Energy Spectra and Normalized Power Spectral Densities of X-Ray Nova GS 2000+25

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ABSTRACT

The X-ray energy spectra and Normalized Power Spectral Densities (NPSDs) of an X-ray nova, GS 2000+25, were investigated. The X-ray energy spectra of the source consist of two components: a hard component, which can be represented by a power-law, and an ultra-soft component, represented by radiation from an optically-thick accretion disk (the disk component). In a model in which the power-law component is the Compton-scattered radiation, it is found that the temperature of the incident blackbody radiation to the Compton cloud decrease from 0.8 keV to 0.2 keV according to the decay of the intensity, which coincides with that of the inner accretion disk. When the source changed from the high-state to the low-state, both the photon index of the power-law component (or Compton y-parameter) and the NPSD of the hard component dramatically changed as did GS 1124-683. That is, the photon index changed from 2.2–2.6 to 1.7–1.8 and the absolute values of the NPSDs at 0.3 Hz of the hard component in the low-state became about 10-times larger than those of the hard component in the high-state. These X-ray properties were similar to those of other black-hole candidates, such as Cyg X-1, GX 339-4, and LMC X-3.
Key words: accretion disk — black holes — stars: individual: (GS 2000+25)— stars: novae — X-rays: binaries

1. Introduction

X-ray novae are classified by their early observations of the energy spectra into “hard” ($kT > 15$ keV) and ”soft” ($kT < 15$ keV) classes (Cominsky et al. 1978). White et al. (1984) proposed the third class of the transients that showed “ultra-soft” ($kT < 3$ keV) energy spectrum. The persistent X-ray sources which show such ultra-soft spectra include a black-hole candidate X-ray binary (BHC-XB), such as Cyg X-1 in the high state and LMC X-3 (White, Marshall 1984). While not all ultra-soft sources may contain accreting black-holes, this empirical classification has proved its predictive power in the case of the ultra-soft transient A0620-00, which McClintock and Remillard (1986) subsequently identified as a BHC-XB based on radial velocity measurements. GS 2000+25 and GS 1124-683, which are mentioned in this work, belong to this class.

The most reliable criterion for a black hole composing an X-ray binary (XB) is that the lower-mass limit must exceed $3 M_\odot$. The current theories predict that a neutron star with more than $3 M_\odot$ cannot remain stable, and will collapse into a black hole (see, e.g., Baym, Pethick 1979). It is known that there are at least ten X-ray binary systems, in which the compact object has a lower mass limit of more than $3 M_\odot$ (e.g. Tanaka, Shibazaki 1996; Barret et al. 1996).

Mainly from observations of Cyg X-1, the following features of X-ray emissions have been considered to be possible black-hole signatures: (1) short-term variations of the X-ray emissions (so-called flickering), (2) an ultra-soft energy spectrum in the high X-ray intensity state (the high state), (3) a hard (power-law type) energy spectrum in the low X-ray intensity state (the low state), and (4) bimodal behavior between these two states. Tanaka (1989) reported that almost all of the observed energy spectra of BHC-XBs could be represented by a two-component model consisting of a multi-colored disk blackbody (Mitsuda et al. 1984) and power-law shape radiation. Subsequently, Miyamoto et al. (1991), Takizawa (1991), Ebisawa (1991), and Ebisawa et al. (1994) reported that the observed energy spectra of BHC-XBs were able to be represented by a two-component model consisting of a multi-colored disk blackbody and power-law radiation with a smeared edge absorption. (For the reviews of the BHC-XBs, see Oda 1977; Liang, Nolan 1984; Tanaka 1989; Gilfanov et al. 1999; Kitamoto 1999, and the references therein.)

The structure of the accretion disk depends on the accretion rate (e.g. Frank et al.
1992; Kato et al. 1998). The standard disk (Shakra, Sunyaev 1973) is one of the stable solutions in the case of an optically-thick accretion disk. Another stable solution in an optically-thick disk is known as advection-dominated accretion flows (ADAFs), or a “slim disk” (Abramowicz et al. 1988, 1995; and references therein), where the X-ray spectrum becomes harder than that of the standard accretion disk (e.g. Watarai et al. 2001). In the case of a low accretion rate, the accretion disk becomes optically thin. There are two solutions: one is the gas pressure being supported and radiately cooled, which is thermally unstable. Another is gas pressure supported by being advectively cooled; this is stable. An original idea concerning the transition from an optically-thick disk to an optically-thin disk for the bimodal behavior between the high and low states of the BHC-XBs was proposed by Ichimaru (1977). Since X-ray novae must change the accretion rate with many orders of magnitude, it is the best target to investigate the behavior of the accretion rate as a function of the mass-accretion rate.

Rapid time variations of X-rays have also been well investigated using the power spectral density (PSD; Terrell. 1972; Weisskopf et al. 1975; Nolan et al. 1981) and other methods (see for instance, Oda 1977; Liang, Nolan 1984; Makishima 1988; and the references therein). In addition, the Normalized Power Spectral Densities (NPSDs) have been used to compare the PSD of Cyg X-1 at different occasions (Belloni, Hasinger 1990), and among different sources (Miyamoto et al. 1991, 1992, 1993, 1994; Kitamoto et al. 1992a, b), which are the power spectral densities normalized by its intensity, where the Poisson noise due to statistical fluctuations is subtracted. Phase lags have also been measured between the time variations of different energy X-rays (van der Klis et al. 1987; Miyamoto et al. 1988, 1991, 1992, 1993, 1994).

Miyamoto et al. (1992) reported that, in the low state of BHC-XBs the shapes and the absolute values of the NPSDs and phase lags of time variations between different energy X-rays were similar. Moreover, they reported that the shapes and the absolute values of the NPSDs in the high state of BHC-XBs were quite different from those in the low state; i.e. the absolute values of the NPSDs in the high state were smaller than those in the low state by factor of about 10–1000 at the frequency range above 0.1 Hz (Miyamoto et al. 1993).

