THE ASTROPHYSICAL JOURNAL, 391:L21–L24, 1992 May 20

CANONICAL TIME VARIATIONS OF X-RAYS FROM BLACK HOLE CANDIDATES IN THE LOW-INTENSITY STATE

SIGENORI MIYAMOTO, SHUNJI KITAMOTO, SAYURI IGA, HITOSHI NEGORO, AND KENTARO TERADA
Department of Earth and Space Science, Department of Physics, Faculty of Science, Osaka University, Machikaneyama 1-1, Toyonaka, Osaka, 560, Japan
Received 1991 December 9; accepted 1992 March 5

ABSTRACT

X-rays from black hole candidates, Cyg X-1, GX 339−4, and GS 2023+338 in their low-intensity state, consist of various shots or burst events, and shapes of the shots are similar among these sources. In their low-intensity states, the normalized power spectrum density functions of the X-rays except for the Fourier frequencies below about 0.2 Hz are the same not only in their shape but also in their absolute values, even if the X-ray energy range is different. Phase lags of time variations between different energy X-rays are also similar for these sources, in addition to the well-known similarity of their energy spectra of a power law. These similarities suggest that although time variations of X-rays from these sources seem to be chaotic, they are canonical, and their X-ray production process and dynamic behavior of accreting matter in the vicinity of the black hole are the same.

During an individual X-ray shot or burst event, the X-ray energy spectrum becomes harder with time, and duration of the shot event is of the order of 0.1–1 s. This time scale is of the order of viscous time scale, on which accreting matter drifts through the X-ray–emitting part of the accretion disk. This coincidence suggests that the X-ray shots are produced by many rings of accreting matter, and the hardening of the energy spectrum of the X-ray shots is due to powering up of the rings of matter by gravitational energy released in the vicinity around black holes.

On the other hand, in the very high intensity state of GX 339−4, the normalized power spectrum density functions are different from those in the low-intensity state as well as their energy spectra, which suggests that X-ray production process in the very high intensity state is different from those in the low-intensity state.

Subject headings: black hole physics — X-rays: bursts — X-rays: stars

1. INTRODUCTION

It has been believed that the existence of the high-intensity state with a soft energy spectrum and the low-intensity state with a hard power-law X-ray energy spectrum and rapid time variations in X-ray intensity are criteria to discriminate the black hole candidates from other X-ray sources, because Cyg X-1, the most probable black hole candidate, has these characteristics. For instance, GX 339−4 has been considered to be a black hole candidate, though we have no information on the mass of the compact star of this X-ray–emitting source. However, recently it was found that an X-ray nova, GS 2023+338, showed large X-ray intensity change by a factor of more than three orders of magnitude and very rapid time variation on time scales from below 0.01 s to hours in its high-intensity state, and continued to have a hard power-law energy spectrum both in its high- and low-intensity states (Kitamoto et al. 1989; Tanaka 1989; Inoue 1991; Terada et al. 1991). Very recently, the mass of the compact star of this source was reported to have 8–15.5 $M_{\odot}$. This indicates that this source is really a black hole candidate (Casares, Charles, & Naylor 1992). Thus, it is difficult to select the black hole candidates by the above criteria, and it is important to see if there are any common characteristics of the rapid time variations among the black hole candidates.

Miyamoto et al. (1988) used the cross-spectrum method to study time variations of X-rays from Cyg X-1 in its low-intensity state. They found that the hard X-ray time lags were not constant for Fourier periods of 0.1–100 s, differing from the Compton scattering model proposed by Sunyaev & Trümper (1979), in which the time lags were predicted to be constant within a certain range of Fourier periods (Miyamoto et al. 1988). They also showed that power spectrum density functions and phase lags could be explained if there was continuous hardening of the X-ray energy spectrum during an individual shot and if the time constants of the shots were about 0.7, 0.2, 0.05, and 0.01 s (Miyamoto & Kitamoto 1989). As Makishima (1988) showed that the power spectrum density function of the black hole candidates had a common power-law slope of about −1.4 in their low-intensity state, it is interesting to investigate whether these sorts of time variations prevail in X-rays from all black hole candidates. Because we have not known clearly what sorts of time variations are indications of X-rays from the black holes, quantitative investigation of the time variations and comparison with those of low-mass X-ray binaries may deduce real characteristics of the time variations of the black hole.

