

Observation of the Long-term Variability of Cygnus X-1 with MAXI

Juri Sugimoto
Department of Physics
Rikkyo University, Japan

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Abstract

We investigated the large-scale structure of an accretion disk around a compact star, especially focusing to the famous black hole binary, Cygnus X-1, by studying the long-term X-ray variability, using 6 years of MAXI data from 2009 to 2016. It is well known that the accretion disk exhibits some different states according to the mass accretion rate. The typical two states are a high/soft state and a low/hard state. The MAXI data includes substantial periods of both the high/soft state and the low/hard state.

First, we analyzed an aperiodic long-term variation, using Normalized Power Spectrum Densities (NPSDs) in three energy bands of $2 - 4$ keV, $4 - 10$ keV and $10 - 20$ keV, in each state. The NPSDs in a frequency from 10^{-7} Hz to 10^{-4} Hz were all approximated by a power law function with indices of $-1.35 \sim -1.29$. This low frequency variation in the above frequency range is the first result for the high/soft state in the world. The fractional RMS variation η , calculated in the above frequency range, was found to show the following three properties; (1) η slightly decreases with energy in the low/hard state; (2) η increases towards higher energies in the high/soft state; and (3) in the $10 - 20$ keV band, η is 3 times higher in the high/soft state than in the low/hard state. These properties were confirmed through studies of intensity-correlated changes of the MAXI spectra. Of these three findings, the first one is consistent with that seen in the short-term variability during the low/hard state. The latter two can be understood as a result of high variability of the hard-tail component seen in the high/soft state with the above very low frequency range. This discovery of the variation in the very low frequency begs the question on the time-scale, because such a low frequency variation cannot be produced in the X-ray emission region in the framework of the conventional model.

We also studied about the 5.6 day orbital modulation of Cygnus X-1. We detected clear intensity modulations with the orbital period in its high/soft state with MAXI data, as well as in its low/hard state. This detection of the intensity modulation in the high/soft state is also the first discovery in the world. In the low/hard state, the folded light curves showed an intensity drop at the superior conjunction of the black hole in the low energy band, overlapping an energy-independent sinusoidal modulation. Spectral analysis in the low/hard state, with a model consisting of a power law and a photoelectric absorption, showed that the hydrogen column density N_{H} increased from 5×10^{21} to $7 \times 10^{21} \text{ cm}^{-2}$ around the superior conjunction, and the unabsorbed flux of the power law component decreased with $3 \pm 2\%$. On the other hand, we detected only the energy-independent intensity modulation in the high/soft state. We applied a model consisting of a power law and a diskblackbody with a photoelectric absorption and found a modulation of the flux of the power law component with $6 \pm 3\%$ in MF , while the modulation of N_{H} was less than $1 \times 10^{21} \text{ cm}^{-2}$. These results can be interpreted as follows; the modulation of both states can be mainly explained by scattering of the X-rays by an ionized stellar wind, but only at the superior conjunction in the low/hard state, a large photoelectric absorption appears, because of a low ionization state of the wind in the line of sight at the phase. Such a condition can be established by reasonable parameters by considering the luminosity difference. However, if we take into consideration of existence of the well-known phenomena called “ absorption

dips ”, the wind should be inhomogeneous.

From our results of the aperiodic long-term variation and of the 5.6 d orbital modulation, we discuss the large-scale structure of the accretion disk. We propose a new large-scale disk structure, which can explain the very low frequency aperiodic variation. In our proposing structure, an optically thin and geometrically thick accretion disk (corona) coexists with an optically thick and geometrically thin, standard accretion disk, which is extending up to a large radius of $\sim 10^{12}$ cm, in both the states. The origin of the optically thin disk (corona) and the origin of the long-term variation are also discussed, considering the wind-fed accretion by the inhomogeneous wind.

Contents

1	Introduction	1
2	Review	4
2.1	X-ray Binary Sources and Accretion	4
2.1.1	X-ray binaries	4
2.1.2	Accretion in binary systems	6
2.2	Eddington limit	8
2.3	Accretion Disk	8
2.3.1	Standard Accretion Disk	8
2.3.2	Time scales	11
2.3.3	RIAF and Slim disk	12
2.4	Stellar wind	16
2.5	Cygnus X-1	19
2.5.1	Bimodal behavior of Cyg X-1	19
2.5.2	Time variability	21
2.5.3	Orbital modulations and Absorption dips in Cyg X-1	24
3	MAXI	27
3.1	About MAXI	27
3.2	Instruments	28
3.2.1	Gas Slit Camera	28
3.2.2	Solid-state Slit Camera	30
4	Observation of Cyg X-1 with MAXI	35
4.1	Light Curve	35
4.2	Definition of spectral states	38
5	Long-Term variations in the low/hard and the high/soft states	40
5.1	Power Spectra	41
5.1.1	Definition of NPSDs	41

CONTENTS

5.1.2	Sampling and gap effects	41
5.1.3	Estimation of the sampling and gap effects	42
5.1.4	Estimation of the Poisson noise	44
5.1.5	Results (1): using the longest data length	46
5.1.6	Results (2): using shorter data lengths	48
5.2	Energy Spectra	53
5.3	Summary and short discussion	57
5.3.1	Summary of data analysis	57
5.3.2	Comparison with short-term variability	60
5.3.3	Spectral variation	61
6	Orbital Modulations in the low/hard and high/soft states	63
6.1	Folded Light Curves and Hardness Ratios	63
6.2	Phase resolved Spectral Analysis	65
6.2.1	Spectral ratio	65
6.2.2	Spectral model fitting	65
6.3	Discussion of the orbital modulation	66
6.3.1	Orbital Modulation	66
6.3.2	Density of stellar wind	68
6.3.3	Stellar wind model	71
7	Discussion	72
7.1	Summary of the observation results	72
7.2	Time scale of the variation	74
7.3	Mass accretion rates through optically-thick accretion disk and corona	74
7.4	X-ray irradiation	75
7.5	Origin of the long-term variation	82
8	Conclusion	85

List of Figures

1.1	The X-ray light curve of Cyg X-1 by the Uhuru satellite (Oda et al., 1971).	2
2.1	An image of the X-ray binary (ESA/Hubble illustration).	5
2.2	Schematic sketch of 16 Milky Way BH binaries with reasonably accurate dynamical data (Remillard and McClintock, 2006).	6
2.3	Two possible modes of mass transfer in a binary X-ray source (Shapiro and Teukolsky, 1986). The solid curves in the two pictures show the Roche lobe. (a) The accretion model of Roche lobe overflow. (b) The accretion model of wind fed.	7
2.4	The sketch of the hydrostatic equilibrium in the disk. The arrows show the balance between the gas pressure and the gravitational force on the disk surface at radius r	11
2.5	Typical solutions of the standard accretion disk calculated by Kato et al. (2008). The horizontal axis is the radius in an unit of the Schwarzschild radius. The vertical axes are (a) the disk half-thickness in an unit of the Schwarzschild radius, (b) the surface density in an unit of g cm^{-2} , (c) the radial velocity in an unit of a light velocity and (d) the disk temperature in an unit of K. The thick solid lines are calculated with $M_{\text{BH}} = 10M_{\odot}$, $\dot{M} = 1M_{\text{E}}$ and $\alpha = 1$. The thin solid lines are with $M_{\text{BH}} = 10^8M_{\odot}$, $\dot{M} = 1M_{\text{E}}$ and $\alpha = 1$	13
2.6	Parameter f dependence of coefficients c_i (Fukue, 2007). These are calculated in the case of $\alpha = 0.1, 0.5, 1$. The dashed lines are obtained by an assumption of a constant $\dot{M}$, and the solid lines are by a non-constant $\dot{M}$	15
2.7	Configuration of the accretion flow in different spectral states shown by Esin et al. (1997). Black thick lines show the optically thick accretion disks. Dots describe ADAF.	17
2.8	The three solution branches for an accreting $10M_{\odot}$ BH at a radius of $r = 10^3$. The vertical and horizontal axes show an mass accretion rate $\dot{M}$ and a surface density Σ . The branch A, B and C correspond to a standard disk, unstable and advection dominated solutions, respectively. The red arrow represents the transition from the standard disk to the RIAF.	18

LIST OF FIGURES

2.9	Evolution of density distribution in the orbital plane of Cygnus X-1 (Čechura and Hadrava, 2015). The left panel shows a start condition of the simulation adjusting the X-ray luminosity of the compact object to the level corresponding to the LHS. The center and right panels represent the transient state and the HSS. The numbers written in the upper right corner correspond the time from the start of the simulation in unit of orbital period.	20
2.10	The radial velocity curve obtained by the optical observation (Brocksopp et al., 1999b). The solid line shows the theoretical curve and the bottom shows the residuals. . . .	20
2.11	Typical energy spectra of Cyg X-1 obtained with Suzaku by Yamada et al. (2013a). The red and black data show the spectrum in the LHS and HSS, respectively.	21
2.12	The X-ray light curve with RXTE/ASM in 1.5–3 keV (black dots) and with MAXI/GSC in 2 – 4 keV (red dots).	22
2.13	The power spectrum densities in the range of $10^{-3} - 10$ Hz by Churazov et al. (2001). The black and green are the PSDs in the LHS, the red is in the HSS.	23
2.14	The power spectrum density in the range of $10^{-7} - 10^{-5}$ Hz by Reig et al. (2002). Circles, squares and crosses are calculated with 1.3–3, 3–5 and 5–12.2 keV band. . . .	24
2.15	The left shows the light curves of Cyg X-1 in the LHS by RXTE/ASM folded by 5.6 d (Wen et al., 1999). The right shows the unfolded light curves and the hardness ratio in the LHS by SAS 3 including the dip period (Remillard and Canizares, 1984).	25
3.1	(top) A sketch of the GSC and pictures of a collimator and a proportional counter. (bottom left) A schematic view of a single GSC camera unit and its field of view (FOV). (bottom right) The FOVs of the six camera units including 12 counters (GSC 0, ..., GSC 9, GSC A, GSC B) on the ISS low-earth orbit. Every two counters, such as GSC 0 and GSC 6, are used as a pair for a redundancy. Left, center, and right camera units cover the area of source-acquisition angle β of $80^\circ < \beta < 0^\circ$, $-40^\circ < \beta < +40^\circ$, and $0^\circ < \beta < +80^\circ$, respectively.	29
3.2	Energy resolution (FWHM) of the MAXI/GSC against the X-ray energy (Mihara et al., 2011). Circles with $1 - \sigma$ error bars represent the measured data with K-shell emission lines from elements.	30
3.3	Relation between the position at which X-ray is absorbed along the anode wire (DETX) and the position-measure parameter derived from the PHA ratio, PM (Mihara et al., 2011). The data in the top panel is fitted with a linear function (solid line), and the bottom panel shows the residuals.	31
3.4	A detection efficiency of the MAXI/GSC. The solid line is at the incident angle $\phi = 0^\circ$ and the dashed line is at $\phi = 40^\circ$	31
3.5	(left) The picture of the SSC. The sixteen of CCDs are aligned. (right) An exploded view of the SSC.	32
3.6	A detection efficiency of the MAXI/SSC.	32