Miyamoto et al. (1994) pointed out, for GS 1124-683 in the high state, that in the 1.2–37 keV energy range, the two energy spectral components (i.e. a power-law component and a disk blackbody component) have power spectral densities (PSD) of their own characteristic shapes; the PSD of the power-law component has a flat-top shape (FT noise function) at frequencies of less than about 2 Hz, and the PSD of the disk blackbody component has a power-law shape (PL noise function). In this state, the FT noise functions normalized by the power-law component are almost the same as in the cases when the photon counts fraction
of the power-law component (PLF) is larger than about 20% of the total photon counts in 1.2–37 keV, and the PL noise functions normalized by the disk blackbody component are also almost the same when the PLF is less than about 10%. Moreover, it is found that the so-called high state can be divided into two kinds of sub states: a very high state and a high quiet state. In the high quiet state, the ultrasoft component dominates the X-ray spectrum, and the time variation is “quiet”. On the other hand, in the very high state, the ultrasoft component dominates, but the power-law component also exists substantially, and the total time variation is relatively high. These completely correspond to the “high state” and the “very high state” by van der Klis (1994a, b). These studies on the rapid time variations and components of X-ray emission must be relate to the structure of the accretion disk. The phenomenological behavior of the BHC-CBs has been reviewed by Belloni (2001).

A bright transient X-ray source in the constellation Vulpecula, GS 2000+25, was discovered with the All Sky Monitor (ASM, Tsunemi et al. 1989a) onboard the Ginga satellite (Makino. 1987) on 1988 April 23 (Tsunemi et al. 1989b). After the discovery of GS 2000+25, the source was observed from 1988 April 30 to 1988 December 16 with the Large Area Counter (LAC; Turner et al. 1989) onboard the same satellite. The observed maximum X-ray intensity was approximately 30 count s⁻¹ cm⁻² (1–20 keV), and the X-ray energy spectra observed at the time of the flare were of the ultra-soft type, and the light curve observed during the decay phase was similar to that of the BHC-XB, A0620-00.

After some trials to determine the mass of the compact star in GS2000+25 (Charles et al. 1991; Callanan et al. 1991; Mineshige et al. 1992a), the orbital motion of the binary system of GS2000+25 was precisely determined based on an optical observation with the W. M. Keck 10 m telescope (Filippenko et al. 1995). The obtained mass function of 4.97±0.10 \( M_\odot \) indicates that the plausible mass of the compact star is 5.9–7.5 \( M_\odot \) assuming that the mass of the companion star is 0.4–0.7 \( M_\odot \), and that the inclination of the orbital plane is 67.5–80 degrees. Casares et al. (1995) also determined a mass function of 5.02±0.46 \( M_\odot \) and implied the probable mass of the compact star is (7.0–7.7)±0.5 \( M_\odot \) based on the spectroscopic detection of the secondary star. Beekman et al. (1996) reported that mass of the compact object lies between 4.8 and 14.4 \( M_\odot \) from the infrared light curve. Callanan et al. (1996) reported that the mass of the compact star is 8.5±1.5 \( M_\odot \) assuming that the companion star is a K dwarf. All of these results suggest that the mass of the compact star is more than 3 \( M_\odot \), indicating that GS 2000+25 is a BHC-XB. Garcia et al. (2001) reported the significant detection of GS2000+25 by a Chandra observation, which shows a luminosity of \( 2.4 \times 10^{38} \) erg s⁻¹. This low luminosity also suggests that the compact star is a black hole.

The X-ray emission from GS 2000+25 decreased over a period of eight months, changing
in the absolute values and appearance of the energy spectra and the NPSDs, the features of which remind us of the so-called bimodal behavior of the BHC-XBs, such as Cyg X-1 and GX 339-4 and GS 1124-683. In this work, the time evolution of the energy spectra and the NPSDs were investigated in detail; the correlation between them is discussed. These results are discussed according to the accretion-disk structure. In this study, the classifications of the state (low state, very high state and high quiet state) are pursuant to those by Miyamoto et al. (1993, 1994).

2. Observation

After the discovery of GS 2000+25 with the ASM on 1988 April 23, GS 2000+25 was subsequently observed with the Large Area Counter (LAC; Turner et al. 1989) intermittently from 1988 April 30 to 1988 December 16. The start and end times, observation modes, energy channels and time resolution of the observation are listed in table 1. Days from 0h 0m 0s (UT) on 1988 April 28, when the X-ray flux observed with the ASM was maximum, are also shown in parenthesis in the table. Hereafter, the origin of time is defined as 0h 0m 0s (UT) on 1988 April 28 and the days from then will be called “days after the peak”, although we do not have any data between April 23 and April 28. In order to investigate the energy spectra, MPC-1 and MPC-2 data, of which the number of energy channels was 48, were used. MPC-3 data, of which the time resolution was 7.8 ms, were used in order to investigate rapid time variability of X-rays.

A further observation, not described in this work, was carried out with the LAC on 1989 May 15, about 12 months after the peak of the outburst, but the source was below the LAC detection limit of $\sim 0.3$ mCrab (Mineshige et al. 1992b).

3. Analysis and Results

3.1. Light Curve

Figure 1 shows light curves (observed photon counts) of GS 2000+25 in the 1–6 keV and 6–20 keV energy ranges and its hardness ratio, observed with the ASM. After the initial detection on 1988 April 23, the X-ray intensity of this source reached about 12 Crab in the 1–6 keV energy range on April 28, and decreased exponentially thereafter (Tsunemi et al. 1989b). It flared up slightly again approximately 70 d and 132 d after the peak in the 1–6 keV energy range. The decay time constant was approximately 30 d until 61.7 d after the peak. In the 6–20 keV energy range, GS 2000+25 flared up again 132 d after the peak, and
the decay time constant was about 20 d until 61.7 d after the peak. That is, hard X-rays decreased faster than soft X-rays in the early phase of the outburst (until 127 d after the peak), as shown by the hardness ratio. The hard X-rays (6–20 keV) were not the main component at the beginning of this outburst, as long as GS 2000+25 was observed with the ASM. The hardness ratio suddenly increased on the 129 d after the peak. As shown in figure 1, slight flarings 70 d and 132 d after the peak are different from the behavior of their X-ray energy spectra.

The light curve obtained with the LAC is shown in figure 2. In the 1.7–37 keV energy range, the decay time constant was 33.9 d until 1988 December 16; 232 d after the peak. Due to intermittent data obtained with the LAC, the re-flares, which were observed in the ASM, were not clear.

3.2. Energy Spectra of X-rays

The energy spectra of X-rays observed with the LAC (1.7–37 keV) over eight months are shown in figure 3. For these data, an aspect correction and background subtraction were performed, but a correction of the detector response was not applied. It should be noted concerning figure 3 that soft X-rays below 8 keV decreased with time, but hard X-rays above 8 keV increased once on September 8 (133 d after the peak).

