. Summary and Future

We modified the programs to obtain a PSD of short-term variability using MAXI/GSC data, and confirmed these were useful for the actual data. We are going to analyze not-so-bright sources using this new window function and its α optimized for the background counts.

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