ISAS-RN-654-A
June 1998

AUG 24 1998

ISAS-RN-654-A

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X-RAY OBSERVATION OF BLACK HOLE NOVAE

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Abstract

X-ray novae are the best objects to study their compact stars. Some of the X-ray novae have been confirmed that they were containing a black hole based on dynamical mass estimations. Besides the dynamical mass estimation, some X-ray novae showed possible black hole natures. In this work, I attempt to explain the black hole natures found by the observation of X-ray novae.

1. Introduction; Why are the X-Ray Novae Important

The word "X-Ray Nova" means the X-ray star which suddenly appears (during several days) and gradually declines and eventually fades away. Some of them show a hard energy spectrum and pulsation in their X-ray intensity. They are considered to contain a magnetized neutron star. Some show X-ray bursts and they are considered to include a non- (or weak-) magnetized neutron star. There is another category in the X-ray novae, which shows neither pulsation or X-ray bursts. Sometimes, they show "ultra soft" energy spectrum during their bright phase. This character of the "ultra soft" energy spectrum is typical in some of the black hole candidates such as Cyg X-1 in its high state and LMC X-3. As well as its dramatic brightening, this suggestion of the black hole nature of the X-ray novae makes them exciting objects.

Actually, in order to study stellar black holes, the X-ray novae are especially important because of the following points:

One important fact is that X-ray novae provide us a good opportunity to determine their dynamical mass after fading the X-ray activity. Majority

of the black hole novae are low mass X-ray binaries. Therefore, during the X-ray is bright, optical light from the accretion disk dominates that from a companion. Thus it is difficult to get an information on the spectral type of the companion. However, in the case of novae, X-ray luminosity becomes faint. After fading away, it becomes possible to get the information of the spectral type of the companion and information of the mass of the companion. This makes it possible to estimate the mass of the X-ray star from the mass function. The first demonstration had been achieved for A0620-00 by McClintock and Reminard (1986).

The second important point is that X-ray novae have a large dynamic range of the accretion rate in one particular source. The observed fluxes of novae have a dynamic range of more than 3 order of magnitude. Figure 1 shows light curves of five bright X-ray novae. Therefore the novae are good laboratories for study of the accretion flow.

Relating this topics, Narayan, Garcia and McClintock (1997) pointed out one possible difference between a neutron star binary and a black hole binary. Their key point is that the dependence of the luminosity on the mass accretion rate changes depending on the existence of the event horizon. If there is a hard core at the center of the accretion flow, at least half of the gravitational energy is released. However, if there is an event horizon at the center of the accretion flow, energy is released only in the accretion disk. Especially, in the case of an advection dominant disk, the released energy is substantially smaller than the total gravitational energy. This difference leads statistical differences of the value of the L_{min}/L_{max} of the neutron star novae and of the black hole novae.

The most important point is a fact that 70% of the stellar black hole candidate are X-ray novae. Actually, 10 black hole binaries have been confirmed by the dynamical mass estimation and among them, 7 are X-ray novae (Tanaka and Shibazaki, 1996; Barret, McClintock and Grindlay,1996).

Consequently, novae are the best laboratory for the study of the black hole nature!

In this work, I will introduce the properties of temporal and spectral variation of X-ray Novae, and discuss the black hole nature of the X-ray novae.

For more detailed review on the X-ray time variation of the black hole candidates, see Miyamoto (1995) and van der Klis (1995). For the hard X-ray properties, see Gilfanov et al. (1995), For the reviews on the X-ray novae, see Tanaka and Shibazaki (1996) and Tanaka and Lewin (1995).