An attempt was made to fit these X-ray energy spectra with three kinds of two-component models; an ultra-soft component and a hard component. To simulate the ultra-soft component, the multi-colored disk blackbody model (Mitsuda et al. 1984; hereafter, termed “the disk component”) was used in all 3 models. For the hard component, the following 3 models were used: (model-1) a power-law component, (model-2) a power-law component with a smeared-edge (Takizawa 1991; Ebisawa 1991; Ebisawa et al. 1994), and (model-3) a Comptonized blackbody component (Nishimura et al. 1986). The best-fit parameters of the energy spectra based on these three models are shown in tables 2, 3 and 4. The error bars quoted here are the 90% CL. For fitting the parameters of the disk component, the innermost disk radius \( (R_{in}) \) multiplied by \( \sqrt{\cos i} \), assuming the distance to the source to be 1 kpc, and the innermost temperature of the disk \( (kT_{in}) \) are listed in the three tables, where \( i \) is the inclination angle of the disk. In tables 2 and 3, the photon index of the power-law component is shown. In table 4, instead of the photon index, parameters of the Compton scattering process are shown, such as \( kT_{bb} \), \( kT_{electron} \), and \( \tau \), which are the temperature of incident blackbody radiation into the Compton cloud, the temperature of the Compton cloud and the radius of the Compton cloud in Thomson scattering depth. The normalization factor of the Comptonized blackbody in table 4 is the surface area of the black-
body radiation incident to the Compton cloud. The normalization factors in tables 2 and 3 were calculated assuming the distance to the source to be 1 kpc. In table 4, the Compton $y$-parameter, which is defined as $(4 \frac{kT_{\text{electron}}}{m_e c^2}) \times \text{Max}(\tau, \tau^2)$, is shown while assuming non-relativistic thermal distributions of the electrons, in order to evaluate the property of the hard component. The fluxes of the disk and the hard component in the tables are the energy fluxes of X-rays from 1.7 keV to 37 keV. The observed photon count fraction of the hard component to the total counts (the count fraction of the power-law component; PLF) and the reduced $\chi^2$ values of the fitting are also given in these tables. Here, the PLF is defined as $I_{\text{hard}}/(I_{\text{hard}} + I_{\text{disk}})$, determined by each energy spectral model convolved by the detector response, where $I_{\text{hard}}$ and $I_{\text{disk}}$ are the observed X-ray counts of the hard and disk components in the 1.7–37 keV energy range, respectively.

Among the above models, the model 2 gives the smallest $\chi^2$ values. The energy spectra with the best-fit curves of model 2 and its residual are shown in figure 4, and the time evolution of the fluxes of the two X-ray components derived by model 2 is shown in figure 5 together with those of GS 1124-683 (Miyamoto et al. 1993). The evolution of the various parameters of models 2 and 3 is shown in figures 6 and 7, respectively. Comparisons of these results with those from GS 1124-683 and further discussions about these two sources are presented in subsection 4.1.

In all models, the innermost temperature $(kT_{\text{in}})$ of the disk near the peak X-ray flux was 1.1–1.2 keV, and then smoothly decreased down to about 0.3 keV as the X-ray flux decreased. At the same time, the innermost disk radius $(R_{\text{in}} \sqrt{\cos i})$ remained almost constant ($\sim 10^6$ cm).

From April 30 (2 d after the peak) to May 7 (9 d after the peak), the photon counts in the 20–37 keV high-energy range are small and statistically poor, as shown in figure 4. Therefore, it is difficult to derive any conclusions relating to the hard component at this time. From June 1 (34 d after the peak) to December 9 (225 d after the peak), the photon indices of the power-law component were larger than about 2.2, and suddenly decreased to about 1.8 on December 16 (232 d after the peak) in the case of models 1 and 2, as shown in tables 2, 3 and figure 6. For model 3, the Compton $y$-parameter was smaller than 0.5 until December 9, and then suddenly increased to about 1.0 on December 16, as shown in figure 7.

The temperature of the incident blackbody radiation to the Compton cloud gradually decreased from 0.8 keV on June 1 (34 d) to 0.2 keV on December 16 (232 d). The cooling of the incident blackbody temperature was similar to that of the inner disk $(kT_{\text{in}})$. In all models, the flux of the hard components reached the maximum on June 1 (34 d after the peak).
On December 16, the PLF was about 90% and the X-ray energy spectrum was a power-law type with a photon index of about 1.7–1.8. This is similar to the energy spectra of Cyg X-1 and GS 1124-683 in the low state (Miyamoto et al. 1992, 1994). Moreover, as mentioned in subsection 3.3, the NPSD on December 16 is similar to those of Cyg X-1 and GS 1124-683 in the low state (Miyamoto et al. 1992, 1994). Therefore, it can be regarded that GS 2000+25 on 1988 December 16 was in the low state. Recently, the intermediate state has been reported for CygX-1 in 1996, GX339-4 in 1998 (Belloni et al 1996, 1999; Esin et al. 1998). According to a similarity of the photon indices and the short-term variability of X-rays, as Belloni et al. (1996) have already suggested, they resemble the very high state of GS1124-68 in 1991 and GX339-4 in 1988 described in the Miyamoto et al. (1993, 1994). Miyamoto et al. (1993) originally called this state of GS1124-68 a high-to-low transition state. Between 130 d and 225 d in the case of GS2000+25, we could apparently recognize a hardening of the spectrum, but still a substantial soft component was observed. Therefore, this term can be considered to be a kind of transition phase, which is different from the case of GS1124-683.

3.3. Normalized Power Spectral Densities (NPSDs)

In order to investigate any short term variability of the X-rays from GS 2000+25, the Normalized Power Spectral Density function (NPSD, Miyamoto et al. 1991, 1992, 1994) was calculated. This function is suitable to compare the time variations of different sources, and also the same source at different intensities. Miyamoto et al. (1992) pointed out that the shapes and values of NPSDs of various BHC-XBs in the low state were very similar to each other, except at frequencies below about 0.2 Hz, which suggested that various BHC-XBs in the low state had the same mechanism of X-ray time variability. Miyamoto et al. (1993) also pointed out that the shape and values of the NPSDs of GX 339-4 and GS 1124-683 in the high state were similar.