2. TIME VARIATIONS OF X-RAYS FROM SEVERAL BLACK HOLE CANDIDATES IN THE LOW-INTENSITY STATE

The power spectrum density functions of X-rays and the phase lags of the time variations between different energy X-rays were investigated to determine whether these were different for different X-ray sources and at different occasions for the same sources. For this study, we analyzed X-ray data of Cyg X-1, GX 339−4, and GS 2023+338 observed with the LAC on board *Ginga* (Turner et al. 1989).

Cyg X-1 was observed in its low-intensity state on two occasions; 1987 August 5–8 and 1990 May 9–11. On 1987

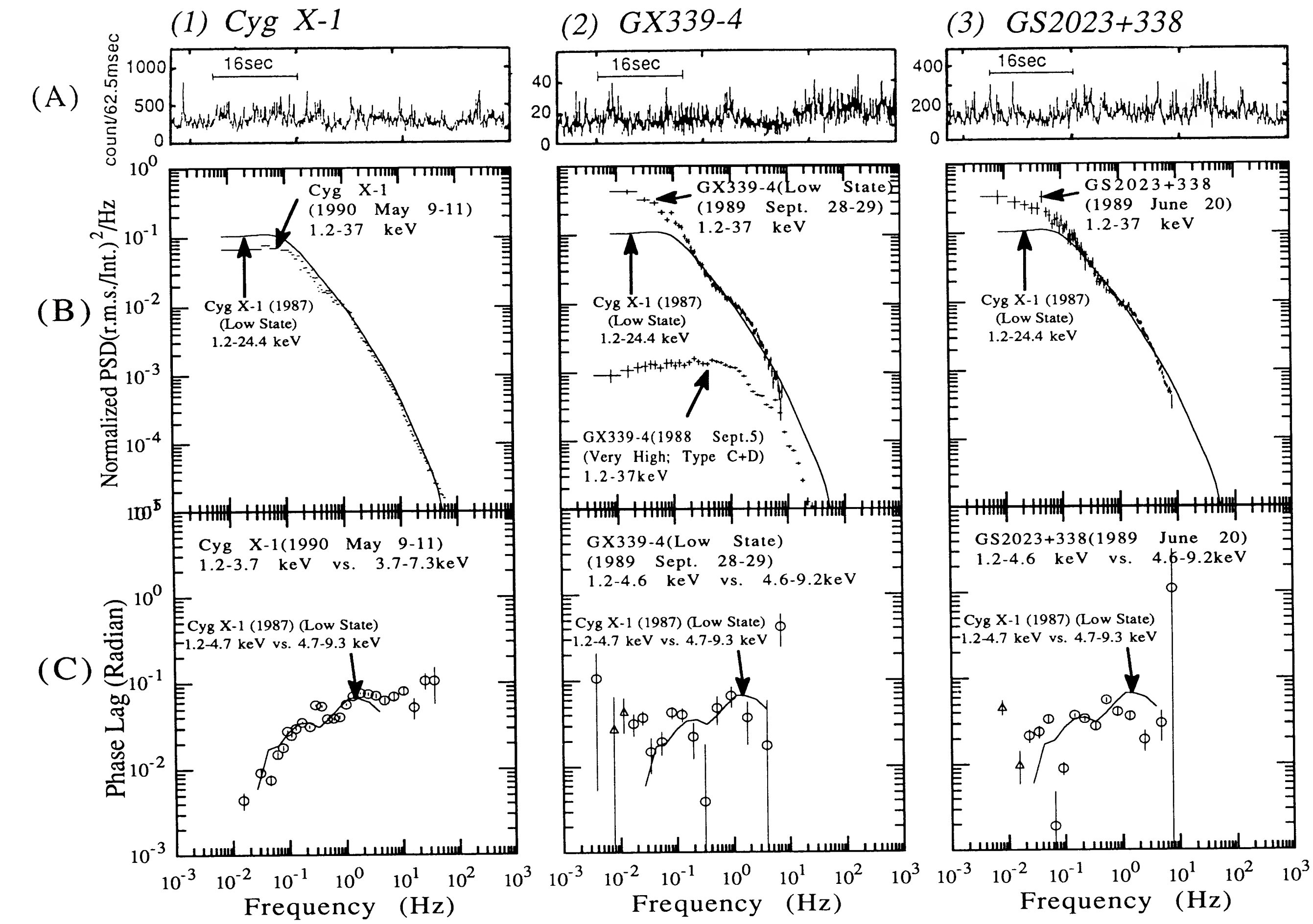

FIG. 1.—X-ray light curves (A), normalized power spectrum density functions (B), and phase lags (C) of X-rays from (1) Cygnus X-1, (2) GX 339−4 and, (3) GS 2023+338 in their low-intensity states (*open circles:* hard X-ray lag; *open triangles*, soft X-ray lag). In (2), the normalized power spectrum density function of GX 339−4 in the very high intensity state is also shown.

August 5–8, its X-ray flux was (1.25–1.44) $\times 10^{-8}$ ergs s^{-1} cm^{-2} in the energy range of 2–20 keV, and the energy spectrum could be expressed by a power law with the photon number index of about −(1.52–1.54). On 1990 May 9–11, high voltage supplied to the LAC was decreased to observe X-rays up to about 60 keV. Its X-ray flux was (1.47–1.49) $\times 10^{-8}$ ergs s^{-1} cm^{-2} in the energy range of 2–20 keV, and the energy spectrum could be represented by a power law with the photon number index of about −(1.53–1.55).

Figure 1 (panel 1) shows X-ray light curves (A), the normalized power spectrum density function (B), and the phase lags (C) of Cyg X-1 for these observations on 1990 May 9–11. In Figure 1, the results of Cyg X-1 on 1987 August 5–8 are also shown by curves for comparison between the results obtained at different occasions and different sources.