LIST OF FIGURES

3.7	Energy resolution of the MAXI/SSC-H as a function of the X-ray energy (Tomida et al., 2011).	33
3.8	The all-sky image obtained by the MAXI/GSC and SSC, accumulated for four and a half years, from 2009 to 2013. The colors, red, green and blue, are corresponding to the X-ray energy bands, 0.7 – 2, 4 – 8 and 8 – 16 keV, respectively.	34
4.1	The MAXI/GSC image in 4 – 10 keV band of Cyg X-1. The circles with green solid lines show the source and background region of Cyg X-1. The dashed circles are contaminating sources.	36
4.2	An example of the energy spectra of Cyg X-1. The green, red and black data correspond to the on-source, background and background-subtracted source spectrum spectra, respectively.	36
4.3	One-day bin light curves and HR histories of Cyg X-1 obtained with the MAXI/GSC. From the top to bottom panels, the 2–4 keV, 4–10 keV and 10–20 keV intensities, and the $I(4-10 \text{ keV})/I(2-4 \text{ keV})$ and $I(10-20 \text{ keV})/I(4-10 \text{ keV})$ ratios are plotted. The blue and red data points indicate the LHS and HSS periods, respectively. Data points with large error bars, due to high background counts, were omitted.	37
4.4	The hardness-intensity diagram (top panel) and the histogram of the 4–10 keV vs. 2–4 keV HR (bottom panel). Blue and red data points specify the LHS and the HSS, respectively, while black points were taken during transitions.	39
5.1	The left figure is a simulated light curve calculated with equation (5.5). The right one is after applying the data gaps and filling them by linear interpolations. The sampling time is $\Delta t = 5400 \text{ s}$	43
5.2	(a) Simulations of the alias effects and sampling effects on the PSD with the index of -1 . The black data are the PSD calculated from 100 fake light curves, each continuous with a bin width of 54s. The red one is the PSD calculated after sparse sampling (once every 5400s), to the original light curves, and blue one further considering the data gaps that are present in the read data. The bottom panel shows the transfer-function, obtained by the dividing the blue PSD by the black one. (b)(c) Same simulations as (a), but the PSD indices are set at -2 and -0.5 , respectively.	45
5.3	The simulated 4–10 keV Poisson-noise contribution (red), compared with the 4–10 keV PSD actually observed from Cyg X-1 in the HSS (black).	47
5.4	NPSDs of Cyg X-1 in the LHS (left) and in the HSS (right), each calculated using the longest data span (No.1-all in table 5.1 and No.8-all in table 5.2). The blue, black and red points represent NPSDs in the 2 – 4 keV, 4 – 10 keV and 10 – 20 keV band, respectively. The vertical line at $2 \times 10^{-6} \text{ Hz}$ indicates the 5.6-day orbital period. . . .	50

LIST OF FIGURES

5.5	The NPSDs calculated over shorter data segments ($40 \text{ d} \times 6$ for the LHS and $43 \text{ d} \times 8$ for the HSS), and averaged. Here, the NPSDs are shown after multiplying with the frequency.	50
5.6	(left) Expanded $10 - 20 \text{ keV}$ light curves (three-day bin) of Data No.1-all and No.8-all, representing the LHS and the HSS, respectively. Ordinates are logarithmic. (right) The same as left, but with linear scales. Data No.1-all and data No.8-all are shown the LHS and HSS, respectively. The data No. is indicated in top panel, and the corresponding MJDs are listed in table 5.1 and 5.2.	51
5.7	A comparison of the MAXI $4 - 10 \text{ keV}$ NPSDs in the LHS (blue) and the HSS (red), with the previous works. The dashed line is the $2 - 13 \text{ keV}$ NPSD in the LHS by Pottschmidt et al. (2003), the dotted line is that in the HSS in $2 - 13 \text{ keV}$ by Cui et al. (1997), and the dot-dashed line is that by Reig et al. (2002) where the most data are in the LHS.	53
5.8	Background-subtracted unfolded MAXI spectra in the LHS (left), and the HSS (right). Red and black indicate the bright-period data of the SSC and GSC respectively, while blue and green indicate the faint periods of the SSC and GSC, respectively. The model is $phabs*(diskbb+nthComp+gaussian)$, with the parameters listed in table 5.6. The $1.5 - 2 \text{ keV}$ energy range is ignored in the fitting. The dotted lines represent contributions of the three components. The bottom panels are residuals from the model.	54
5.9	Ratios of the GSC spectra in the bright period to that in the faint period, in the LHS (left panel), and in the HSS (right panel).	55
6.1	Folded light curves and hardness ratios in the LHS (left) and the HSS (right).	64
6.2	Spectral ratios in the LHS (left) and the HSS (right). The spectra in the three phases, $0.9 - 0.2$, $0.2 - 0.4$ and $0.7 - 0.9$ were divided by that in the phase $0.4 - 0.7$, for both states.	65
6.3	Spectra in the $0.0 - 0.1$ in the LHS (left) and the HSS (right). The black and the red were the GSC and the SSC spectra, respectively.	66
6.4	The parameter histories in the LHS (left) and the HSS (right). Photon indices and T_{in} were fixed at 1.65 and 0.2 keV in the LHS, and 2.9 and 0.5 keV in the HSS. The disk normalization was fixed at 5×10^5 in the LHS.	67
6.5	The expected light curves for four values of parameter η . The observed folded light curves were also plotted. All the light curves were adjusted to be one at the peak intensity.	70

LIST OF FIGURES

7.1	Illustrations of accretion models (left) and the NPSD which is same as figure 5.7. Red lines show time-scales which correspond to breaks in the NPSD. (a) Focusing on the NPSD in the LHS in the high frequency, in the frequency less than 10^{-3} Hz (corona + disk), the NPSD is roughly $\frac{1}{25}$ of the extrapolation of the NPSD above 0.1 Hz (corona only). (b) Focusing on the NPSD in the LHS and HSS in the low frequency, below 10^{-4} Hz, the normalized power of the HSS is about six times larger than that in the LHS. .	76
7.2	Illustrations of accretion models in the LHS (left) and in the HSS (right). The optically-thick accretion disk is shown with a thick black line, which is truncated at a certain radius in the LHS, but extends down to the ISCO in the HSS. In both states, the optically-thin flow extends up to $\sim 10^5 r_S$, while it turns into the Comptonizing corona at small radii. The percentages mean the fractional mass accretion rate in each state.	76
7.3	A simple schematic of a model of an irradiated accretion disk in figure 1 in Ko and Kallman (1991).	77
7.4	The heating rate per unit area Q_{vis} and Q_X . r is divided by Schwarzschild radius. . .	78
7.5	The modeled temperature for the normalized disk height (z/r) with various radius r calculated by Jimenez-Garate et al. (2002).	79
7.6	The schematic description of the evaporated plasma by the X-ray irradiation. Most of the evaporated plasma forms a thin disk, but a part of it becomes a disk wind. . . .	80
7.7	The modeled proton density for the normalized disk height (z/r) with various radius r calculated by Jimenez-Garate et al. (2002).	81
7.8	The upper schematic shows the grand structure of the binary system of Cyg X-1. Blue clouds scattered in the stellar wind indicate blobs. The inside of the lower square is a magnified drawing of the BH and the accretion disk in side view. Blobs hit and disturbe the accretion disk. The drift velocity v_{drift} in the optically-thin flow (the red regions) is faster than that in the optically-thick disk (the black lines).	84

List of Tables

3.1	The specifications of the MAXI/GSC and SSC.	34
4.1	Spectral states of Cyg X-1 during the MAXI observation.	38
5.1	Data segments used in calculating NPSD in the LHSs.	49
5.2	The same as table 5.1but for the HSS.	49
5.3	The fractional RMS η of NPSDs from 10^{-6} to 9.2×10^{-5} Hz.	52
5.4	The flux ratio R of equation (5.8), and the RMS variation η' of equation (5.9).	57
5.5	The best-fit parameters of the absorbed <i>diskbb</i> plus <i>powerlaw</i> model.	58
5.6	The best-fit parameters of the model consisting of a <i>diskbb</i> and <i>nthComp</i> taking account of the photo-electric absorption.	59
6.1	Parameters used in calculation.	69

Chapter 1

Introduction

In the universe, there are various phenomena involving a mass accretion. One of them is an accretion disk, which is formed around a compact star in an X-ray binary system. Such a compact star brights with the X-ray by the gas accretion from the companion star. The X-ray binary, especially the compact star of which is a black hole (BH), is studied by a lot of researchers, focusing on the accretion disk, including the accretion flow.

A model for the accretion disk constructed by Shakura and Sunyaev (1973) is assumed that the disk is geometrically thin and optically thick and the accreting material orbits the central compact object with the Keplerian motion. This model, which can well explain an energy spectrum in a certain state called a high/soft state (hereafter HSS), is called as the standard disk. On the other hand, it is known that there is another state, called a low/hard state (hereafter LHS), whose energy spectrum cannot be explained by the standard model. To explain the energy spectrum in the LHS, various models are constructed, such as a radiative inefficient accretion flow (RIAF) or an advection dominated accretion flow (ADAF), after an epoch-making work by Ichimaru (1977), and has developed. Some sources go back and forth between these different states. These states are controlled by amount of the mass accretion rate to the compact star. It is interpreted that, while the mass accretion rate is high, the star stays in the HSS, and, if it is low, it stays in the LHS (Esin et al., 1997). In addition, it is also known that, when the accretion rate is higher, the accretion disk becomes the other mode, called as a slim disk. These models can explain the observed X-ray energy spectrum to some extent. However, after refining the observation, it became apparent that the hard tail component appears during the HSS and the observed spectrum in the LHS needs multiple components in order to simulate the observed spectra (Makishima et al., 2008). The physical interpretation of them is still not clear.

The another important information obtained from the observation is a time variation. Especially, the typical BH binary, Cygnus X-1 (Cyg X-1), is drawn attention to its violent time-variation since its discovery in 1960's. It has an irregular and large-amplitude variation in the range of $0.1 \sim$ a few second (see figure 1.1). For testing the accretion model, since it is a key to whether such a time variation can be explained or not, a lot of researches have been conducted (Mineshige et al., 1994;

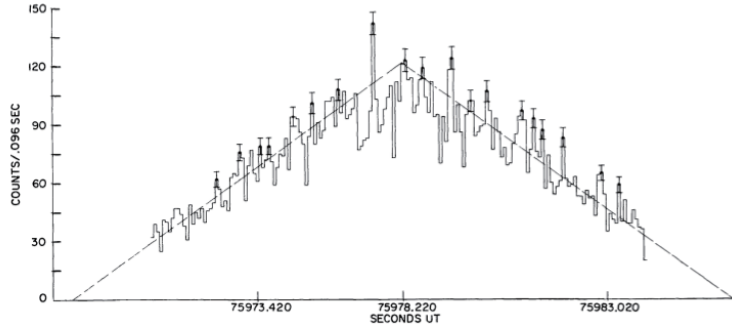


Figure 1.1: The X-ray light curve of Cyg X-1 by the Uhuru satellite (Oda et al., 1971).

Churazov et al., 2001), especially the short time scale less than 1000s. The cause of the time variation is associated with the characteristic of the accretion flow in the accretion disk, especially within $10r_S$ (r_S is the Schwarzschild radius) where majority of X-rays are emitted. As one of the examples, a model, that the light curve is constructed with superposition of the short random shot-noises by the accretion of the blob, is proposed (Miyamoto and Kitamoto, 1989; Negoro et al., 1994; Yamada et al., 2013b). However, in the HSS, the observation is poor and the origin of the time variation is not clear.

Furthermore, the long-term variation more than 1000s is not well understood. Because most of observations are made by X-ray telescopes mounted on the satellites orbiting a low Earth orbit, the observation cannot continue beyond ~ 1800 s. Therefore, to advance the study of the long-term variation more than 1000s, the difficult analysis, applying to unevenly distributing discrete data, is required. Usual observations, using the instrument having large effective area, are carried on less than few days, then the studying of the time variation more than several days is also extremely difficult. The observation by all-sky monitors has started since 1970's, but their statistics are not enough to analyze the time variation with a special information of most of X-ray binaries.

Such a time variation in the scale of a several ten days is important to understand the complete structure of the accretion disk. So far, some models of the structure of the accretion disk are proposed. For example, the accretion disk at the outer part is evaporated by an X-ray irradiation from the center region and a corona is formed on the disk (Liang and Price, 1977; Bisnovatyi-Kogan and Blinnikov, 1977; Hayakawa, 1981). To reveal the behavior of such a corona, we should study the long-term variation.