The NPSD is the power spectral density normalized to its intensity, where the Poisson noise due to statistical fluctuations is subtracted, which is defined as the square of the ratio of the root-mean-square amplitude of the two-sided power spectral density in unit frequency band (Hz$^{-1}$) to the total signal photon number as shown below (Miyamoto et al. 1994):

$$\text{NPSD}_{k} = \frac{(\alpha_{k}^{2} + B_{k}^{2} - \frac{1}{n}\sigma^{2}) \times T}{(\tau - B)^{2}},$$  \hspace{1cm} (1)
where \( x_j \) is the number of counts in the \( j \)th bin of \( n \) consecutive time bins, \( \bar{x} \) (counts per bin) is their mean value and their background \( B \) (counts per bin), \( \sigma^2 \) is the estimated power due to the Poisson statistics of the data (=-\( \bar{x} \)), \( T \) is \( n \Delta T \) (s) (\( \Delta T \) is the bin length), and the frequency \( f \) (Hz) is given by \( f = k/T \) (Miyamoto et al. 1991, 1992, 1993, 1994; Kitamoto et al. 1992a, b).

The NPSDs of GS 2000+25 at three different PLF are shown in figure 8. The numerals in each diagram are the PLF, the observed date and the days after the peak. Typical NPSDs of GS 1124-683 and of Cyg X-1 are also shown in this figure; the thin solid line is the NPSD of GS 1124-683 obtained on 1991 January 11 (PLF=0.80). The dotted line is the NPSD of GS 1124-683 obtained on February 26 (PLF=0.066). The broken line is the NPSD obtained on June 13 and July 22 when GS 1124-683 was in the low state (PLF=0.95 and 0.99). The thick solid line is the NPSD of Cyg X-1 in the low state (1990 May 10).

From figure 8, it was found that the NPSD on December 16 coincided with the NPSDs of GS 1124-683 (broken lines) in the low state, which together with the energy spectrum mentioned in subsection 3.2, clearly indicates that GS 2000+25 is in the low state on December 16. It was also found that both the energy spectra and the NPSD of GS 2000+25 and GS 1124-683 also had similar shapes in the high state.

Miyamoto et al. (1994) showed that the two energy spectral components had their characteristic PSD noise functions in the high state of GS 1124-683; the flat-top shape noise for the power-law component and the power-law shape noise for the disk component, respectively. Applying the same noise functions to GS 2000+25, we obtained the following results:

Following Miyamoto et al. (1994), the NPSDs of GS 2000+25 were fitted with a model that consisted of two characteristic power spectrum densities (PSDs), PSD\text{powerlaw} and PSD\text{flattop}, which were represented by a Lorenzian function of zero central frequency. That is,

\[
\text{NPSD}_{\text{observed}}(f) = \text{PSD}_{\text{powerlaw}}(f) + \text{PSD}_{\text{flattop}}(f)
\]
\[ = A_1 f^{-k} + A_2 \frac{(\Gamma/2)^2}{f^2 + (\Gamma/2)^2}, \tag{2} \]

where \( f \) is the frequency, \( \Gamma \) is the FWHM of the Lorenzian, \( A_1 \) and \( A_2 \) are constants.

In some cases, these two-component models are not necessarily required from a statistical point of view, because the F-test shows no significance for the two components. However, judging from an analogy with GS1124-683, we assumed that the NPSDs could be expressed by a combination of two characteristic shape functions, the power-law type and the flat-top type; furthermore, a QPO was necessary in the case of September 8.

At first, the values of \( k \) of the power-law component, \( A_1 f^{-k} \), were investigated by applying a single power-law model to the NPSDs on May 2, May 4, May 7, and May 8, when the PLF was smaller than 0.03. The values of \( k \) and its reduced \( \chi^2 \) values are given in table 5. The \( k \) value of 0.807 on May 7 will be used as a fixed value, because the PLF is the smallest and the NPSD in May is considered to be the time variabilities of the disk component.

Next, in order to determine the value of \( \Gamma \), fitting the NPSDs on September 8, October 18 and November 5 with \( A_1 f^{-0.807} + A_2 \frac{(\Gamma/2)^2}{f^2 + (\Gamma/2)^2} \) was tried. In the case of September 8, another Lorenzian function with a center frequency, \( f_{\text{QPO}} \) of about 2.27 Hz was added in order to simulate the Quasi Periodic Oscillation (QPO). The values of \( \Gamma \) and a reduced \( \chi^2 \) are given in Table 6. The reduced \( \chi^2 \) value on September 8 is not small enough, because the NPSDs at a low-frequency range less than 0.06 Hz tend to deviate from the sum of the two functions. At a higher frequency range, especially above about 0.3 Hz, the sum of the two functions can represent the observed NPSDs well. Thus, the \( \Gamma \) value of 8.96 Hz on September 8 will be used as a fixed value, because the PLF obtained on September 8 was the largest, except for December 16. These values were similar to those of GS 1124-683, where \( k \) was 0.7 and \( \Gamma \) was about 8 Hz (Miyamoto et al. 1994).

At last, fitting the NPSDs with equation(2) was tried, while fixing \( k \) and \( \Gamma \) values to be 0.807 and 8.96, respectively. In figure 9, the NPSDs of GS 2000+25 over eight months and their fitting results are shown. The numerals in each diagram are the observed date, the days after the peak, and the PLF. The dotted line, the broken line and the thin line are PSD\text{powerlaw}, PSD\text{flattop}, and their sum. The thick line in the figure for December 16 is the NPSD of Cyg X-1 in the low state on 1990 May 9. The fitting results of the NPSDs and the time resolution of each datum are given in table 7.
3.4. Relation between the NPSDs and the Power–law Fraction (PLF)

The relation between the values of the NPSDs at 0.3 Hz and the PLFs for GS 2000+25 was investigated. Here, the PLF values derived by model 2 and the NPSD values at 0.3 Hz by equation (2) with two fixed values of $k = 0.807$ and $\Gamma = 8.96$ were used. The relation is shown in figure 10, together with the results of GS1124-683 (Miyamoto et al. 1994). Here, we note that the value of 0.3 Hz is not a single data point, but a representative value which was derived from the best-fit model.

As shown in figure 10, a notable correlation between the values of NPSDs and the PLF is recognized. That is, the larger is PLF, the larger is the value of NPSD. More noteworthy is that this correlation between the PLF and the value of NPSD of GS 2000+25 (filled circle) is very similar to that for GS 1124-683 (open square, Miyamoto et al. 1994). This reveals that the two sources show not only the same energy spectral type, but also the same time variability on the way from the outburst to the low state, even though details of the evolution of the two sources from the outburst to the low state are different, as shown in figure 5, and will be mentioned in subsection 4.1.