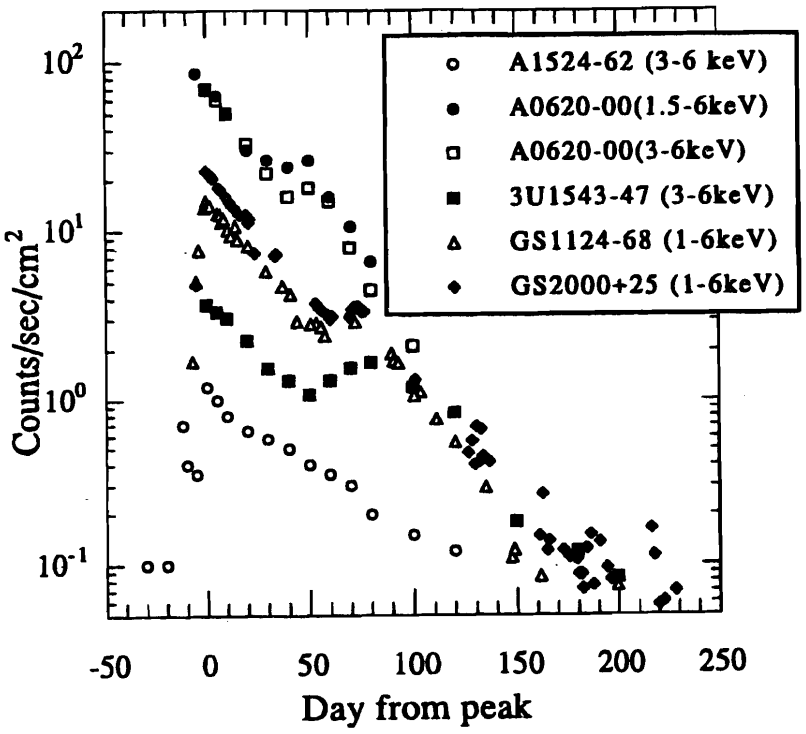

Figure 1. X-ray light curves of five bright X-ray Novae. (3U1543; Li, Sprott and Clark (1976), A1524-62; Kaluzienski et al. (1975), A0620-00; Matilsky et al. (1976), Kaluziensky et al. (1977), GS1124-683 and GS2000+25; Kitamoto (1992)).

2. Long Term Variation of Black Hole Novae

2.1. EXPONENTIAL-DECAY

The most notable fact is that many of the black hole novae had shown beautiful exponential-decays. Recent report of GRO J0422+32 also showed beautiful decay (van der Hooft, 1998). The decaying time scale is roughly 30 days (Kitamoto, 1992).

If we see the light curve more carefully, we can find that there are another peaks; second and third peaks. At least four sources showed the second peak on about 50 days after the main peak. However the reason of the second peak is not clear now. The third peak was observed in A0620-00, GS1124-683, GS2000+25 and GRO J0422+32 on about 150 days after the main peak. The third peak is accompanied with a hardening of the

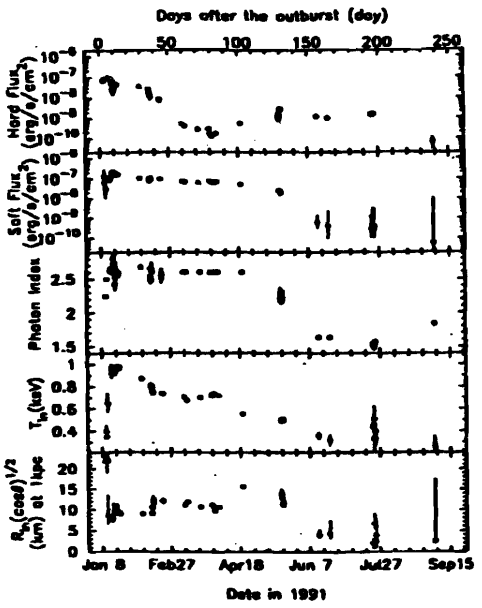

Figure 2. Spectral analysis results of GS1124-683 after Ebisawa et al. (1994). A two-component spectral model, which is composed of a disk blackbody (soft component) plus a power law (hard component), was applied to fit the data obtained with the LAC onboard *Ginga*.

energy spectrum. The good quality data of GS1124-683 clearly showed the energy spectral change at the third peak. Ebisawa et al.(1994) analyzed the *Ginga* data of GS1124-683. They applied a particular two component model; a soft component (disk-black body; Mitsuda et al. 1984)) + a hard component (power law), to fit the spectral data. Figure 2 shows their result. At the third peak (~130 days after the main peak) one can see prominent decreasing of the soft X-ray flux and changing the power law index of the hard component.