The accretion matter is provided from the companion star via a Roche lobe over flow or a capture of the stellar wind (Friend and Castor, 1982). In the case of Cyg X-1, because the companion star does not fill its Roche lobe (Gies et al., 2003), the accretion matter is supplied by the capture of the stellar wind from the companion star. The capturing process might be not steady and a particular flow-structure, a focused wind, would be formed (Gies and Bolton, 1986). The stellar wind of early type stars, like

a companion of Cyg X-1, does not smoothly flow, and a density fluctuation spontaneously grows up (Lucy and White, 1980). This inhomogeneity is also pointed out by observation of “ absorption dips ” of Cyg X-1, which is a sudden intensity drop around the superior conjunction of the BH (Kitamoto et al., 1984; Boroson and Vrtillek, 2010). Such an inhomogeneous wind and the particular structure at the capture process should affect the grand shape of the accretion disk and possibly also become a cause of the long-term variations.

In order to investigate the grand structure of the accretion disk, especially of Cyg X-1, we studied aperiodic long-term variation of the intensity and the energy spectrum as well as the spectral variation according to the binary orbital motion. We use the X-ray data obtained by MAXI, which provides us a statistically good X-ray intensity and a spectrum every 90min, and spans more than six years. In chapter 2, we review several models of the accretion disk and previous works relating this work. MAXI is briefly described in chapter 3. In chapter 4, the long-term data obtained by MAXI is explained. The analyses and results on the long-term variation are described in chapter 5. Those about the orbital modulation are in chapter 6. In chapter 7, we discuss the obtained results and propose the grand structure of the accretion disk of Cyg X-1 as well as the origin of the long-term variation. Finally, we summarize this thesis as a conclusion in chapter 8.

Chapter 2

Review

Contents

2.1	X-ray Binary Sources and Accretion	4
2.1.1	X-ray binaries	4
2.1.2	Accretion in binary systems	6
2.2	Eddington limit	8
2.3	Accretion Disk	8
2.3.1	Standard Accretion Disk	8
2.3.2	Time scales	11
2.3.3	RIAF and Slim disk	12
2.4	Stellar wind	16
2.5	Cygnus X-1	19
2.5.1	Bimodal behavior of Cyg X-1	19
2.5.2	Time variability	21
2.5.3	Orbital modulations and Absorption dips in Cyg X-1	24

2.1 X-ray Binary Sources and Accretion

2.1.1 X-ray binaries

Some of sources in a universe emit high energy radiation, X-ray (X-ray star). Most of them have binary systems composed of a compact star, such as a BH, a neutron star or a white dwarf, and an ordinary star. They are called as X-ray binaries (see figure 2.1). Two stars are gravitationally bounded and orbiting around each other. Sometimes their separation is comparable to the diameter of the companion star, constructing a “ close binary system ”. X-ray binaries are classified into two types in terms of masses of their companion stars. In the case that the companion star is later type



Figure 2.1: An image of the X-ray binary (ESA/Hubble illustration).

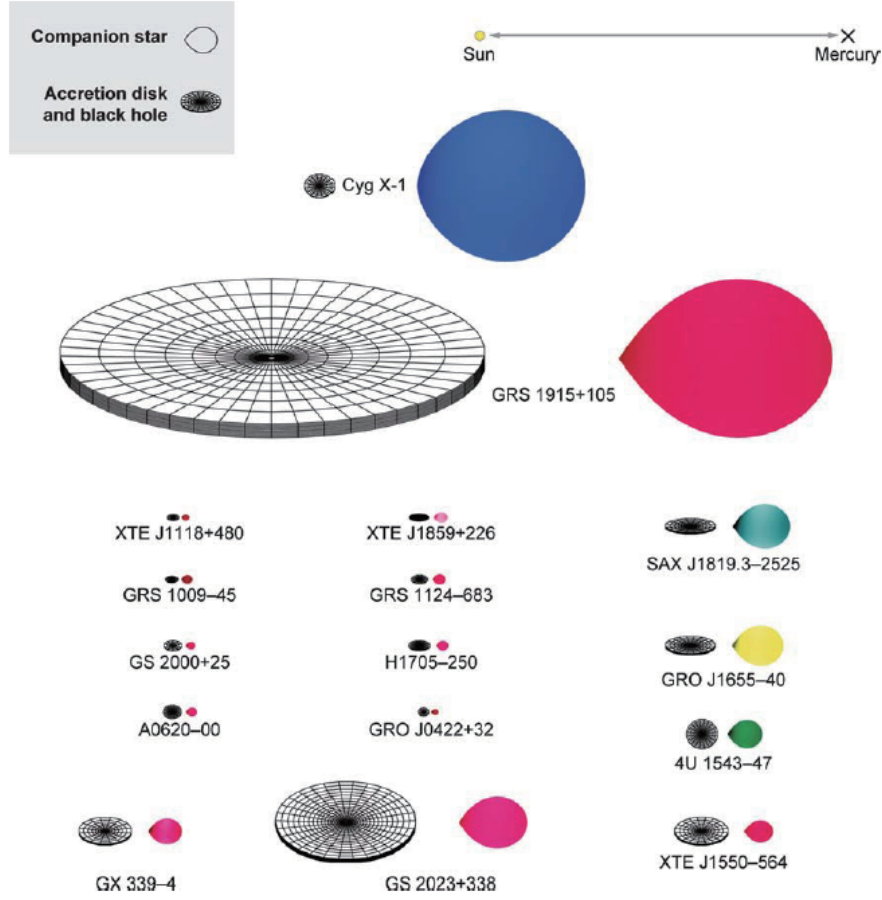


Figure 2.2: Schematic sketch of 16 Milky Way BH binaries with reasonably accurate dynamical data (Remillard and McClintock, 2006).

than A-type, the binary is called as a low-mass X-ray binary (LMXB). If the companion is an O- or B-type star and whose mass is more than ten times of solar mass, the binary is called as a high-mass X-ray binary (HMXB). The binary type is subdivided by the kind of their compact star. Figure 2.2 shows schematic sketches of various binaries with a BH (BH binaries) by Remillard and McClintock (2006). These pictures include rough informations of the binary size, the inclination angle and the surface temperature of the companion star.

2.1.2 Accretion in binary systems

When we consider equipotential surfaces in a rotating-frame with the binary motion, a particular surface, which includes a saddle point between the two stars, shows a shape of “ 8 ”, and is called a

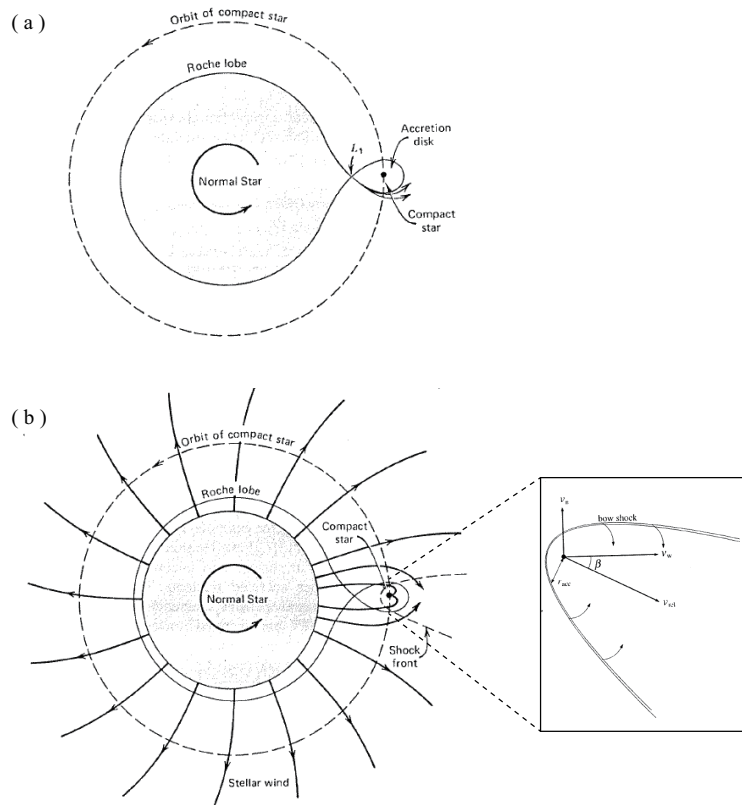


Figure 2.3: Two possible modes of mass transfer in a binary X-ray source (Shapiro and Teukolsky, 1986). The solid curves in the two pictures show the Roche lobe. (a) The accretion model of Roche lobe overflow. (b) The accretion model of wind fed.

Roche lobe. The saddle point is identified as the first Lagrangian point, L_1 , where the forces from the two stars are balanced. When the companion star fills the Roche lobe by its radius-expansion as its evolution, the stellar gas is pushed by a gas pressure and an outer atmosphere of the companion star flows into the compact star through L_1 point (Roche lobe overflow; figure 2.3(a)). Since the gas has an angular momentum, it rotates around the compact star and forms an accretion disk. A part of the gas loses an angular momentum by viscosity and falls inward, and, eventually accretes to the compact star, then the disk shines brightly. If the companion star does not fill the Roche lobe, such mass transportation does not occur. However, if the companion star is a high-mass star, which usually has a million times larger stellar wind compared with that of the sun (high mass X-ray binary; HMXB), a part of the strong stellar wind from the companion is captured by the compact star (wind fed). A wind velocity is expressed as $v_w \sim v_{\text{esc}} = \left(\frac{2GM_*}{R_*}\right)^{1/2}$, M_* and R_* are a mass and a radius of the companion star, and v_{esc} is an escape velocity at the surface. v_w is around a few thousand km s^{-1} . When the BH rotates around the companion star with orbital velocity v_{orb} , a relative velocity between the BH and the stellar wind is represented as $v_{\text{rel}} \cong (v_{\text{orb}}^2 + v_w^2)^{1/2}$. Then the radius, where the potential by the compact star is equal to the kinetic energy of the wind, can be defined as, $r_{\text{acc}} \sim \frac{2GM_n}{v_{\text{rel}}^2}$, which is called an accretion radius. If the wind enters in the accretion radius, it is captured by the companion star (see figure 2.3(b)). In this case, the accretion does not occur smoothly and a shock or a wake will be formed.

2.2 Eddington limit

When we consider an accretion onto the compact star, we have to take account of the pressure by the radiation from the compact star. Then we can find a maximum luminosity, an Eddington luminosity, L_E , which is determined by only the mass of the compact star. L_E can be derived by an equation of the balance between the radiation pressure, $\sigma_T L / (4\pi cr^2)$, and the gravity, $GM_{\text{BH}}m_p/r^2$, acting to a Hydrogen atom, and is given as

$$L_E = \frac{4\pi c G M_{\text{BH}} m_p}{\sigma_T} = 1.25 \times 10^{38} \left(\frac{M_{\text{BH}}}{M_\odot} \right) \quad [\text{erg s}^{-1}]. \quad (2.1)$$

Here, σ_T is Thomson cross section ($\sigma_T = 6.65 \times 10^{-25} \text{cm}^2$), and m_p is a mass of a proton. An Eddington mass accretion rate (critical mass accretion rate), $\dot{M}_E$, associated with L_E is defined as

$$\dot{M}_E = \frac{L_E}{c^2}. \quad (2.2)$$

2.3 Accretion Disk

2.3.1 Standard Accretion Disk

A standard accretion model was constructed by N. Shakura and R. Sunyaev in 1973. In this model, it is assumed that the accretion disk is geometrically thin ($H/r \ll 1$, H is a half thickness of the disk

and r is a radius) and optically thick ($\tau \gg 1$, τ is an optical thickness) and the gas accreted from the companion star rotates around the compact star with almost Keplerian rotation. A mass accretion rate $\dot{M}$ is constant anywhere on the accretion disk. $\dot{M}$ is expressed as

$$\dot{M} = 4\pi r H \rho v_r. \quad (2.3)$$

Here, ρ is a density and v_r is a radial velocity. Using a distance from the BH, r , and a mass of the BH, M_{BH} , a rotational velocity (Keplerian velocity) and an angular velocity of the gas are represented as

$$v_K = \sqrt{\frac{GM_{\text{BH}}}{r}}, \quad \Omega_K = \sqrt{\frac{GM_{\text{BH}}}{r^3}}. \quad (2.4)$$

Since the gas velocity is proportional to $r^{-1/2}$, a viscosity works and the angular momentum is transferred toward outer disk. The gas, which loses the angular momentum, moves inward. The viscosity converts a kinetic energy into a thermal energy and heats the gas in the disk, then the X-ray is radiated.