If it is assumed that each of the hard (power-law) and disk components has their characteristic values of the NPSD at 0.3 Hz, and that these are independent from each other, the observed NPSD (0.3) should be expressed as a function of the PLF by (Miyamoto et al. 1994):

\[
\text{NPSD}(0.3) = \frac{(\text{NPSD}_{\text{hard}}(0.3) \times I^2_{\text{hard}} + \text{NPSD}_{\text{disk}}(0.3) \times I^2_{\text{disk}})}{(I_{\text{hard}} + I_{\text{disk}})^2} = \text{NPSD}_{\text{hard}}(0.3) \times \text{PLF}^2 + \text{NPSD}_{\text{disk}}(0.3) \times (1 - \text{PLF})^2,
\]

where NPSD_{\text{hard}}(0.3) and NPSD_{\text{disk}}(0.3) are the NPSDs of the hard and disk components at 0.3 Hz normalized by the hard and disk components, respectively. In figure 10, the most probable fitting results of this formula to the NPSD values at 0.3 Hz derived from equation (2) with two fixed values, except for the data in the low state, are shown by the solid line for GS 2000+25 and the broken line for GS 1124-683 (Miyamoto et al. 1994). The values of NPSD_{\text{hard}}(0.3) and NPSD_{\text{disk}}(0.3) of GS 2000+25 are $(1.59 \pm 0.06) \times 10^{-3}$ and $(2.4 \pm 1.0) \times 10^{-5}$, respectively (reduced $\chi^2 = 3.7$). Also, those of GS 1124-683 are $(9.4 \pm 0.9) \times 10^{-4}$ and $(1.36 \pm 0.53) \times 10^{-5}$, respectively (Miyamoto et al. 1994). These curved lines approximately show the observed values of the NPSDs, although there are several exceptions. This suggests that the NPSD_{\text{hard}}(f) and the NPSD_{\text{disk}}(f) have almost similar characteristic values of about $10^{-3}$ and $10^{-5}$ at 0.3 Hz, respectively, on various occasions and various BHC-XBs in the
high state. Moreover, the values of $NPSD_{\text{hard}}(0.3)$ in the low state are larger than those of $NPSD_{\text{hard}}(0.3)$ in the high state by a factor of about 10 at 0.3 Hz. This is common to both GS 2000+25 and GS 1124-683. It is of interest to note that in the high state both of the values of $NPSD_{\text{hard}}(0.3)$ and the $NPSD_{\text{disk}}(0.3)$ of GS 2000+25 are larger than those of GS 1124-683 by a factor of 1.7–1.8. Both the hard and disk components of GS 2000+25 should have a higher variability by a factor of 1.7–1.8 than those of GS 1124-683. One can not shift the solid line to the lower side by adding a constant DC X-ray flux component to GS2000+25.

3.5. $NPSD_{\text{powerlaw}}(f)$ and $NPSD_{\text{flattop}}(f)$

It is described in subsection 3.3 that the observed NPSDs can be represented by two components of the shape functions of $PSD_{\text{powerlaw}}(f)$ and $PSD_{\text{flattop}}(f)$. In subsection 3.4, it is shown that the NPSD consists of two components, the NPSD$_{\text{hard}}$ and the NPSD$_{\text{disk}}$, which have almost constant characteristic values at different PLF, and even in different sources. It is natural to assume that $PSD_{\text{powerlaw}}(f)$ and $PSD_{\text{flattop}}(f)$ correspond to the PSD of the disk and the hard component, because when the PLF is negligibly small (May 7) the NPSD shows the power-law shape, and when the PLF is largest in the high state the NPSD shows the flat-top shape (September 8). That is, the $PSD_{\text{powerlaw}}(f)$ and the $PSD_{\text{flattop}}(f)$ normalized by the intensities of the disk component and the hard component, respectively, should correspond to the NPSD$_{\text{disk}}(f)$ and the NPSD$_{\text{hard}}(f)$. With this assumption, the values of the $PSD_{\text{powerlaw}}(f)$ and the $PSD_{\text{flattop}}(f)$ at 0.3 Hz, normalized by the intensities of the disk component and the power-law component with a smeared edge (model-2), respectively, are shown in figure 11. The data of GS 1124-683 are also shown in this figure (open square; Miyamoto et al. 1994).

In the case of GS 2000+25 in the high state (PLF < 0.61), the mean value of the $PSD_{\text{powerlaw}}$ at 0.3 Hz normalized by the disk component is $(2.7\pm0.6)\times10^{-5}$, assuming that the values of the NPSD$_{\text{disk}}$ are constant (the upper panel in figure 11; reduced $\chi^2=1.7$). On the other hand, the mean value of the $PSD_{\text{flattop}}$ at 0.3 Hz, normalized by the power-law component with a smeared edge (model-2), is $(9.7\pm1.8)\times10^{-4}$ in the high state (PLF < 0.61), assuming the values of the NPSD$_{\text{hard}}$ are constant (the lower panel in figure 11; reduced $\chi^2=1.2$). These are almost consistent with values of the NPSD$_{\text{disk}}(0.3)$ and NPSD$_{\text{hard}}(0.3)$ in subsection 3.4. It is also shown that the values of the PSDs at 0.3 Hz, normalized by each component, are almost constant. Thus, it is confirmed that two energy spectral components have characteristic NPSDs in the high state, and that the correlation between the PLF and the value of the NPSDs at 0.3 Hz (in subsection 3.4) are explained by the characteristic
NPSDs normalized by the two energy spectral components and their independent variabilities from each other (in subsection 3.5).

It was reported that the normalized values of the PSDs of each component were not constant in the case of GS 1124-683, as shown in figure 11 (Miyamoto et al. 1994). The property of GS 2000+25 is different from that of GS 1124-683, as follows. When the PLF is above 0.1, the normalized PSD_{powerlaw} of GS 1124-683 tends to increase, but this tendency is not seen in the case of GS 2000+25. This may be due to the poor statistics of the data of GS2000+25. Especially, the value of the NPSDs of GS 1124-683 at a PLF of 0.80 is larger than that of GS 2000+25 at a PLF of 0.61 by two orders of magnitude. This difference may result from the difference in the evolution stage of the hard component, because in GS 1124-683, the datum of a PLF of 0.8 is in the initial phase of the nova (5 d before the X-ray maximum). On the other hand, the datum of the PLF=0.61 of GS 2000+25 is after a re-increase of the hard component (in the high to low transition phase; Miyamoto et al. 1993).