In figure 3, light curves and hardness rations of GS2000+25 and of GS1124-683 are plotted together. They seems to be twin brothers. One can see GS2000+25 also showed all properties such as beautiful decays, second and third peaks and change of the hardness ratio. These sudden change of the spectral properties at the third peak is implying the transition of the accretion disk structure.

As shown in figure 2, Ebisawa et al.(1994) derived the parameters of the disk black body model. The intensity decay is explained by the temperature decreases while the inner disk radius is constant until the third peak.

Here, we got an important result. During the decay phase, simple cooling model can explain the observation. This fact strongly supports that the

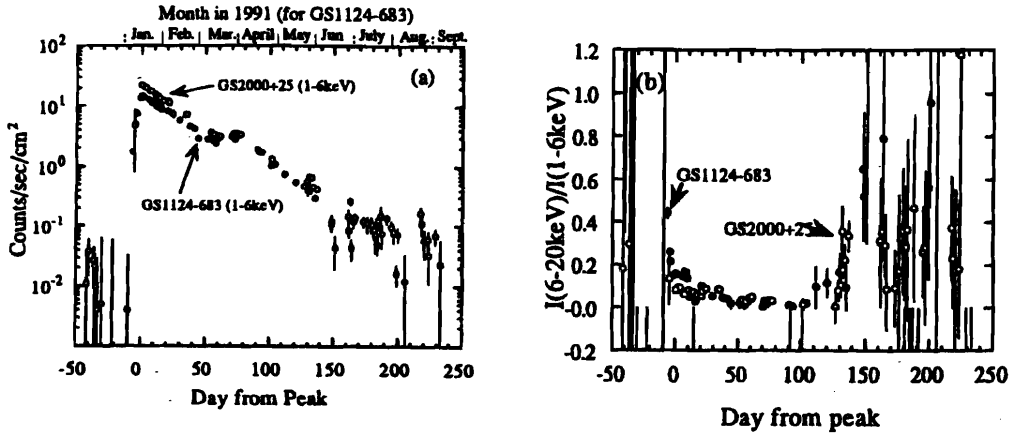

Figure 3. Light curves (a) and hardness ratio histories (b) of the GS1124-683 and of GS2000+25 obtained by the All Sky Monitor onboard *Ginga* after Kitamoto (1992).

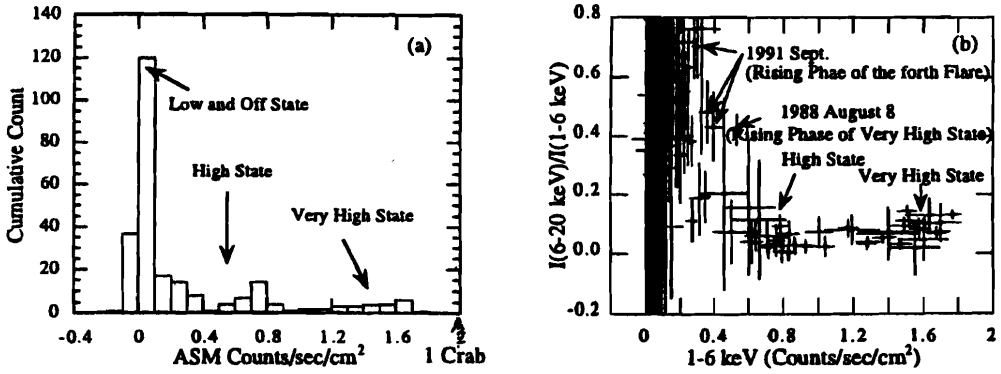

Figure 4. Cumulative count distribution (a) and a intensity-hardness map (b) of 4.5yr history of GX339-4 observed with the All Sky Monitor onboard *Ginga*, after Kitamoto et al. (1991).

disk blackbody model is correct and there is no hard core at the center of the accretion flow. Also if there is a neutron star, the difference of the cooling time scale between the neutron star and the accretion disk makes the intensity decay more complex.