The standard accretion disk is steady. A mass inflow indicates that the angular momentum is transferred outward constantly in any radius. The inflow rate of the angular momentum, J , is expressed as

$$\dot{M}l + 2\pi r \cdot 2H \cdot r t_{r\varphi} = J = \text{const}. \quad (2.5)$$

Here, l is an angular momentum per unit mass and $t_{r\varphi}$ is a viscous tensor. $r t_{r\varphi}$ corresponds a torque by the viscous force. At the innermost radius, $r = r_{\text{in}}$, the torque is free, so

$$\dot{M}l_{\text{in}} = J. \quad (2.6)$$

Therefore

$$\dot{M}(l - l_{\text{in}}) = -2\pi r \cdot 2H \cdot r t_{r\varphi}. \quad (2.7)$$

Here, substituting $l = r^2 \Omega_K = \sqrt{r G M_{\text{BH}}}$ and $l_{\text{in}} = \sqrt{r_{\text{in}} G M_{\text{BH}}}$, equation (2.7) can be rewritten as

$$2t_{r\varphi}H = -\frac{1}{2\pi} \sqrt{\frac{GM_{\text{in}}}{r^3}} \dot{M} \left(1 - \sqrt{\frac{r_{\text{in}}}{r}}\right). \quad (2.8)$$

The heating rate by the viscosity is

$$Q_{\text{vis}} = \int_{-\infty}^{+\infty} \nu \rho \left(r \frac{d\Omega_K}{dr}\right)^2 dz \sim \nu \rho \left(r \frac{d\Omega_K}{dr}\right)^2 2H = -\frac{3}{2} t_{r\varphi} \Omega_K 2H. \quad (2.9)$$

Here, ν is a kinematic viscosity. Using ν , $t_{r\varphi}$ is expressed as

$$t_{r\varphi} = \rho \nu r \frac{d\Omega_K}{dr}. \quad (2.10)$$

Substituting equation (2.8), which is obtained from the angular momentum transport, into equation (2.9),

$$Q_{\text{vis}} = \frac{3GM_{\text{BH}}\dot{M}}{4\pi r^3} \left(1 - \sqrt{\frac{r_{\text{in}}}{r}}\right). \quad (2.11)$$

For the standard accretion disk, it is assumed that the radiation from the surface of the disk is blackbody. Taking account of the radiation from both sides of the accretion disk, the radiative cooling rate Q_{rad} is represented as

$$Q_{\text{rad}} = 2\sigma T_{\text{eff}}^4, \quad (2.12)$$

where T_{eff} is an effective temperature. In the disk, Q_{vis} is in balance with Q_{rad} ($Q_{\text{vis}} = Q_{\text{rad}}$). Therefore, from equation (2.11) and (2.12),

$$\frac{3GM_{\text{BH}}\dot{M}}{4\pi r^3} \left(1 - \sqrt{\frac{r_{\text{in}}}{r}}\right) = 2\sigma T_{\text{eff}}^4. \quad (2.13)$$

The temperature of the disk is obtained as

$$T_{\text{eff}} = \left\{ \frac{3GM_{\text{BH}}\dot{M}}{8\pi\sigma r^3} \left(1 - \sqrt{\frac{r_{\text{in}}}{r}}\right) \right\}^{\frac{1}{4}}. \quad (2.14)$$

A disk luminosity L_{d} is obtained by integrating the above emission as

$$L_{\text{d}} = 2 \int_{r_{\text{in}}}^{\infty} \sigma T_{\text{eff}}^4 2\pi r dr = \frac{GM_{\text{BH}}\dot{M}}{2r_{\text{in}}}. \quad (2.15)$$

If r_{in} is three times of the Schwarzschild radius, $r_{\text{in}} = 3r_{\text{S}} = \frac{6GM_{\text{BH}}}{c^2}$, which is the radius of the inner most stable circular orbit (ISCO) of the Schwarzschild BH, L_{d} can be calculated as

$$L_{\text{d}} = \frac{1}{12} \dot{M} c^2. \quad (2.16)$$

Therefore, in the case of the Newtonian approximation, a conversion efficiency of the mass to the radiation energy is $\frac{1}{12}$. We can understand that the accretion disk is a very efficient energy conversion engine. When we consider the relativistic effect, the efficiency is 0.057 for a non-rotating BH (Schwarzschild BH). For maximally rotating hole (an extreme Kerr BH), it is 0.42 (Shapiro and Teukolsky, 1986).

The micro mechanism of the kinematic viscosity, ν , is not well understood and its numerical expression is not clear. Then Shakura and Sunyaev (1973) assumed that the viscous tensor, $t_{r\varphi}$, is proportional to the gas pressure, expressed as

$$t_{r\varphi} = -\alpha P, \quad (2.17)$$

here α is a viscous parameter. The standard disk model representing with α is also called as α disk model. From equation (2.10) and (2.17),

$$\nu = \frac{2}{3} \frac{\alpha P}{\rho \Omega_{\text{K}}}. \quad (2.18)$$

The disk is in the equatorial hydrostatic equilibrium. From the balance between the gravitational force and the gas pressure (figure 2.4),

$$G \frac{M_{\text{BH}} \rho}{r^2} \frac{H}{r} = \frac{dP}{dz} \sim \frac{P}{H}. \quad (2.19)$$

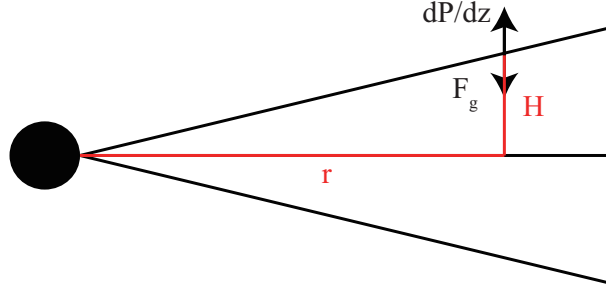


Figure 2.4: The sketch of the hydrostatic equilibrium in the disk. The arrows show the balance between the gas pressure and the gravitational force on the disk surface at radius r .

Therefore

$$\frac{P}{\rho} \sim G \frac{H^2 M_{\text{BH}}}{r^3} = \Omega_K^2 H^2. \quad (2.20)$$

Substituting this into equation (2.18), we obtain $\nu = \frac{2}{3} \alpha \Omega_K H^2$.

With the sound speed defined as c_s , the gas pressure, P , is also written as

$$\begin{aligned} P &= \frac{\rho}{m_p} kT \\ &\sim \frac{\rho}{m_p} \frac{1}{2} m_p c_s^2 \\ &= \frac{1}{2} \rho c_s^2. \end{aligned} \quad (2.21)$$

Then we obtain $\frac{P}{\rho} \sim c_s^2$. Using equation (2.20), c_s can be represented as

$$c_s \sim \Omega_K H. \quad (2.22)$$

Equation (2.18) can be rewritten as

$$\nu \sim \alpha c_s H. \quad (2.23)$$

2.3.2 Time scales

A dynamical time scale, t_d , is defined as

$$t_d = \frac{r}{v} \sim \frac{r}{v_\varphi} = \Omega_K^{-1}, \quad (2.24)$$

where v_φ is a rotational velocity around the compact star. A thermal time scale, t_{th} , can be estimated as

t_{th} = (heat content per unit disk area)/(energy dissipation rate per unit disk area). The heat content between radius r and $r + dr$ of the disk is given by

$$\frac{1}{2}\rho c_s^2 \cdot 2H \cdot 2\pi r dr = 2\rho c_s^2 H \pi r dr \sim 2PH\pi r dr. \quad (2.25)$$

Here, we use $\rho c_s^2 \sim P$. The net energy dissipation by viscous force is given by

$$t_{r\varphi} \cdot \frac{d}{dr}(r\Omega_K)dr \cdot 2H2\pi r = -t_{r\varphi} \cdot \Omega_K dr 2H\pi r = \alpha P \Omega_K dr 2H\pi r, \quad (2.26)$$

where, $t_{r\varphi}$ is a viscous tensor, and we use equation 2.17. With equation (2.25) and (2.26), t_{th} can be represented as

$$t_{\text{th}} = \frac{2PH\pi r dr}{\alpha P \Omega_K dr 2H\pi r} = \frac{1}{\alpha \Omega_K}. \quad (2.27)$$

On the other hand, the viscous time scale, t_{vis} , is given by

$$t_{\text{vis}} = \frac{\text{angular momentum}}{\text{torque}}. \quad (2.28)$$

The angular momentum, $L(r)$, between radius r and $r + dr$ of the disk is

$$L(r) = \rho \cdot 2\pi r 2H dr \cdot r^2 \Omega_K, \quad (2.29)$$

and the net torque by viscosity, $G(r)$, is obtained as

$$G(r) = t_{r\varphi} 2\pi r 2H dr = -\alpha P 2\pi r 2H dr = -\alpha \rho \Omega_K^2 H^2 2\pi r 2H dr. \quad (2.30)$$

The viscous time scale is, thus, obtained as

$$t_{\text{vis}} = \frac{L(r)}{G(r)} = \frac{\rho(2\pi r H dr) r^2 \Omega_K}{\alpha \rho \Omega_K^2 H^2 2\pi r 2H dr} = \frac{1}{\alpha \Omega_K} \left(\frac{H}{r}\right)^{-2}. \quad (2.31)$$

Since α is less than 1, we can compare the time scales and confirm the relation, $t_{\text{vis}} \gg t_{\text{th}} > t_{\text{d}}$. The radial velocity of the gas is represented by r/t_{vis} . Therefore we can also confirm the assumption that the gas rotates with Keplerian rotation. Figure 2.5 presents an example of the disk structure which is solved by taking into consideration of the effect of the gas pressure and the radiation pressure. It is shown that the disk scale height, H , is roughly $10^{-2}r$.