### 3.6. Phase Lags

Another way to investigate the short-term variability of the X-ray intensities is the phase lags between the time variations of different energy X-rays (van der Klis et al. 1987; Miyamoto et al. 1988). Miyamoto et al. (1992, 1993) reported that the phase lags between the short-term variations of different energy X-rays from BHC-XBs in the low state were similar. They also showed that just after the flaring up of GS 1124-683 and GX 339-4, a peculiar large peaked phase lag was observed. However, in the case of GS 2000+25, the results are inconclusive owing to the large error in the data.

### 4. Discussion

#### 4.1. Long–Term Variability

In figure 5, the long term evolution of the two components of GS2000+25 and of GS1124-683 are shown; in figures 6 and 7, the long-term histories of various parameters of the X-ray energy spectra are plotted. The photon indices of the power-law component were about 2.2–3.0 until 225 d after the peak in GS 2000+25 and 121 d after the X-ray maximum (1991 January 17) in GS 1124-683, respectively. The hard component decreased faster than the other component at the early phase. The second flare (the re-flare) of the X-ray flux occurred after the hard component has decreased to its bottom intensity (GS 1124-683).
The hard component increased again with the same photon index as that of the initial phase of the outburst. Then, the disk component decreased and the state changed to the low state; the photon index became 1.5–1.7, which is similar to the values of other BHC-XBs in the low state, such as Cyg X-1 (Ebisawa 1991; Miyamoto et al. 1993). Considering the value of the power spectral density and this photon index of the power-law component in the energy spectrum, the re-increase of the hard component around 121 d after the maximum of GS2000+25 is not the beginning of the low state.

The temperatures, $kT_{\text{in}}$, of the innermost accretion disk dropped smoothly as the flux decreased, except for the case of the second flare up of GS 1124-683. The time constants of the decay of $kT_{\text{in}}$ of GS 2000+25 and GS 1124-683 were about 170 d and 176 d, respectively. Radius $R_{\text{in}}$ of the innermost accretion disk remained roughly constant in the early phase of the decay for both sources. For GS 2000+25, $R_{\text{in}}$ was almost constant until 225 d after the peak, and then suddenly decreased 232 d after the peak. The temperature ($kT_{\text{bb}}$) of the incident blackbody radiation photons to the Compton cloud decreased similarly to that of the inner edge of the disk ($kT_{\text{in}}$), although that of GS 1124-683 was variable at the beginning of the outburst. In the case of GS 2000+25, $kT_{\text{bb}}$ took almost the same values as $kT_{\text{in}}$ within a factor of 0.6–1.1, which supports the view that the seed photons of the hard component (Compton scattered component) were produced near the inner edge of the accretion disk (Miyamoto et al. 1994). The Compton $y$-parameters of GS 2000+25 and GS 1124-683 were below 0.5 until 225 d and 121 d after the peak, respectively, and subsequently increased up to about 1. More noteworthy is that the transition from the high state to the low state occurred between 225 and 232 d after the peak in the case of GS 2000+25, which was confirmed by changes of not only the photon index, but also the absolute values of the NPSDs of the hard component. Thus, the transition had finished within 7 d. In the case of GS 1124-683, the transition occurred between 121 d and 148 d.

In the case of GS 2000+25, the transition from the high state to the low state occurred about 100 days after the re-increase of the hard component. While in the case of GS 1124-683, the transition occurred within about 25 d after the re-increase. Thus, although the light curves of total X-rays from these two X-ray novae are similar, the evolution of the two energy spectral components is different from each other. In this connection, it is of interest to note that at the beginning of the nova GS 2000+25, the hard component was not the main component, as long as GS 2000+25 was observed with the ASM. In the case of GS 1124-683 the hard component was the main component at the beginning of the nova (Miyamoto et al. 1993; Ebisawa et al. 1994), as shown in figure 5.

Naturally, the mass-accretion rate can be considered to be the maximum at the peak of the outburst. The peak luminosities of the two sources, GS2000+25 and GS1124-683, were
roughly \(10^{38} \left(\frac{D}{3 \text{kpc}}\right)^2\) erg s\(^{-1}\). Since the low-energy component can be represented by the disk component with an inner radius of \(\sim 10\) km, it is reasonable to understand that an optically-thick standard disk is formed. However, a substantial hard component was observed. This hard component was clearly different from that observed during the low state, because the photon index was different (also short term variation is different). When we assume the comptonized black body model for the hard component, the source photons can be recognized as those from the inner disk. The high-temperature electrons may surround the inner accretion disk like a corona. The existence of the standard disk, even at the peak of the outburst, suggests that a transition to the optically thick ADAF did not occur, although hot electrons must exist around the inner accretion disk, which might be the ADAF component co-existing with the standard disk component.

To explain the second and third flares during the decline phase of the outburst, Augustijn et al. (1993) proposed that the intensity jumps were due to enhanced mass flow from the companion star, which was responding, essentially linearly, to heating by X-rays from the primary (the X-ray star), and called them echoes. They applied their model to GS 2000+25 and could explain the X-ray light curve with the second flare (62 d after the peak) and the third flare (132 d after the peak) during the outburst in the 1–20 keV energy range. According to their model, the process goes on continuously, triggered by the initial burst, and a time delay of a few months corresponds to the time scale of flow of the matter from the inner Lagrangian point, L1, to the compact object. Chen et al. (1993) also proposed the following scenario. The main outburst is caused by a disk instability and the second maximum is due to mass transfer from the X-ray-irradiated secondary star surface. They also explained that the third flare observed in A0620-00 was due to a mass-transfer instability caused by hard X-ray heating of the sub-photospheric layer of the secondary. However, it was found that in the case of GS 2000+25 the feature of the second flare (70 d after the peak) was different from that of the third flare 132 d after the peak, as shown in figure 1. That is, the second and third flares were due to increases of the soft and hard X-rays, respectively. These observational results suggest that the causes of the second and the third flare were different, and they can not be explained by such a simple “echoing” mechanism.