The normalized power spectrum density function is the function normalized to the squared mean intensity and the effect due to statistical fluctuation is subtracted from the computed values. This function is suitable to compare among time variations of different sources and also those of the same source at different occasions, because this function corresponds to the squared Fourier amplitude (a_f^2) Hz^{-1} divided by the squared mean double intensity (a_0^2), i.e. $(a_f/a_0)^2$ Hz^{-1} (Miyamoto et al. 1991).

From this figure one can find that except for the frequencies below about 0.2 Hz, the normalized power spectrum density functions of Cyg X-1 observed on two different occasions have the same values. The function at different occasions has a knee at different frequency and has a flat or saturated part below about 0.2 Hz, which was also observed by Belloni & Hasinger (1990). The saturated value is larger for the smaller X-ray intensity as shown in Figure 1 (panel 1, part B). The phase lags on these two occasions are similar. The energy spectra are also similar as mentioned previously. It must be remarked that even if the energy ranges are different the normalized power spectrum density functions are similar.

GX 339−4 was observed on 1989 August 28–29 and September 28–30 (Iga, Miyamoto, & Kitamoto 1991). Both energy spectra could be represented by a power law. On August 28–29 the X-ray flux of 2–20 keV and the photon number index of the energy spectrum were (8.3–9.1) $\times 10^{-11}$ ergs s^{-1} cm^{-2} and −1.8, respectively, and on 1989 September 28–30 the flux of 2–20 keV and the photon number index were (6.1–6.3) $\times 10^{-10}$ ergs s^{-1} cm^{-2} and −1.6, respectively. The X-ray flux on September 28–30 shows that GX 339−4 was in its low-intensity state and the flux was about 7 times larger than that on August 28–29.

In Figure 1 (panel 2), X-ray light curves (A), the normalized power spectrum density function (B), and the phase lags (C) of GX 339−4 in its low-intensity state (1989 September 28–29) are shown and compared with those of Cyg X-1 in its low-intensity state on 1987 August 5–8. From these figures one can find that except for the frequencies below about 0.2 Hz, the normalized power spectrum density function of GX 339−4 has values similar to that of Cyg X-1, and the phase lags are also similar except for the frequencies below about 0.2 Hz.