2.3.3 RIAF and Slim disk

For the standard accretion disk model, it is assumed that the gas rotates around the BH with Keplerian velocity and the disk is geometrically thin. Caused by the angular momentum transport by the viscosity, the gas in the disk gradually accretes toward the compact star, and becomes high temperature, and then, radiates blackbody from the surface of the optically thick disk. The dynamical, thermal and viscous time scales, are represented as follows,

$$\begin{aligned} t_{\text{d}} &= \Omega_K^{-1}, \\ t_{\text{th}} &\sim (\alpha \Omega_K)^{-1}, \\ t_{\text{vis}} &\sim (\alpha \Omega_K)^{-1} (H/r)^{-2}. \end{aligned} \quad (2.32)$$

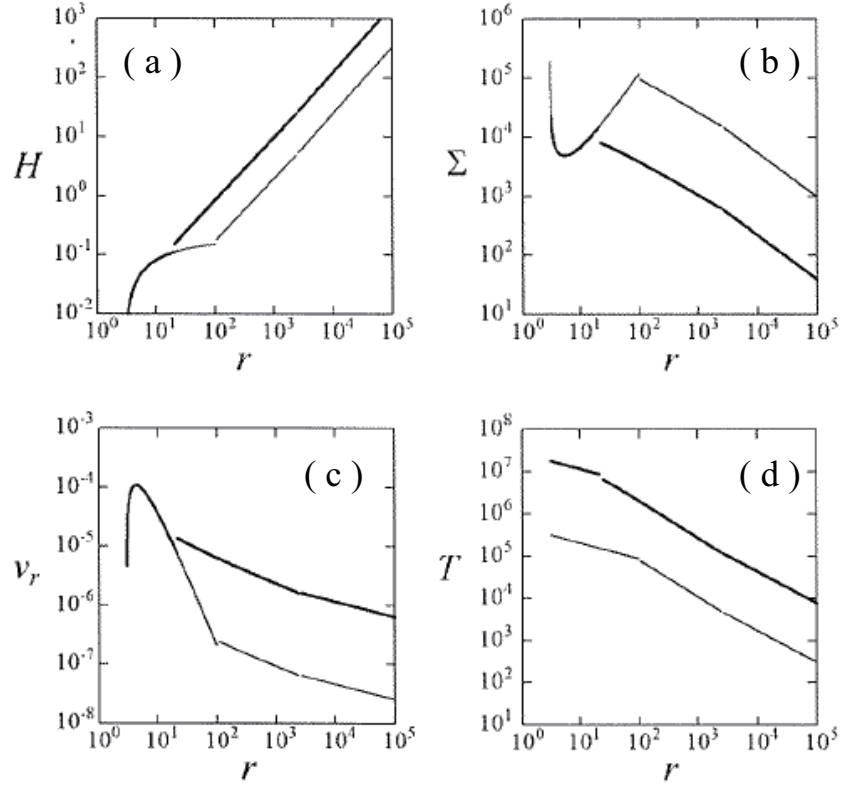


Figure 2.5: Typical solutions of the standard accretion disk calculated by Kato et al. (2008). The horizontal axis is the radius in an unit of the Schwarzschild radius. The vertical axes are (a) the disk half-thickness in an unit of the Schwarzschild radius, (b) the surface density in an unit of g cm^{-2} , (c) the radial velocity in an unit of a light velocity and (d) the disk temperature in an unit of K. The thick solid lines are calculated with $M_{\text{BH}} = 10 M_\odot$, $\dot{M} = 1 M_E$ and $\alpha = 1$. The thin solid lines are with $M_{\text{BH}} = 10^8 M_\odot$, $\dot{M} = 1 M_E$ and $\alpha = 1$.

Since we consider the situation $H \ll r$, then $t_{\text{vis}} \gg t_{\text{d}}$. However, the assumption that the disk is optically thick does not apply when the mass accretion rate is small. Then the disk cannot radiate efficiently and gets extremely high temperature. In this case, the disk is expected to swell by a large amount in the vertical direction. Then the assumptions of $t_{\text{vis}} \gg t_{\text{d}}$ and the Keplerian motion are not applicable (Ichimaru, 1977). Narayan and Yi (1994) proposed the model, Advection Dominated Accretion Flow (ADAF), which is a solution of the accretion flow when the mass accretion rate is small. After that, the model was improved and called Radiation Inefficient Accretion Flow (RIAF).

In the RIAF model, the disk is geometrically thick ($H/r \sim 1$) and the optically thin. The radial velocity of the gas v_r is a little less than the Keplerian velocity, v_K . Since a radiation cooling, Q_{rad} , does not work well, then a viscous heating, Q_{vis} , is sucked into the BH. Although this phenomena is not the real cooling process, the heating is transferred inward by the gas moving, so that it is called as an advective cooling, Q_{adv} . Therefore

$$Q_{\text{vis}} = Q_{\text{rad}} + Q_{\text{adv}}. \quad (2.33)$$

Here, we consider the basic equations, the equation of continuity, the angular momentum transfer and the hydrostatic equilibrium in the vertical structure of the disk, which are basically same to those of the standard model. Under the assumption that $Q_{\text{rad}} = (1 - f)Q_{\text{vis}}$ and $Q_{\text{adv}} = fQ_{\text{vis}}$, f is a fraction of the advective cooling, we can also write down the energy equation. In the equation of motion, we have to include the advection term and the gas pressure gradient. The solution for these equations can be solved with the assumption of the following relations;

$$v_r(r) = -c_1 \alpha v_K(r), \quad (2.34)$$

$$v_\phi(r) = c_2 v_K(r), \quad (2.35)$$

$$c_s^2(r) = c_3 v_K(r)^2. \quad (2.36)$$

where c_1 , c_2 and c_3 are constant values. Figure 2.6 shows an example solved as the function of f . We can confirm that the radial velocity is a few percent of the Keplerian velocity and the equation, $H = c_s \Omega_K^{-1}$, leads $H = \sqrt{c_3} r \propto r$, therefore $H/r \sim 1$, for $f \sim 1$ and $\alpha \sim 0.1$.

In the RIAF model, the mass accretion rate, $\dot{M}$, is small and the density of the accretion disk is small. If the temperature of the accretion disk becomes high, its density becomes more smaller, and eventually the gas will ionize and the photoelectric effect will not work. Then the disk becomes optically thin. And, the radiation efficiency becomes further smaller, the disk becomes thicker, the density becomes lower and the temperature becomes higher. Therefore

$$\frac{H}{r} = \frac{c_s}{\Omega_K r} \sim \sqrt{\frac{kTr}{GM_{\text{BH}}m_p}} \sim \sqrt{\frac{T}{T_{\text{vir}}}} \sim 1. \quad (2.37)$$

Here equation (2.21) and (2.22) were used. T_{vir} is a virial temperature, expressed as $T_{\text{vir}} = \frac{3}{2} \frac{GM_{\text{BH}}m_p}{k_B r}$. When the temperature increases to around T_{vir} , the accretion disk will be $H/r \sim 1$. From equation

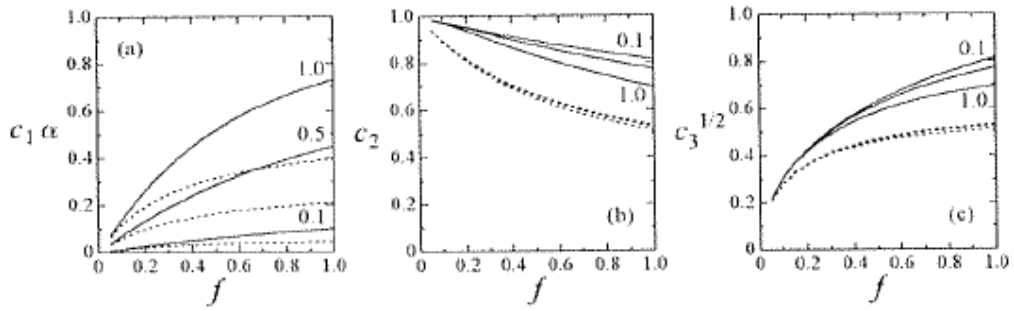


Figure 2.6: Parameter f dependence of coefficients c_i (Fukue, 2007). These are calculated in the case of $\alpha = 0.1, 0.5, 1$. The dashed lines are obtained by an assumption of a constant $\dot{M}$, and the solid lines are by a non-constant $\dot{M}$.

(2.37), $H \propto \sqrt{T}$. Since the velocity of the gas is not more than the sound speed, we can assume that the pressure equilibrium is achieved, and hence the pressure at the same radius is constant even if the disk becomes thick. Furthermore the pressure at a given radius and a given height can be assumed to be the same order in both the disks. As shown in equation (2.17), the viscous friction is assumed to be proportional to the pressure. Then, even if the temperature arises, the force per unit area in the direction of shear, the torque, will not change. However, the thickness of the disk, H , at the radius, r , becomes thick, so that the area of the entire section of the disk at r ($= 2\pi r \times 2H$) increases. Therefore the total force at the cross-sectional area becomes large, and the falling time, t_{vis} , becomes small. As a result, the falling velocity, v_r , becomes very faster than that in the standard disk.

When the mass accretion rate is very high, the disk becomes high temperature because of a big amount of materials and expands in the vertical direction. However, the disk is optically thick. This model is called as a slim disk (Abramowicz et al., 1988). In this model the relation $t_{\text{vis}} \gg t_{\text{d}}$ is also not satisfied, which means that the gas does not rotate with Keplerian motion and the radial accretion velocity becomes very fast.

Figure 2.7 was drawn by Esin et al. (1997), which indicates the change of the accretion disk (the standard disks shown by black thick lines and the ADAF represented by dots) with the change of the mass accretion rate $\dot{M}$.

In the standard disk, with the virial theorem, the half of the potential energy which is released by the gas-accretion changes into the kinetic energy for the Keplerian rotation, and the other half is radiated away. The standard disk having high density emits as a blackbody and is effectively cooled by radiation. The gas accretes stably. Figure 2.8 is a thermal equilibrium curve by Narayan and Yi (1995). The branch A shows the solution of the standard disk. Using figure 2.8, let us consider a possible structure of the accretion disk, by focusing the case of $\log(\dot{M}) = -6$, as an example. At the outer disk, the temperature is low, then the standard disk can be formed on the branch A. However, at the inner part, the temperature increases and the disk swells. The density of the disk decreases and the temperature increases. In this case, since the friction in the disk is large and the accretion velocity is fast, we should consider an effect of an advection, which is ignored in the standard model. The disk makes transition into the RIAF taking into account the advection term. Although the mass accretion rate, $\dot{M} = 2\pi r v_r \Sigma$, does not change, the surface density Σ becomes small if the radial velocity v_r becomes fast. Therefore the disk on the branch A transitions to that on the branch C (figure. 2.8, the arrow).

2.4 Stellar wind

As explained in section 2.1.2, in the HMXB the accretion mass is mainly supplied by the stellar wind from the companion star. A strong stellar wind is captured by the BH and probably forms a characteristic structure around the BH like a focused wind (Friend and Castor, 1982). The wind exposed to luminous X-rays should be ionized and also considered to be clumpy (Bahucińska-Church

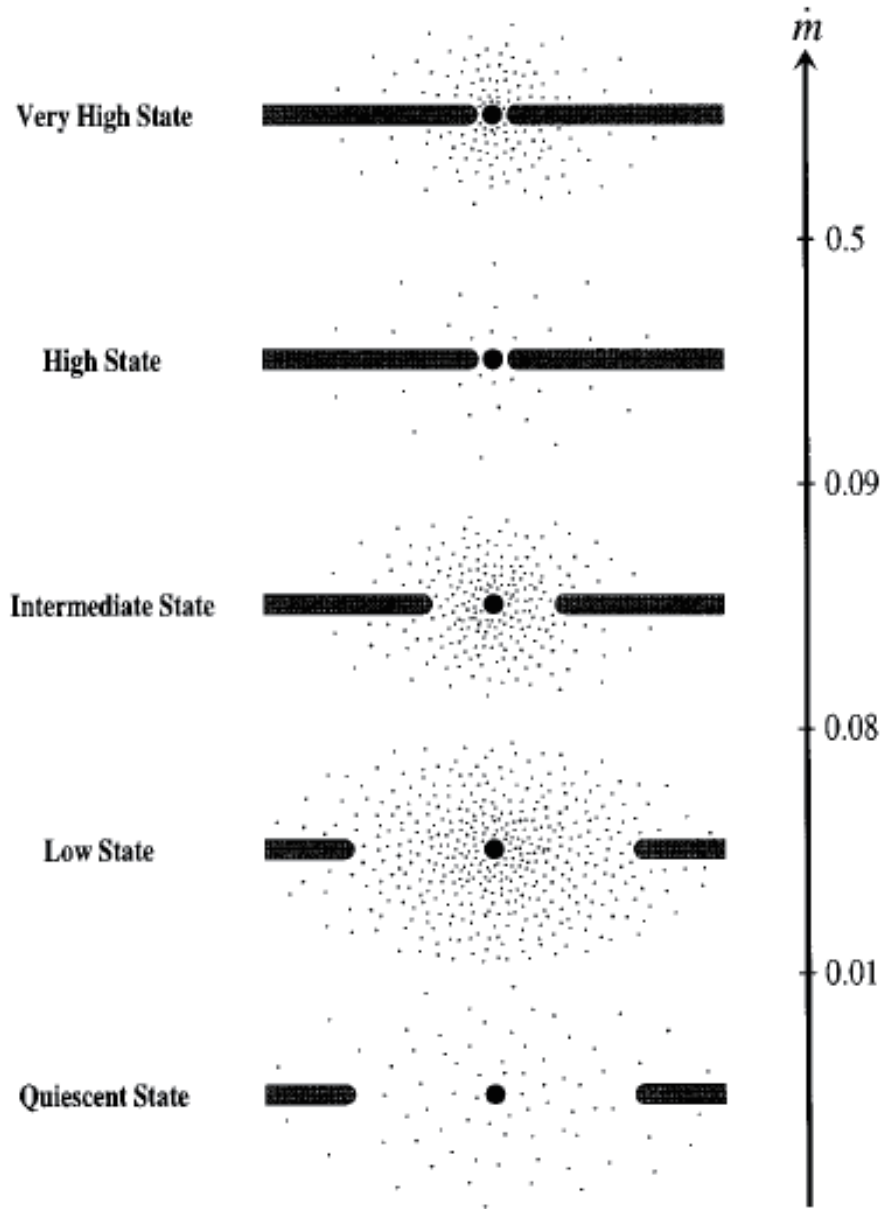


Figure 2.7: Configuration of the accretion flow in different spectral states shown by Esin et al. (1997). Black thick lines show the optically thick accretion disks. Dots describe ADAF.