2.2. CHANGE OF THE STATES

As shown in the previous subsection, there are some (at least two) states in the disk structure. More detailed study indicates that there are three states in the black hole X-ray novae. In the conventional two states; the hard (or low) and the soft (or high) states, the soft state can be divided into two different states, called very high state and high (quiet) state. The characteristics of these states are summarized in Table 1. In the very high state, the intensity is very bright and the spectrum is represented by a combination of a soft disk component and a power low component with a photon index of ~ -2.5. The temporal variation is large. The high (quiet) state is also bright state, but its power law component becomes small and its temporal variation is quiet. In the hard (or low) state, the intensity is faint and the spectrum can be represented by a power law with a photon index of ~ -1.5. The temporal variation is very variable.

TABLE 1. Three States in the Black Hole Binaries

State	Intensity	Spectrum	Variation	Photon Index
Very High	Very Bright	Soft +PL	Variable	-2.5
High (quiet)	Bright	Soft	Quiet	...
Low	Faint	PL	Variable	-1.5

Miyamoto et al.(1991) first pointed out the existence of the three states from the observation of GX339-4. In the figure 4, the cumulative counts distribution sorted by the intensity and intensity-hardness-map are plotted from the data obtained by the 4.5 yr observation by the ASM onboard *Ginga*. The cumulative counts distribution shows three distinct concentration and in the intensity hardness map we can see three concentration, indicating the existence of the three states (Kitamoto et al., 1991). Figure 5 shows the another light curve of the GS1124-68. The X-ray fluxes were decomposed into the power law component and the disk black body component. It showed a very high state, high quiet state. After the transition, it became a low state (Miyamoto et al., 1993). I like to note that GS2023+338 also showed a possible soft sate. The spectrum at the brightest phase was represented by a power law model with a photon index of about -2.5 (Kitamoto et al., 1989).

Consequently three stable states can be seen in the X-ray novae.

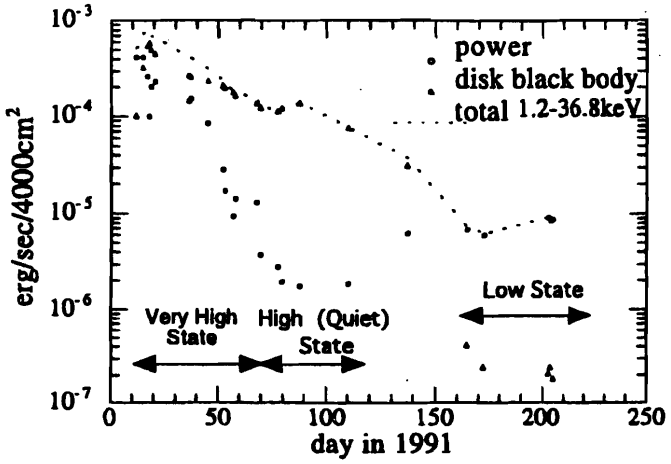

Figure 5. Light curve of the GS1124-683, after Miyamoto et al. (1993). A two-component model was applied to fit the data obtained wit the LAC onboard *Ginga*.

2.3. HYSTERETIC BEHAVIOR

This behavior was first pointed out by Miyamoto et al. (1995). If we look at the spectral evolution of GS1124-683 shown in figure 5 more carefully, we can find that the hard state continues till around the peak of the flare. Also a possible hard spectra were observed in the rising phase of GS2000+25 (see figure 3) and of GX339-4 (see figure 4(b)). However the hard state appear after decreasing down to 1/100. This behavior can be stated that there is a hysteretic behavior on the transition between the state.

3. Short Term Variation of Black Hole Novae

3.1. CANONICAL TIME VARIATION ON THE LOW STATES

In the low state, Miyamoto et al.(1992) pointed out that there is a canonical time variation. Figure 6 shows the light curves, power spectral densities (PSDs) and phase lag of the hard component, of the three black hole candidates; Cygnus X-1, GX339-4, and GS2023+338. Note that the PSDs are normalized by the mean intensities. In the Cygnus X-1 panel, two different data obtained from two different observations are shown. Both are the data in the low state. In the GX339-4 panel, both the data in the low state and in the high state are plotted together with the Cygnus X-1 data. The PSD in the high state is completely different from the low state data. However, if we look at the low state data above 0.2 Hz, the PSDs show very similar shapes and values. Also similar phase lags were obtained in the low states.