A natural explanation of the third flare is a transition of the disk structure from the standard disk to the optically thin ADAF solution, which was originally pointed out by Ichimaru (1977). The disappearance of the disk component at the transition directly coincides with this idea. It is also interesting to note a view by Miyamoto et al. (1995) that X-ray flares or X-ray novae start their X-ray flux increase in a state in which the photon index of the power-law component of energy spectra is about 1.7 (they termed it “the power-law-hard-state”) and the source change to the state in which the photon index of the power-law component of about 2.7 (they termed it “the power-law-soft-state”), near their X-ray (1–100
keV) flux maximum, where X-ray novae have been discovered in soft X-rays (1–20keV). This behavior also suggests that before a soft X-ray flare the accretion disk is an optically thin ADAF.

4.2. Short – Term Variability

Assuming that the low and very high state noises (short-term variations) are one phenomenon, van der Klis (1994a, b) concluded that in the flat-top noise the cut-off frequency increases with the mass-accretion rate, and that the flat-top level (fractional amplitude) decreases with the mass-accretion rate. However, in the high state, the two energy spectral components (the hard component and the ultra-soft component) should be taken into account to examine the noise. For the cases of GS2000+25 and GS1124-683, such a kind of variation of the cut-off frequency in the high state was not confirmed. Therefore, we discuss the fitting results using a constant Gamma for the flat-top noise, as described in subsections 3.3 through 3.5.

The following points were clarified from an analysis using the NPSDs, as mentioned in subsections 3.3, 3.4, and 3.5. (1) The variations of the observed NPSD of GS 2000+25 in the high state can be explained by the assumption that the disk component and the power-law component have the characteristic shape of NPSDs; that is, the power-law shape NPSD for the disk component and the flat-top shape NPSD for the hard component, which can be represented by a Lorenzian function of zero central frequency. Moreover, the normalized flat-top level of the power-law component is constant during the high state, as shown in figures 10 and 11. This is consistent with the conclusion obtained in GS 1124-683 by Miyamoto et al. (1994). (2) In the high state, the NPSDs of the hard component are larger than those of the disk component by a factor of about 70 at 0.3 Hz. The NPSDs in the low state are still larger than those of the hard component in the high state by a factor of more than 10, which is also consistent with the conclusion which Miyamoto et al. (1994) obtained for GS 1124-683. (3) The values of the characteristic NPSD of the two components of GS 2000+25 are similar to those of GS 1124-683.

Also, it should be noted that the hard components of GS 2000+25 and GS 1124-683 in the low state are quite different from those in the high state with respect to not only the photon index of the power-law energy component (or the Compton y-parameter of the Compton scattering component), but also to the values of the NPSDs.

If we assume that the accretion disk at the low state is an optically thin ADAF, although it is a stable solution, it must have a highly variable structure. From this point of short-term
variability in the low state, the other branch, a gas-pressure supported and radiative cooled disk may also be possible, since it is thermally unstable and spontaneously produces the complex structure of the accretion disk.

4.3. Bimodal Behavior of the BHC—XBs

Remarkable distinctions between the high and low states were found not only in the energy spectra, but also in the Normalized Power Spectral Density (NPSD) of GS 2000+25 and GS 1124-683. Thus, the relations between the photon index of the power-law component and the value of NPSD were investigated for other BHC-XBs: Cyg X-1, LMC X-3, GX 339-4, GS 1826-24, GS 1354-64 and GS 2023+338, in addition to GS 2000+25 and GS 1124-683. For this investigation, we used data observed with the Ginga satellite. The observation logs are given in table 8. The relations between the photon indices and the values of the NPSDs at 0.3 Hz are shown in figure 12. Because GS 2023+338 showed rapid variabilities in its X-ray energy spectra and in the NPSDs due to the partial absorption by cold matter (Oosterbroek et al. 1997), only the data which did not show partial absorption were used.

It is recognized that all of the data can be clearly divided between the high and low states; In the low state, the photon index is 1.4–1.8 and the values of NPSDs at 0.3 Hz are about $10^{-2}$. In the high state, the photon index is 2.1–3.0 and the values of the NPSDs at 0.3 Hz are $10^{-5}$–$10^{-3}$; i.e. both the energy spectra and the NPSDs are different between the high and low states. More noteworthy is that there is a "gap" between the high and low states on the NPSD vs the photon index diagram in spite of various occasions to observe eight sources. The separation between the very high state and the high quiet state, which are sub-states of the so-called high state, could be approximately given by values of approximately $10^{-4}$ for the NPSD at 0.3 Hz.

The correlation between the PLF and the value of NPSD at 0.3 Hz for various sources in various states is shown in figure 13. Although some exceptions exist, the same correlation as mentioned in subsection 3.4 has been confirmed for the other BHC-XBs. The fitting result for all data in the high state with equation (3) in subsection 3.4 is also shown in this figure by the thick line. The most probable values of $\text{NPSD}_{\text{hard}}(0.3)$ and $\text{NPSD}_{\text{disk}}(0.3)$ in the high state are $(7.7 \pm 0.1) \times 10^{-4}$ and $(1.7 \pm 0.6) \times 10^{-5}$ (reduced $\chi^2=15$). Thus, it is clear that the solid line based on the fitting result approximately represents the relation between the PLF and the value of NPSD at 0.3 Hz in the high state (both the very high state and the high quiet state) within a factor of about 4, although its reduced $\chi^2$ is large. Miyamoto et al. (1992) pointed out that the NPSDs of various sources in the low state are almost the same, which correspond to that the data of which the PLF are above 0.9. This is also confirmed
in figure 13, and the mean value of $N_{\text{PSD}}_{\text{hard}}(0.3)$ in the low state is about $2.5 \times 10^{-2}$. Thus, similarities of the NPSDs of the various BHC-XBs are shown not only in the low state, but also in the high state.

Nowak (1994) assumed that the $N_{\text{PSD}}_{\text{powerlaw}}$ and the $N_{\text{PSD}}_{\text{flattop}}$ were due to viscous instabilities and the thermal instability of the accretion disk, respectively, and calculated NPSD in the very high state (a sub-state of the high state, where the power-law component is dominant). He showed in figure 1 of his paper (Nowak 1994) that the flat-top level of the NPSD increased with the mass-accretion rate. This could be consistent with our observations of GS2000+25 and GS1124-683 shown in figure 10. However, he did not calculate the amounts of the hard and ultra-soft components. We thus could not estimate the values of PLF and compare his results directly with the values shown in figure 10 and 11. He also showed a large change of the cut-off frequency of the $N_{\text{PSD}}_{\text{flattop}}$, which seemed not to be consistent with our observation. Nowak (1994) also mentioned that the very high state is a transition phase between the high and low states. This can be true because Miyamoto et al. (1995) showed that the black hole X-ray nova in its rising phase increases its X-ray intensity in the power-law hard state (the low state), and at its near maximum it changes to the power-law soft state (the high state).