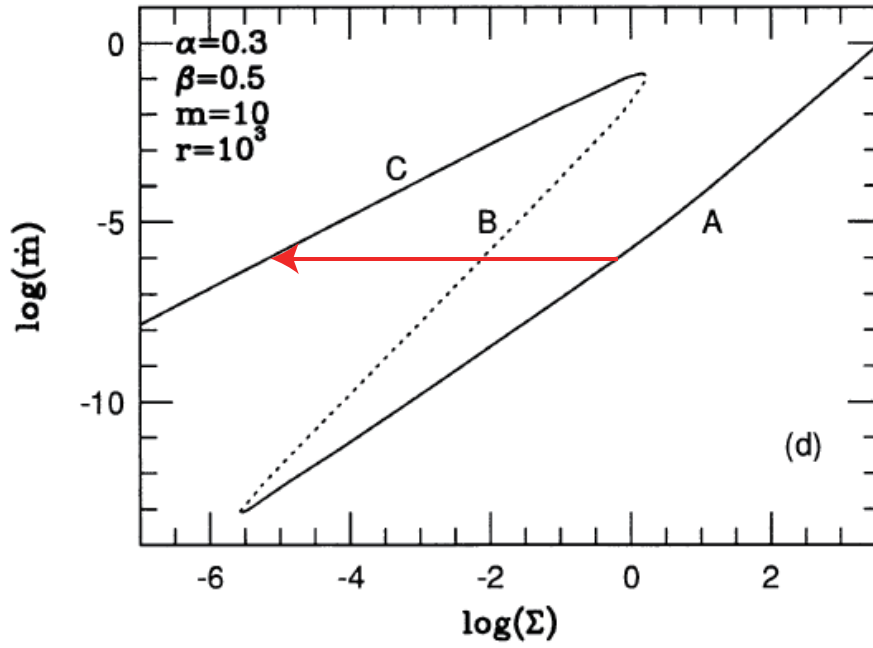


Figure 2.8: The three solution branches for an accreting $10M_{\odot}$ BH at a radius of $r = 10^3$. The vertical and horizontal axes show an mass accretion rate $\dot{M}$ and a surface density Σ . The branch A, B and C correspond to a standard disk, unstable and advection dominated solutions, respectively. The red arrow represents the transition from the standard disk to the RIAF.

et al., 2000; Feng and Cui, 2002), then the structure should be very complex. It is also indicated that the stellar wind from the O-star is not steady and is inhomogeneous, including the cold dense clump (Sako et al., 1999, 2002).

The wind velocity profile is characterized by Castor et al. (1975) as

$$v(r) = v_{\infty} \left(1 - \frac{R_*}{r}\right)^{\beta}. \quad (2.38)$$

Here, r is a distance from the companion star, v_{∞} is a terminal velocity of the wind, R_* is a radius of the companion star and β is a number that typically lies in the range $0.5 - 1.0$ (Sako et al., 2002). If we assume a spherically symmetric wind, the wind density at radius, r , is expressed as

$$n(r) = \frac{\dot{M}}{4\pi m_H v_{\infty}} \frac{1}{r^2} \left(1 - \frac{R_*}{r}\right)^{-\beta} \quad (2.39)$$

If a star is not isolated and fills Roche lobe as Cygnus X-1, the stellar wind from the companion star becomes non-spherically symmetric, and then the dense gas stream toward the BH is formed (focused wind; Friend and Castor (1982); Hanke et al. (2009)). Figure 2.9 shows a simulation of density distribution in the orbital plane of Cygnus X-1 calculated by Čechura and Hadrava (2015). In the HSS, since the luminosity is set to two times of that in the LHS and the ionization parameter, ξ , becomes larger, the fully-ionized region almost reaches the surface of the companion star and the wind is prevented from achieving the escape velocity. The wind falls back and the outflow from the direction of L_1 point is interrupted. Then, the dense gas stream is disrupted (figure 2.9, right panel). Caused by the focused wind or the clump in the stellar wind, “dip” event in the X-ray light curve, that the intensity of the soft X-ray decreases around the superior conjunction of the BH, occurs (The details are described in section 2.5.3).

2.5 Cygnus X-1

The BH binary Cygnus X-1 (hereafter Cyg X-1) is persistently bright in the X-ray band. Cyg X-1 was found in 1960’s. In 1970’s it was observed in detail by the Uhuru satellite, and M. Oda and others discovered a very short-term variability less than 1 sec (Oda et al., 1971). Then, they identified it as the world’s first candidate of a BH binary. The mass of the BH is estimated as $14.8 \pm 0.1 M_{\odot}$, and the companion, HDE 226868, is a O9Iab supergiant star, the mass of which is $19.2 \pm 1.9 M_{\odot}$ (Orosz et al., 2011). The distance is obtained as $1.86^{+0.12}_{-0.11}$ kpc (Reid et al., 2011). An orbital period of the binary is obtained as 5.6 days with optical observation (Mason et al. (1974); Bolton (1975); Brocksopp et al. (1999b); figure 2.10), and the inclination angle is 27° (Orosz et al., 2011).

2.5.1 Bimodal behavior of Cyg X-1

Cyg X-1 shows two spectral states (Oda, 1977), a LHS and a HSS. In the LHS, the mass accretion rate is low and the X-ray luminosity is less than a few percent of L_E . A energy spectrum is dominated

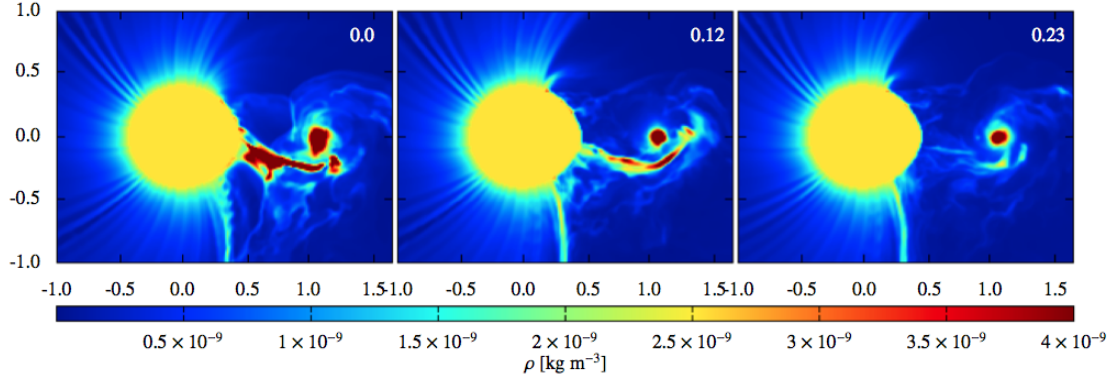


Figure 2.9: Evolution of density distribution in the orbital plane of Cygnus X-1 (Čechura and Hadrava, 2015). The left panel shows a start condition of the simulation adjusting the X-ray luminosity of the compact object to the level corresponding to the LHS. The center and right panels represent the transient state and the HSS. The numbers written in the upper right corner correspond to the time from the start of the simulation in unit of orbital period.

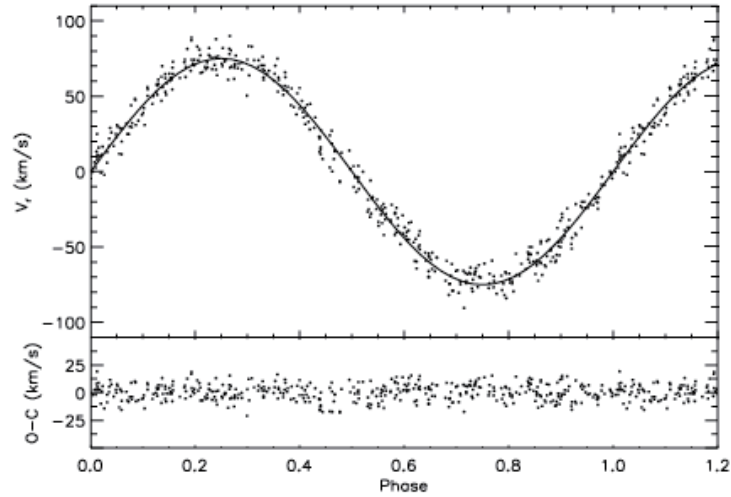


Figure 2.10: The radial velocity curve obtained by the optical observation (Brocksopp et al., 1999b). The solid line shows the theoretical curve and the bottom shows the residuals.

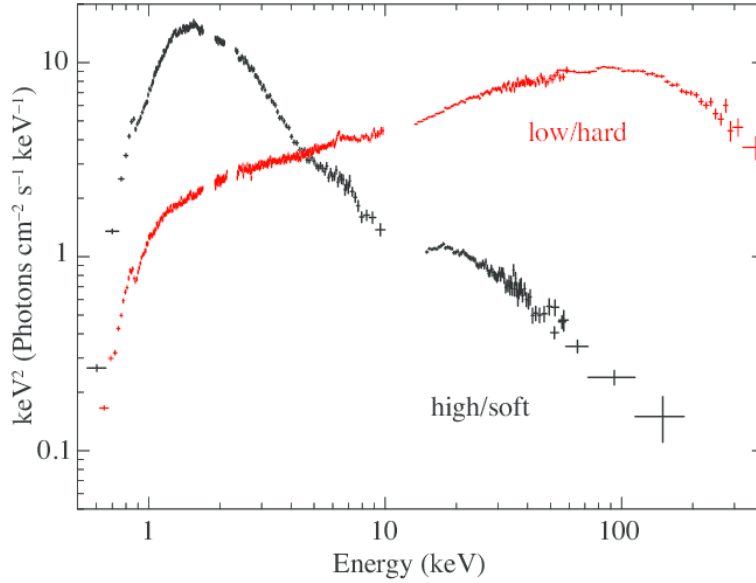


Figure 2.11: Typical energy spectra of Cyg X-1 obtained with Suzaku by Yamada et al. (2013a). The red and black data show the spectrum in the LHS and HSS, respectively.

by a power law spectrum, $\propto E^{-\alpha}$, in the energy range between ~ 1 keV and ~ 100 keV. A break is seen around one hundred keV, as shown in Figure 2.11. This LHS is possibly corresponding to the RIAF (Ichimaru, 1977). If the mass accretion rate and the luminosity increase, Cyg X-1 shows a transition to the HSS, which is dominated by an optically-thick thermal emission from an accretion disk, i.e. the standard disk (Shakura and Sunyaev, 1973; Tanaka and Shibazaki, 1996; Remillard and McClintock, 2006; Done et al., 2007). The HSS has a hard tail component starting close to the peak of the standard disk component to a few MeV.

Cyg X-1 repeats transitions between the two states in several days to several hundred days. Figure 2.12 is a light curve with the RXTE/ASM and the MAXI/GSC in low energy band. Until 2009, it was mainly in the LHS with short terms in the HSS, however, after starting MAXI observation at MJD55058, it almost stays in the HSS.