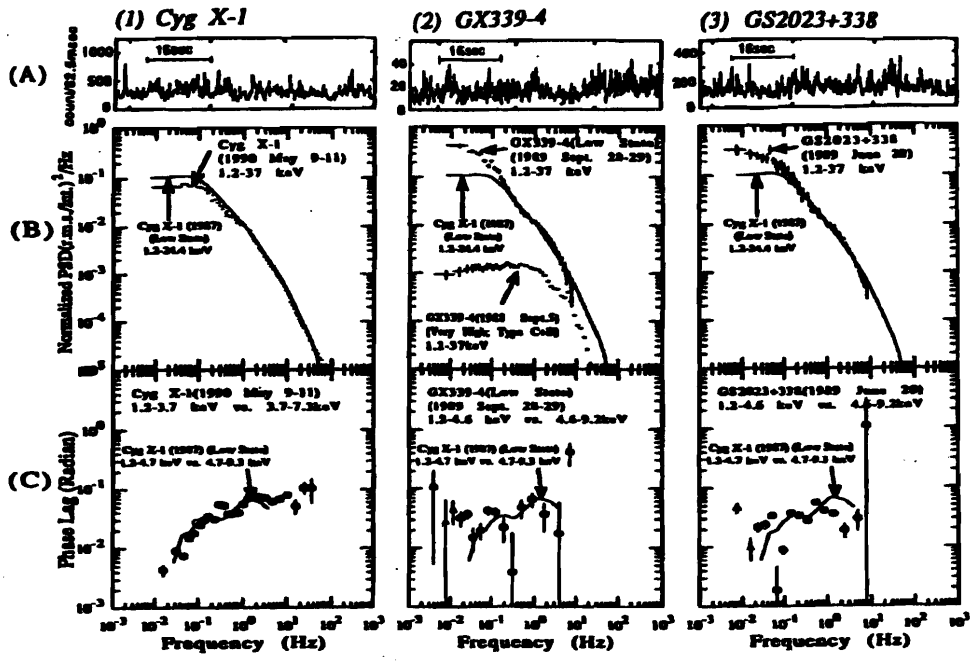

Figure 6. Time variation in the low state of three black hole candidates; Cyg X-1, GX339-4, and GS2023+338, after Miyamoto et al. (1992). Upper panels show an example of light curves. Middle panels show the power spectral densities (PSDs). The lower panels show the phase lag of the high energy component respect to the low energy component.

These properties indicate that the time variation can be described by one canonical phenomenon. This similarity is also confirmed by the similar shot structures of some black hole candidates found by Negoro (1998).

3.2. ANOTHER CANONICAL TIME VARIATION

Another canonical time variation in the high state was reported by Miyamoto et al.(1993). In the high state, the PSDs do not show same shape every time. Figure 7 shows typical PSDs of two black hole candidates and one neutron star binary. In the all sources, we can see two types of the shape; one is the power law shape and another is a flat top shape. Even in the neutron star binary; GX 5-1, it also shows similar power law shapes. There might be two components in the PSDs.