The normalized power spectrum density function of GX 339−4 on August 28–29 is similar to that on September 28–29 except for the frequencies below about 0.2 Hz, and the saturated value is larger on August 28–29, when the X-ray intensity is smaller. Though errors of the phase lags on August 28–29 are large, they are also consistent with those of Cyg X-1 in the low-intensity state. Thus GX 339−4 was in the low state on August 28–29 even though the X-ray intensity was smaller by a factor of about 10.

GS 2023+338 is an X-ray nova, which started to flare up on 1989 May 21 and showed rapid time variation on time scales from below 0.01 s to hours even in its high-intensity state, and its energy spectrum was harder than the ultrasoft spectrum of the black hole candidates in their high-intensity state (Kitamoto et al. 1989; Tanaka 1989; Inoue 1991). On May 30 it reached its maximum and had a saturated energy flux of 9.7×10^{-7} ergs s^{-1} cm^{-2} (2–37 keV), and then the flux decreased with rather violent fluctuation. On June 4, this source reached a certain state with a power-law energy spectrum, though its X-ray intensity continued to decrease gradually. On June 4 the energy flux was $(1.1 \pm 0.1) \times 10^{-8}$ ergs s^{-1} cm^{-2} with a power-law energy spectrum of the photon number index of −(1.1–1.3) and on June 20 the flux was $(7.9 \pm 0.1) \times 10^{-9}$ ergs s^{-1} cm^{-2} (2–20 keV) with the photon number index of −1.4. The results of GS 2023+338 on 1989 June 20 are shown in Figure 1 (panel 3). One can find that the normalized power spectrum density function and the phase lags of GS 2023+338 are again similar to GX 339−4 and Cyg X-1 in this state.

From June 4 to June 20, the normalized power spectrum density functions are similar except for the frequencies below about 0.2 Hz, and their saturation values have a tendency to be larger for smaller X-ray intensities, though there are a few exceptions. Their phase lags are almost similar to those shown in Figure 1 (panel 3).

This source had a hard energy spectrum even in its high-intensity state, which was different from the case of Cyg X-1. However, in its low-intensity state, the time variation was similar to those of Cyg X-1 as shown above.

From these described above, one can recognize the following in the time variations of the black hole candidates in their low-intensity state.

1. The X-ray light curves of different sources consist of many shot or burst events, and they are similar to those of Cyg X-1.

2. Except for the Fourier frequencies below about 0.2 Hz, all the normalized power spectrum density functions are similar, not only in their shape but also in their absolute values. The normalized power spectrum density functions are similar even if the X-ray energy range is different. These hold for the same source on different occasions and even for different sources.

3. At the frequencies below about 0.2 Hz, the normalized power spectrum density functions have knees and show saturation at different values. Even in the same source, the saturation values are different on different occasions. There is a tendency that the saturation values are larger for smaller X-ray flux in the same source.

4. The hard X-ray phase lags of time variations of X-rays from those of soft X-rays are similar at different occasions for the same source and for different sources, though there are small local differences from others as shown in Figure 1 (panel C).

5. In the low-intensity state, time variations of GS 2023+338 are similar to those of Cyg X-1 in its low-intensity state, though GS 2023+338 had a hard energy spectrum even in its high-intensity state.

These results suggest that in these black hole candidates in the low-intensity state, the X-ray production process and dynamic behavior of accreting matter are the same except for the processes which correspond to the Fourier frequencies below about 0.2 Hz.

3. DISCUSSIONS

It is interesting to compare these results with those in the other state. As for Cyg X-1, we have no data. But for GX 339−4, we have interesting results.

It is well known that in the high-intensity state, GX 339−4 has a softer energy spectrum than that in the low-intensity state and the time variation of the X-rays is rather quiet. It does not show rapid variations on any time scales between 16 ms and 20 minutes (Makishima et al. 1986).