2.5.2 Time variability

A time variation of the X-ray intensity is an important aspect of BH X-ray binaries. Especially Cyg X-1 has provided rich information through the short-term variability in both states (e.g. Churazov et al. (2001); Grinberg et al. (2014)). The power spectrum density (PSD) in the LHS (figure 2.13, black and green) has a power law shape with an index of about -1 in the frequency range from 10^{-4} to 10^{-2} Hz. Between 10^{-2} Hz and 10^{-1} Hz, the PSD is constant as a white noise. Above 10^{-1} Hz, the

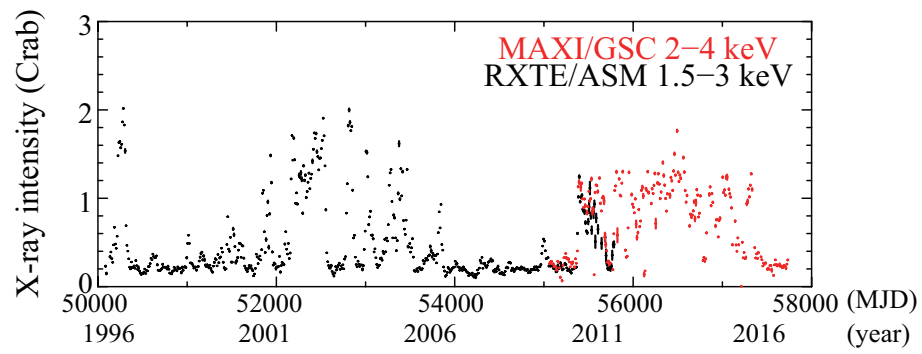


Figure 2.12: The X-ray light curve with RXTE/ASM in 1.5–3 keV (black dots) and with MAXI/GSC in 2–4 keV (red dots).

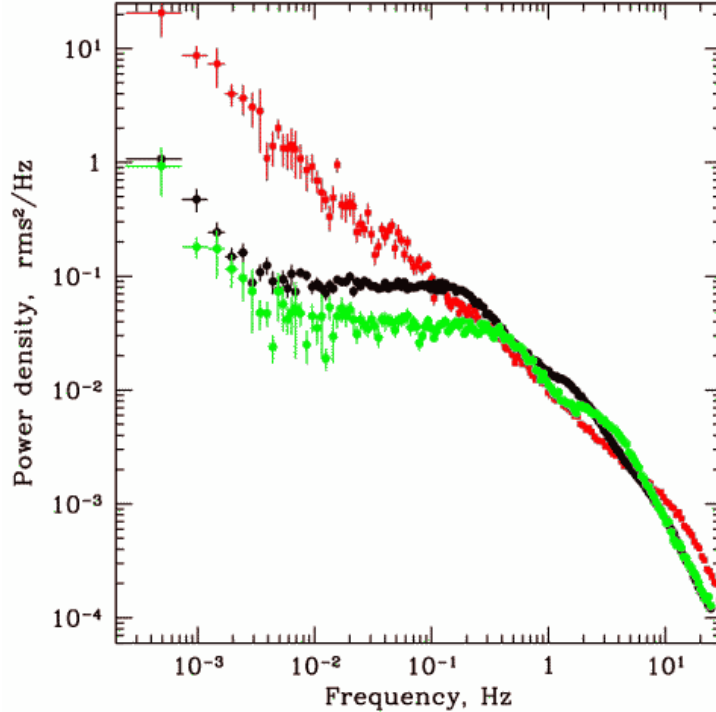


Figure 2.13: The power spectrum densities in the range of $10^{-3} - 10$ Hz by Churazov et al. (2001). The black and green are the PSDs in the LHS, the red is in the HSS.

index returns to about -1 . There is a break again at around 1 Hz, above which the index becomes steeper (e.g., Belloni and Hasinger (1990); Nowak (2000); Negoro et al. (2001); Pottschmidt et al. (2003)). These time scales are thought to reflect the dynamics of accretion flows, and the process of an energy dissipation or a particle acceleration in a vicinity of the BH. The break at 1 Hz in the LHS can be interpreted as a decay time scale of individual shots, which appears in the light curve (Negoro et al., 1994). In the HSS, the PSD (figure 2.13, red) is approximated by a power law also with an index of -1 , but this form continues without flattening, from 10^{-4} Hz up to 20 Hz, beyond which it steepens. The PSD extending with a constant index -1 suggests that the accretion flows in the HSS have no characteristic time scales over the $10^{-4} - 20$ Hz range. Churazov et al. (2001) explained the overall shape of the PSD in the LHS and the HSS of Cyg X-1 with a phenomenological model that the optically-thick disk is sandwiched by optically-thin accretion flows extending up to a large distance from the BH. In the LHS the optically-thick disk is truncated at some distances from the BH, turning into optically-thin and geometrically thick accretion flows (Makishima et al., 2008).

On frequencies lower than 10^{-4} Hz (time scales of 0.1 d), the variability of Cyg X-1 has been studied mainly by the data obtained with RXTE observations. Reig et al. (2002) calculated PSDs

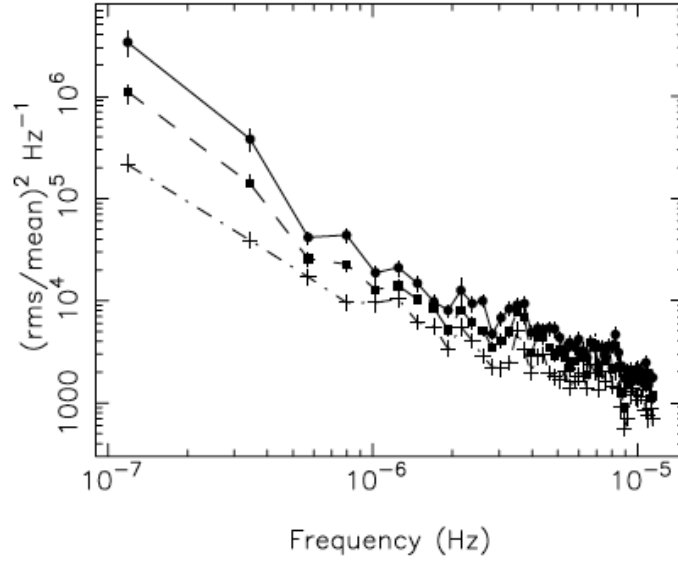


Figure 2.14: The power spectrum density in the range of $10^{-7} - 10^{-5}$ Hz by Reig et al. (2002). Circles, squares and crosses are calculated with 1.3–3, 3–5 and 5–12.2 keV band.

of Cyg X-1 using more than eleven years data obtained by the RXTE/ASM (figure 2.14). They do not distinguish the spectral state of Cyg X-1 and analyzed data combined in both the states. They showed that PSDs in the range of $10^{-7} - 10^{-5}$ Hz can be expressed by a power law with an index of -1 , and that the values of the PSDs depend on the energy (over 1.3 – 12.2 keV) by a factor of $3 \sim 5$. The long-term variability of hard X-rays from Cyg X-1 was studied by Vikhlinin et al. (1994), down to 4×10^{-4} Hz, using the GRANAT/SIGMA data. They detected a very low frequency QPO (Quasi-Periodic Oscillation) around 0.04–0.07 Hz. However, on frequencies of $\lesssim 10^{-4}$ Hz, our understanding of variability seen in Cyg X-1 has remained much poorer, especially in the HSS, than the rich information accumulated on the short-term variability.

2.5.3 Orbital modulations and Absorption dips in Cyg X-1

Cyg X-1 orbits around the companion star every 5.6d. Although the eclipse is not seen in the X-ray light curve, an orbital modulation in the X-ray intensity has been observed in its LHS (Priedhorsky et al., 1995; Wen et al., 1999; Brocksopp et al., 1999a; Kitamoto et al., 2000), especially in the low energy band (see folded light curves in the LHS by the RXTE/ASM, shown in figure 2.15, left). However, the intensity modulation has not been detected in the HSS (Wen et al., 1999; Brocksopp et al., 1999a). Boroson and Vrtilek (2010) reported that a peak of 5.61 d in the periodogram of the hardness ratio was detected during a part of the HSS period, using the RXTE/ASM data, but it was

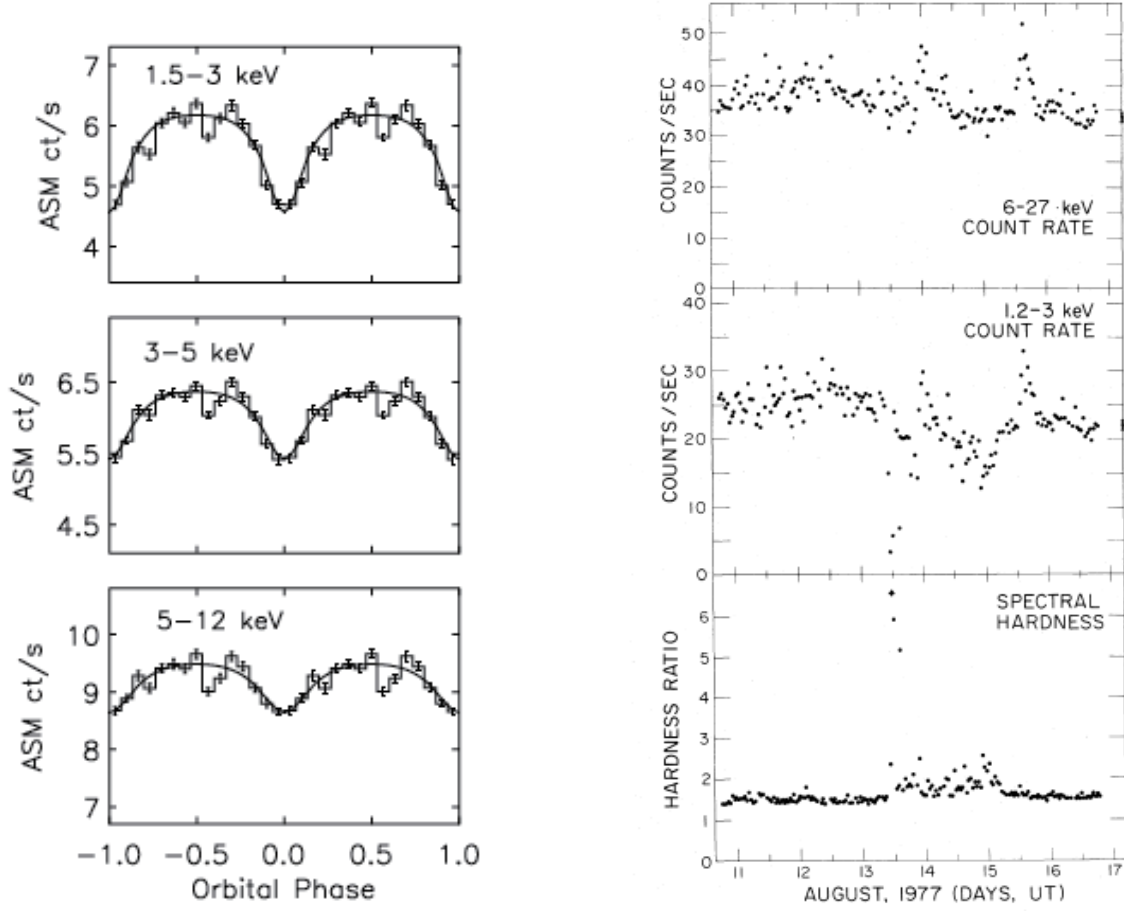


Figure 2.15: The left shows the light curves of Cyg X-1 in the LHS by RXTE/ASM folded by 5.6 d (Wen et al., 1999). The right shows the unfolded light curves and the hardness ratio in the LHS by SAS 3 including the dip period (Remillard and Canizares, 1984).

weaker than that in the LHS. The absorption dip in the low energy band was detected in the LHS, which is an abrupt intensity drop in the soft X-ray band around the superior conjunction of the BH (Li and Clark (1974); Kitamoto et al. (1984); Miller et al. (2005); Hanke (2011), see figure 2.15, right). Various depth and the duration of dips have been observed (Kitamoto et al., 1984; Bałucińska-Church et al., 2000). The duration of the dip is distributed from several seconds to more than 10 min. The probability of the dip is high around the superior conjunction of the BH at phase $0.9 \sim 0.1$. The cause of the dips is interpreted by an absorption by the clumpy and inhomogeneous stellar wind (Kitamoto et al., 1984; Boroson and Vrtilak, 2010). From the time structure of the dip, the diameter of the clumps is estimated to be $\sim 10^9$ cm (Kitamoto et al., 1984). In the spectrum among the dip period, Fe-K absorption edge was observed, implying an ionization state $< \text{FeV}$. The hydrogen column densities

depend on the orbital phase and they become maximum around phase 0 (Grinberg et al., 2015). On the other hand, in the HSS, weaker dips than the LHS is reported (Yamada et al., 2013c; Grinberg et al., 2015). Yamada et al. (2013a) detected Fe absorption edge at 7.5 keV and He-like and H-like Fe- K_α absorption line in the energy spectrum around the dip. However, Cyg X-1 was mainly in the LHS before 2011, the observation in the HSS was poorer than that in the LHS.