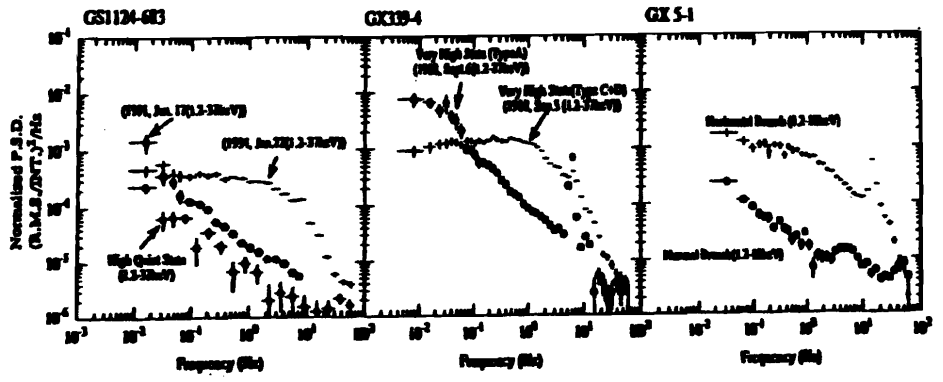

Figure 7. Power spectral densities (PSDs) in the high state of two black hole candidates; GS1124-683 and GX339-4 and one neutron star binary; GX 5-1, after Miyamoto et al. (1993).

4. Two Components

4.1. TWO COMPONENT IN ENERGY SPECTRA

We studied much more on the two component hypothesis. In the energy spectrum of the neutron star binaries, we can expect two emissions; from the accretion disk and from the surface of the neutron star (Mitsuda et al., 1984). In the case of the black hole binaries, we can expect the emission from only the accretion disk. Actually, the energy spectrum in the soft state is described by a disk blackbody model. The energy spectra of typical neutron star binaries can be roughly fitted by a 2 keV blackbody from the neutron star and disk blackbody with an inner edge temperature of about 1 keV. On the other hand the typical energy spectra of black hole candidate in their high state can be described by a disk emission only. This fact is an important support of the non-hard core at the center of the accretion flow in the black hole candidate.

However, the above discussion is not true. If we look at the high energy side above 10 keV of the spectra of the black hole candidates, there is an another component. The spectra of the neutron star binaries and of black hole binaries are shown in figure 8 (Tanaka and Sibazaki, 1996). The upper three panels show spectra of the neutron star binaries and the lower three panels show spectra of the black hole candidates. Spectra of neutron star binaries are well described by the sum of the neutron star component and the accretion disk component. While the spectra of the black hole candidates are roughly described by the accretion disk component but there

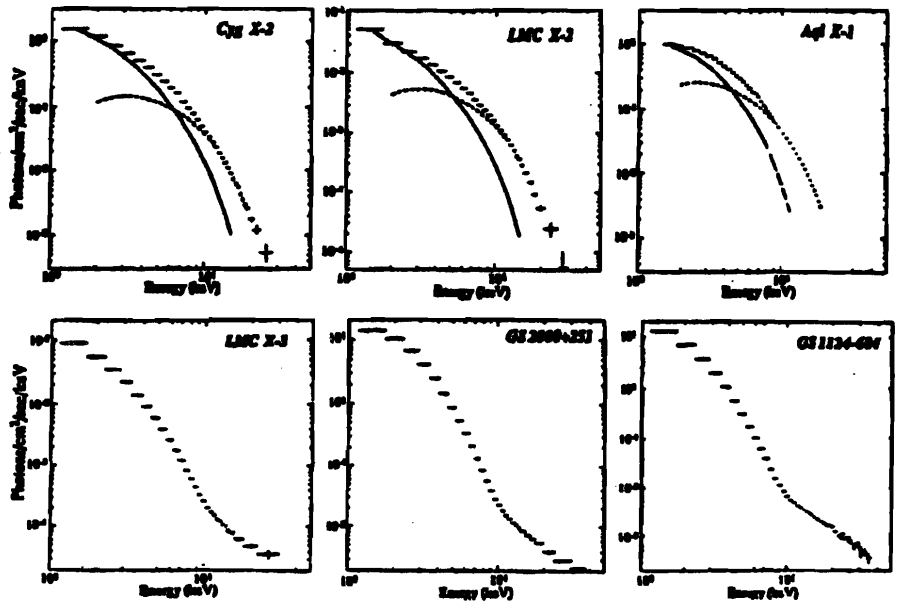

Figure 8. Energy spectra of three neutron star binaries and three black hole binaries, after Tanaka and Shibazaki (1996).

are another high energy component. We call them as a hard component. The energy spectra of black hole binaries can be decomposed into a disk component and a hard component.