In the very high intensity state, where GX 339−4 was just after the peak of a flare, it showed very rapid time variations on time scales below minutes (Miyamoto et al. 1991). The very high intensity state corresponds to the state that the hard X-ray component, which appeared at the rising phase of the flare of the source, still remain at its early decaying phase (Kitamoto et al. 1992). In this state, the normalized power spectrum density function changes with time and there are different substates such as A, B, C, D, etc., even in the same intensity state, and these normalized power spectrum density functions and the phase lags are different from those in the low state (Miyamoto et al. 1991). An example is inserted in Figure 1 (panel 2, part B), where the normalized power spectrum density function in the substate type C+D of the very high intensity state is compared with those in the low-intensity state. The values of the function are smaller than those in the low intensity state.

Thus both in the very high intensity state and in the high-intensity state, time variations of X-rays from GX 339−4 are different from those in the low-intensity state. This suggests that the X-ray–emitting process in the very high state is quite different from that in the low-intensity state as discussed by Miyamoto & Kitamoto (1991) and Miyamoto et al. (1991).

The normalized power spectrum density functions in the low-intensity state are similar even if the energy range is different. This can be explained if X-rays of at least 2–40 keV range are producing similarly and simultaneously and these constitute almost only one component in the low-intensity state. If there are other X-ray components which have different energy spectra and different time variations, the normalized power spectrum density functions should have different shapes and different values in different X-ray energy ranges.

We found that in the low-intensity state the normalized power spectrum density function had similar values at the frequencies higher than about 0.2 Hz even in different sources and on different occasions, and its saturation values at the lower frequency region had a tendency to be larger for smaller X-ray flux. These may be due to the following situation. In the low-intensity state, geometrical structure and dynamic behavior of the inner part of the accretion disk, which is the origin of the rapid time variations, are similar even if those of the outer part of the accretion disk are different. The slower time variations are due to the dynamics and the structure of the outer part of the accretion disk, and a smaller accretion rate induces larger time variations in the outer part of the accretion disk.

Comparing the power spectrum density functions and the phase lags of Cyg X-1 in the low-intensity state with those expected from the shots of several time durations of 0.01–1 s, Miyamoto & Kitamoto (1989) concluded that both the power spectrum density function and the phase lags could be explained if these shots became harder in their energy spectrum with time. This result is consistent with the result obtained by Negoro, Miyamoto, & Kitamoto (1991) that before the peaks of X-ray shots, the intensity of hard X-rays increases later but more rapidly than that of soft X-rays, and after the peaks, the hard X-ray intensity decreases more slowly than the soft X-rays. Their result is consistent with that obtained by Lochner, Swank, & Szymkowiak (1991).

Assuming the thin accretion disk model, let us examine X-ray–emitting processes which might cause the time duration of the X-ray shots to be of the order of 0.1–1 s in this model, and what sort of physical processes might cause the hardening in the X-ray shots. With this thin accretion disk model, comparing various time scales such as that of Kepler motion [$t_k \sim R/v_k$, $v_k = (GM/R)^{1/2}$], that of hydrostatic equilibrium in the vertical direction of the disk (t_h), a thermal dissipation time scale [$t_{\rm th} \sim$ (heat content)/(dissipation rate)], and a viscous time scale ($t_{\rm visc} \sim R/v_R$, where v_R is the velocity with which accreting matter drifts through the disk under the effect of viscous torque), one can get the following relations (see, for instance, Frank, King, & Raine 1985),

$$t_k \sim t_h \sim \alpha t_{\rm th} \sim \alpha (H/R)^2 t_{\rm visc} ,$$

where α is the α parameter of Shakula & Sunyaev (1973) and $\alpha \lesssim 1$, M is the mass of the black hole, R is the radius of the X-ray–emitting disk and H is the scale height of the disk and is given by $H \sim c_s[R^3/(GM)]^{1/2}$, where c_s is the sound speed in the disk.

If we choose $M = 5\ M_\odot$, $R = 10R_S$ (R_S: Schwarzschild radius), and $T = 10^9$ K, we get $t_k \sim 2$ ms and $t_{\rm visc} \sim 1./\alpha$ s and only the viscous time scale ($t_{\rm visc}$) can be the same order of the duration of the X-ray shots. Thus the time width of the shots seems to be due to the drift time of matter in the X-ray–emitting region of the disk onto the black hole.