5. Summary

The X-ray energy spectra and NPSDs of GS 2000+25 were investigated. These results indicate that there were, at least, three X-ray emission mechanism during the 1988 outburst of GS 2000+25: the ultra-soft component in the high state, the hard component in the high state, and the hard component in the low state. The ultra-soft component in the high state could be represented by radiation from an optically-thick accretion disk (the disk component). The hard component in the high state had a power-law shape, which could be explained by Compton-scattered radiation, of which the Compton $y$-parameter was 0.3-0.5. The incident photons to the Compton cloud are emitted from the central part of the accretion disk. The values of the NPSD of the hard component in the high state were larger than those of the disk component by factor of about 50-70 at 0.3 Hz. The hard component in the low state had a power-law shape of which the photon index ranged from 1.4 to 1.8. The values of the NPSD of the hard component in the low state were still larger than those of the hard component in the high state by a factor of more than 10. Thus, the hard components in the high and low states in essence differed from each other.

We can speculate our results according to the current accretion-disk models as follows: (1) Even in the peak of the outburst, the standard disk exits. (2) There are a high-
temperature electrons around the inner disk, which may relate to the optically thick ADAF. (3) The optically thin ADAF in the low state is very variable, and not a steady flow.

These features of three components are common to other BHC-XBs, such as Cyg X-1, GX 339-4, GS 1124-683, LMC X-3.

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Figure Legends

Fig. 1. X-ray light curves of GS 2000+25 and its hardness ratio observed with the ASM onboard the Ginga satellite. In the upper panel, the data in the 1–6 keV and 6–20 keV energy ranges are shown; their ratios are shown in the lower panel.

Fig. 2. X-ray Light curve (1.7–37 keV) of GS 2000+25 observed with the LAC.

Fig. 3. X-ray energy spectra of GS 2000+25 from 1988 April 30 to December 16.

Fig. 4. Fitting results of energy spectra and its residual from 1988 April 30 to December 16. The adopted model is model 2 (the disk component and the power-law component with a smeared edge).

Fig. 5. Time evolution of X-ray flux of GS 2000+25 (a) and GS 1124-683 (b) in the 1.7–37 keV energy range. The results of model 2 were used.

Fig. 6. Time evolution of the best-fit values of various parameters of the energy spectral fitting. (●, GS 2000+25; ○, GS 1124-683). Here, we used model 2 (the disk component and the power-law component with a smeared edge).

Fig. 7. Time evolution of the best-fit values of various parameter of the energy spectral fitting (●, GS 2000+25; ○, GS 1124-683), where the adopted model is model 3 (the disk component and the Comptonized blackbody component).

Fig. 8. Comparisons of the NPSDs of GS 2000+25 with those of GS 1124-683 and Cyg X-1. The thin solid line is the NPSD of GS 1124-683 obtained on 1991 January 11 (PLF=0.80). The dotted line is the NPSD of GS 1124-683 obtained on 1991 February 26 (PLF=0.066). The broken line is the NPSD obtained on 1991 June 13 and July 22 when GS 1124-683 was in the low state (PLF=0.95 and 0.99). The thick solid line is the NPSD of Cyg X-1 in the low-state (on 1990 May 10). These NPSDs were the fitting results of raw NPSD data.

Fig. 9. Fitting results of NPSDs of GS 2000+25 by two functions: the power-law-shape function and the flat-top-shape function (Lorenzian function). The dotted line, the broken
line and the thin line are $\text{PSD}_{\text{powerlaw}}$, $\text{PSD}_{\text{flattop}}$, and their sum. The thick line in the figure on December 16 is the NPSD of Cyg X-1 in the low state on 1990 May 9.

Fig. 10. Relations between the PLFs and the NPSDs at 0.3 Hz of GS 2000+25 (filled circle) and GS 1124-683 (open square). The most probable fitting results with equation (3) in subsection 3.4 except for the data in the low state, are shown by the solid line for GS 2000+25 and the broken line for GS 1124-683 (Miyamoto et al. 1994). The values of the $\text{NPSD}_{\text{hard}}(0.3)$ and the $\text{NPSD}_{\text{disk}}(0.3)$ of GS 2000+25 are $(1.59 \pm 0.06) \times 10^{-3}$ and $(2.4 \pm 1.0) \times 10^{-5}$, respectively (reduced $\chi^2=3.7$). The values of the $\text{NPSD}_{\text{hard}}(0.3)$ and the $\text{NPSD}_{\text{disk}}(0.3)$ of GS 1124-683 are $(9.4 \pm 0.9) \times 10^{-4}$ and $(1.36 \pm 0.53) \times 10^{-5}$, respectively (Miyamoto et al. 1994).

Fig. 11. Relations between the Normalized $\text{PSD}_{\text{powerlaw}}$ (the $\text{NPSD}_{\text{disk}}$) and the Normalized $\text{PSD}_{\text{flattop}}$ (the $\text{NPSD}_{\text{hard}}$) and the PLFs. The symbols of filled circles and open squares mean the data of the GS 2000+25 and of the GS 1124-683, respectively. In the high state ($\text{PLF} < 0.61$), the mean values of the $\text{PSD}_{\text{powerlaw}}$ and $\text{PSD}_{\text{flattop}}$ at 0.3 Hz normalized by the disk component and the power-law component of GS 2000+25 are $(2.7 \pm 0.6) \times 10^{-5}$ and $(9.7 \pm 1.8) \times 10^{-4}$, respectively, assuming the values are constant (broken lines).

Fig. 12. Relations between the photon-index of the power-law component and the values of the NPSDs at 0.3 Hz for various BHC-XBs.

Fig. 13. Relations between the PLFs and the values of the NPSDs at 0.3 Hz of various BHC-XBs. The fitting result for all of the data in the high state with equation (3) in subsection 3.4 is also shown in this figure by the solid line. The most probable values of $\text{NPSD}_{\text{hard}}(0.3)$ and $\text{NPSD}_{\text{disk}}(0.3)$ in the high-state are $(7.7 \pm 0.1) \times 10^{-4}$ and $(1.7 \pm 0.6) \times 10^{-5}$ (reduced $\chi^2=15$).