4.2. TWO COMPONENT IN PSD

Figure 9 shows the collection of the PSDs of GS1124-64 (Miyamoto et al., 1994). Some have the flat top shape and some have power law shape. And some shows a combination of them. We studied the relation between this various power law shapes and the energy spectral shape. We introduce the PLF(fraction of the hard component); which is a ratio of the count rate of the hard component to the total count rate. The PLFs are indicated at the corner of the figures. If the PLF is large, the PSD shows the flat top shape. On the other hand, if the PLF(fraction of the hard component) is small, the PSD shows the power law shape. In summary; when the energy spectral shape has small hard component, the PSD shows power law shape and when the hard component is large in the energy spectrum, the PSD

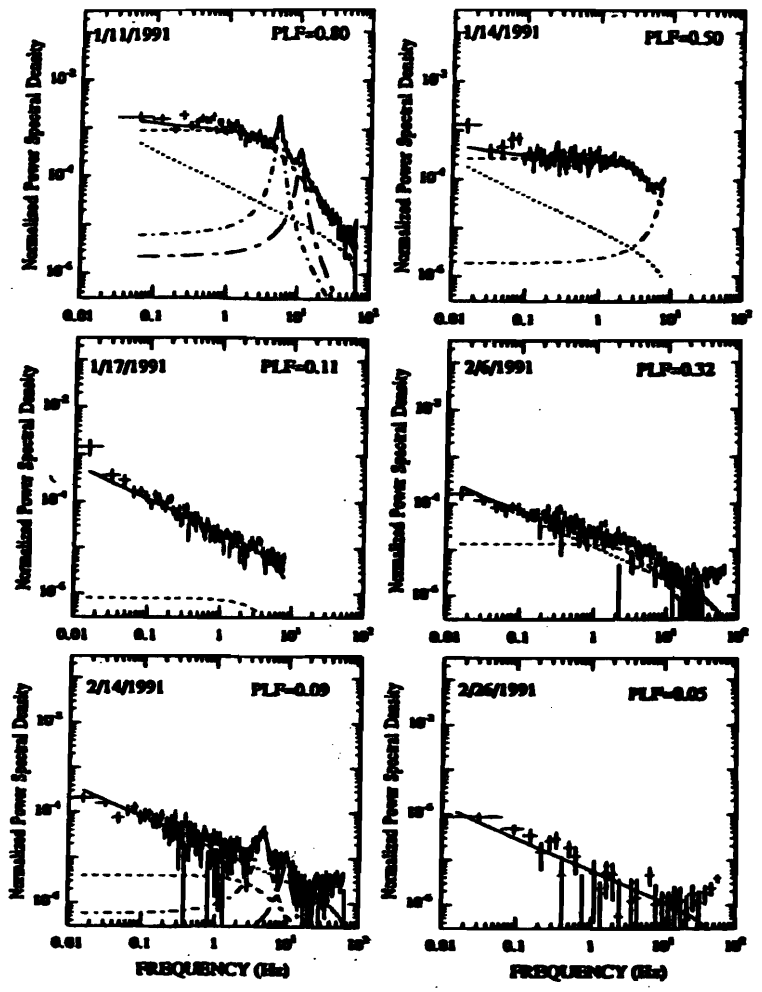

Figure 9. Collection of PSDs of GS1124-683, after Miyamoto et al. (1994).

shows flat top shape. This suggests that the PSD of the hard component has a flat top shape and the PSD of the disk component has a power law shape.

4.3. INHERENT TIME VARIATION OF THE TWO SPECTRAL COMPONENTS

Then let's assume that the flat top shape PSD is a variation of the hard component and the power law shape PSD is a variation of the disk component. Furthermore, we assume that both component varies independently and each have their own inherent value of the time variation.