As X-rays are composed of many X-ray shots, the accreting matter should form many lumps, which may be caused by possible instability at the inner part of the accretion disk. As the X-ray shot has the duration (τ) of about 0.3 s, the length of the lump in the radius direction should be about $v_R \tau \sim (H/R)^2 v_k \tau \sim 5 \times 10^6$ cm. As R ($\sim 10\ R_S$) is also about 10^7 cm, due to different Kepler velocities at different radii, the lumps should form rings around the black hole.

The continuous hardening of the energy spectrum of the X-rays during the shot may be due to powering up of the matter of the rings by gravitational energy released in the vicinity around black holes: possibly heating up of the matter, though there is no established interior disk model and we cannot clearly describe the process occurring in these rings of matter.

4. CONCLUSIONS

We found canonical time variation in the X-rays from the black hole candidates, Cyg X-1, GX 339−4, and GS 2023+338 in their low-intensity state. The energy spectra, the X-ray light curves, the normalized power spectrum density functions, and the phase lags of the X-rays from these sources are almost the same. The normalized power spectrum density functions are similar even if the energy range is different. These suggest that the X-ray production processes and dynamic behavior of accreting matter in the vicinity of these black hole are the same in their low state.

Based on the thin accretion disk model, we deduced the following conclusions: the X-ray shots are due to rings of accreting matter around the black hole, and the continuous hardening of the energy spectrum with time during the shot is due to powering up of the matter by gravitational energy released in the vicinity of black holes. The different saturation values in the power spectrum density function may reflect the different dynamic behavior in the outer part of the accretion disk.

In the very high intensity state of GX 339−4, the normalized power spectral density functions and the phase lags are different from those in the low-intensity state as well as their energy spectra, which suggests that the X-ray production process in the very high intensity state is quite different from those in the low-intensity state.

REFERENCES

Belloni, T., & Hasinger, G., 1990, A&A, 230, 103
Casares, J., Charles, P. A., & Naylor, T. 1992, Nature, 355, 614
Frank, J., King, A. R., & Raine, D. J. 1985, Accretion Power in Astrophysics (London: Cambridge Univ. Press)
Iga, S., Miyamoto, S., & Kitamoto, S. 1991, in Frontiers of X-Ray Astronomy, ed. Y. Tanaka & K. Koyama, in press
Inoue, H. 1991, ISAS Research Note 469, in Proc. of 15th Texas Symposium on Relativistic Astrophysics, Ann. NY Acad. Sci., in press
Kitamoto, S., et al. 1989, Nature, 342, 518
Kitamoto, S., et al. 1992, ApJ, in press
Lochner, J. C., Swank, J. H., & Szymkowiak, A. E. 1991, ApJ, 376, 295
Makishima, K. 1988, in Physics of Neutron Star and Black Holes, ed. Y. Tanaka (Tokyo: Universal Academy Press), 175
Makishima, K., et al. 1986, ApJ, 308, 635
Miyamoto, S., Kitamoto, S., Mitsuda, K., & Dotani, T. 1988, Nature, 336, 450
Miyamoto, S., & Kitamoto, S. 1989, Nature, 342, 773
———. 1991, ApJ, 374, 741
Miyamoto, S., Kimura, K., Kitamoto, S., Dotani, T., & Ebisawa, K. 1991, ApJ, 383, 784
Negoro, H., Miyamoto, S., & Kitamoto, S. 1991, in Frontiers of X-ray Astronomy, ed. Y. Tanaka, & K. Koyama, in press
Shakula, N. I., & Sunyaev, R. A. 1973, A&A, 24, 337
Sunyaev, R. A., & Trümper, J. 1979, Nature, 279, 506
Tanaka, Y. 1989, in Proc. 23rd ESLAB Symposium (ESA SP-296), Vol. 1, 3, ed. J. Hunt & B. Battrick (Noordwijk: ESA), 1, 3
Terada, T., Miyamoto, S., Kitamoto, S., Tsunemi, H., & Hayashida, K. 1991, in Frontiers of X-Ray Astronomy, ed. Y. Tanaka & K. Koyama, in press
Turner, M. J. L., et al. 1989, PASJ, 41, 345