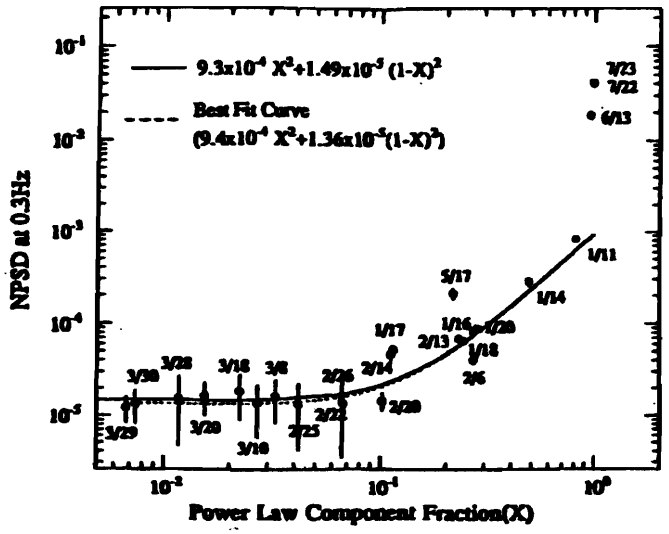

Figure 10. Normalized PSD at 0.3Hz as a function of PLF of GS1124-683, after Miyamoto et al. (1994).

Then the normalized PSD should be expressed by the following equation.

$$A \times X^2 + B \times (1 - X)^2 \tag{1}$$

where X is the PLF (fraction of the hard component), A is the inherent value of the PSD of the hard component and B is that of the disk component.

Figure 10 shows the normalized PSD values at 0.3 Hz as a function of PLF(X) derived from the GS1124-68 data. Except for the low state data, the data can be well explained by the assumed equation. The best fit values are $[9.4 \times 10^{-4}]$ (rms/int)^2/Hz and $[1.36 \times 10^{-5}]$(rms/int)^2/Hz for A and B respectively. Furthermore, if we decompose the energy spectra into the disk component and the hard component, and decomposed the PSDs into the power law shape component and the flat shape component, and normalize the PSDs by the each energy component, we got roughly constant values for the both components. These facts means that the assumptions are correct. Therefore, we conclude that the two spectral components varies independently and each has its own inherent value and shape of the PSD.

4.4. THE CASE OF NEUTRON STAR BINARY; GX 5-1

It is well known that the energy spectrum of GX 5-1 can be decomposed into two components; the disk component and the neutron star component

(Mitsuda et al., 1984). The PSD also shows sometimes power law shape and sometimes flat top shape (see figure 7). Therefore, according to the GS1124-68 case, we again fitted the normalized PSD as a function of the fraction of neutron star component(Kamado et al., 1997). First the normalized PSDs are plotted as a function of the fraction of the neutron star component. However, the square equation (equation (1)) does not fit well. Furthermore we normalized the each PSD components by its corresponding spectral component. The disk component seems constant during the small fraction of the neutron star component. It is interesting that the value of the disk component is very similar to that of the disk component of GS1124-68. However when the fraction of the neutron star component becomes large, the PSD value of the neutron star component increases steeply. Even the PSD value of the disk component becomes large. Thus we conclude that the decomposition of the two component may be correct but there is a correlation between the variations of the disk component and the neutron star component.

This is again important conclusion. In the case of neutron star binaries, the neutron star component is strongly coupling with the disk component. This is a natural result. However, in the case of black hole binaries, the hard component is independent from the disk component. We do not know the origin of the hard component, but it is not strongly coupling with the accretion disk.

5. Discussions; What is the black hole nature?

The difference between the neutron star binaries and black hole binaries is the center of the accretion flow;

The black hole binaries have an event horizon.
The neutron star binaries have a hard core, i.e. a neutron star.

From the observation of X-ray novae, we found a lot of interesting but difficult properties, among them, there are some observational support on the non-hard-core at the center of the accretion flow;

1. The spectral shape in the soft state shows no neutron star component. There is a hard component in the black hole binaries. But the hard component is not originate from the hard core, because the central hard core should directly couples with the accretion disk component.

2. The simple exponential decaying light curve can be explained by a simple cooling of the disk component. This also supports the non-central-hard core.

6. Acknowledgment

This review is based on the works with Porf. Miyamoto and other colleagues.

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