Chapter 3

MAXI

Contents

3.1	About MAXI	27
3.2	Instruments	28
3.2.1	Gas Slit Camera	28
3.2.2	Solid-state Slit Camera	30

3.1 About MAXI

Monitor of All-sky X-ray Image (= MAXI) is a Japanese all-sky X-ray monitor which is attached to the Japanese Experimental Module (JEM) Kibo of the International Space Station (ISS). The operation started on 3rd, August, 2009 (JST). As the ISS orbits the earth in every 92 min, MAXI scans over nearly the entire sky.

Most of X-ray sources show variations of their intensity, and sometimes a new X-ray source appears or a known X-ray source disappears, unlike the optical stars. The radiation mechanism and the origin of the variation of such X-ray sources are still mysterious. To figure out these mysteries, we should observe various faces of the sources from the appearance or the starting to be bright to the former state. However, most of X-ray telescopes with high sensitivity, such as Suzaku, have a narrow field of view, and it can only see one ten-thousandth of the whole-sky. Therefore, the detection of an appearance of a new X-ray source or an observation of a change of their state is difficult. The main purpose of MAXI is monitoring the variable sky with X-ray, the discovery of X-ray novae and the detection of the change of the known sources. The breakthrough is that MAXI can inform the world-wide researchers and observatories of new finding within very short time on the Internet and stimulate their follow-up observation with various wave-length including X-ray, optical, infrared and radio.

Another important roll for MAXI is a long-term continuous observation. By accumulating long-term histories of X-ray sources, we can reveal the various characteristics of them. MAXI has the highest detection sensitivity among the previous all-sky monitors. The all-sky catalog was created by

HEAO-1 in 1980's with a high sensitivity, but it is just a mosaic of short-term snap-shots collected during half year. MAXI can provide us about 90% sky data, almost every day, which contains more than five hundreds sources (Hiroi et al., 2013).

Now, MAXI is collaborating with Swift and Suzaku. In the future, MAXI will collaborate with the next-generation instruments, such as CALET/GBM and NICER. Furthermore, the collaboration with the gravitational-wave observatories in the world is planned. The identification of a gravitational-wave source is hopefully expected.

3.2 Instruments

3.2.1 Gas Slit Camera

MAXI has two kinds of X-ray cameras. One is a Gas Slit Camera (GSC: Mihara et al. (2011), figure 3.1, top), which is a one-dimensional position-sensitive proportional counter using carbon fibers. The GSC has the highest sensitivity among the X-ray all-sky monitors operated before. It covers more than 90% of the all-sky everyday in the range of 2 – 30 keV energy band. The one set of the camera is constituted by two proportional counters, a collimator and a slit, and the three sets of each are arranged in a horizontal direction (GSC-H) and a zenith direction (GSC-Z). Two fields of view (FOV) are restricted to be narrow but long by slat collimators, as $1.5^\circ \times 160^\circ$ (figure 3.1, bottom). As the ISS rotates around the earth, those narrow FOVs scan the celestial sphere. When the ISS goes through the high latitude area, MAXI stops its operation in order to protect high background events by charged particles. Nevertheless, most of X-ray sources in the whole-sky are scanned every 92 min, which is the orbital period of the ISS, except for a narrow region in the direction of the rotation axis of the ISS. The both cameras can determine the one-dimensional direction along the long field of view, using the detected position in the detector. The direction of the field of view can be determined by the attitude of the ISS in any time. Using these two informations, the arrival direction of the individual X-ray photons can be determined. Although the localization accuracy of one photon is $1.5^\circ \sim 2^\circ$, collecting a lot of photons, the position of the X-ray source can be detected with accuracy of 0.1° for point sources.

The gas which is composed Xe (99%) + CO₂ (1%) is enclosed in the proportional counter, which is sealed by the beryllium foil with a thickness of 100 μm . The proportional counters employ six carbon fibers as anodes which are surrounded with veto anodes. The particle background can be rejected by anti-coincidence between the carbon fibers or the carbon and veto fibers. The produced electrons by the incident X-ray are captured on the anode wires and are detected as Pulse Height Amplitudes (PHA) of two charge sensitive amplifiers attached at both ends of the anodes. The energy of the incident X-ray is proportional to the total amount of the charge generated in the gas counter. The X-ray photon energy is determined by the summation of the two PHAs. The energy resolution measured before launch is shown in figure 3.2. We define the PHA read out at left anode end as

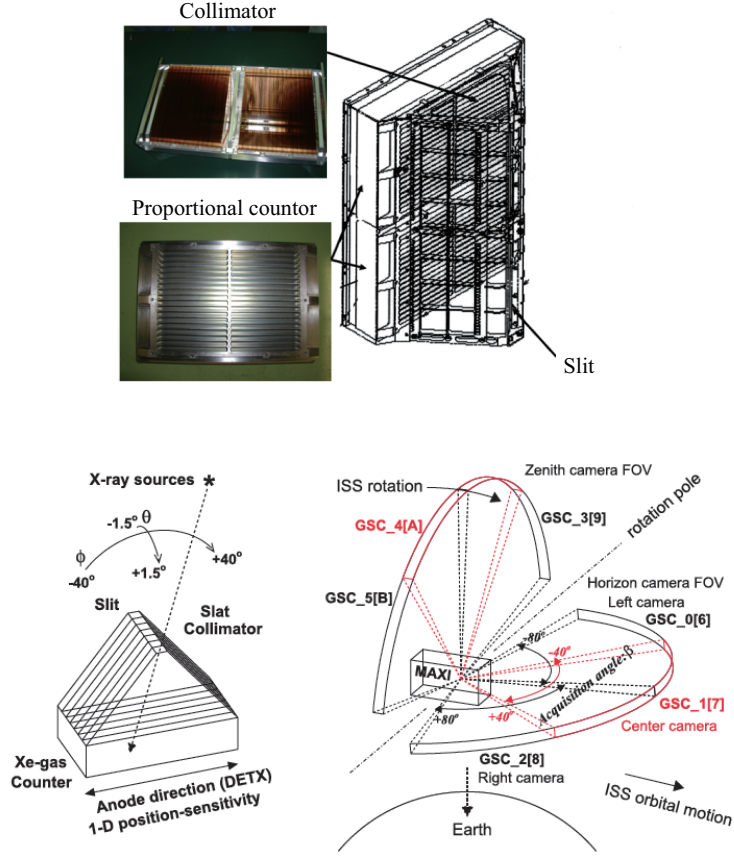


Figure 3.1: (top) A sketch of the GSC and pictures of a collimator and a proportional counter. (bottom left) A schematic view of a single GSC camera unit and its field of view (FOV). (bottom right) The FOVs of the six camera units including 12 counters (GSC 0, ..., GSC 9, GSC A, GSC B) on the ISS low-earth orbit. Every two counters, such as GSC 0 and GSC 6, are used as a pair for a redundancy. Left, center, and right camera units cover the area of source-acquisition angle β of $80^\circ < \beta < 0^\circ$, $-40^\circ < \beta < +40^\circ$, and $0^\circ < \beta < +80^\circ$, respectively.

PHA_L and right as PHA_R , and introduce a position-measure parameter, PM ,

$$PM = \frac{PHA_R - PHA_L}{PHA_R + PHA_L}. \quad (3.1)$$

PM has an approximately linear relation with the event location where the X-ray is absorbed along the anode wire. After correction of the non-linearity by using the calibration data, the detected position on the anode wire, DETX, is derived (figure 3.3). The arrival direction of the X-ray is determined by the position on the beryllium window, BEX, by correcting the effect of the incident angle of the X-rays, and the position on the detector, DETX.

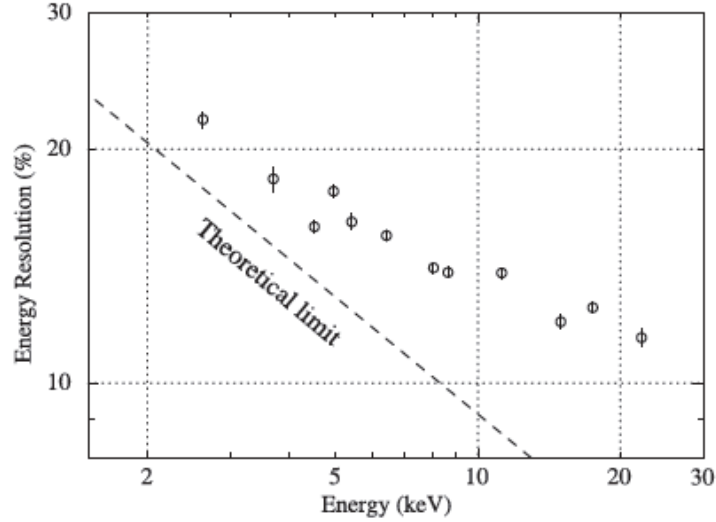


Figure 3.2: Energy resolution (FWHM) of the MAXI/GSC against the X-ray energy (Mihara et al., 2011). Circles with $1 - \sigma$ error bars represent the measured data with K-shell emission lines from elements.

Figure 3.4 shows detection efficiencies of GSC when the incident angle is $\phi = 0^\circ$ and $\phi = 40^\circ$. The structure appearing at 34.5 keV corresponds a Xe-K absorption edge.

The on-orbit energy calibration of the MAXI/GSC is performed by the following strategy. First, we adjusted the gain of each anode using $K\alpha$ lines of Ti and Cu emitted from camera body and collimator, respectively. In order to correct the artificial features in the low energy below 3 keV and around 5 keV (Xe L-edge) we modified energy response. The correction factor is calculated by comparing actual Crab data and referenced model parameters, $N_H = 0.35 \times 10^{22} \text{ cm}^{-2}$ and photon index = 2.1 by Kirsch et al. (2005) (Sugizaki, 2010).

3.2.2 Solid-state Slit Camera

The another camera is a Solid-state Slit Camera (SSC: Tomida et al. (2011)). The SSC has a higher sensitivity in the soft X-ray below 2 keV than that of the GSC. It covers in the range of 0.5 – 12 keV band. The FOV of the SSC is also restricted by the slit and the collimator as $1.5^\circ \times 90^\circ$. For the SSC, sixteen CCD units are arranged in one camera (figure 3.5, left), and two cameras are mounted. One monitors the horizontal direction of the ISS (SSC-H), and another one sees the zenithial direction (SSC-Z) (figure 3.5, right). One CCD has 1024×1024 pixels with $24 \mu\text{m}$ square. Thin aluminum with $0.2 \mu\text{m}$ is coated on the CCD surface to avoid optical and infrared light. A detection efficiency of the SSC is shown in figure 3.6. The energy resolution is 145 eV at 5.9 keV, as shown in figure 3.7.

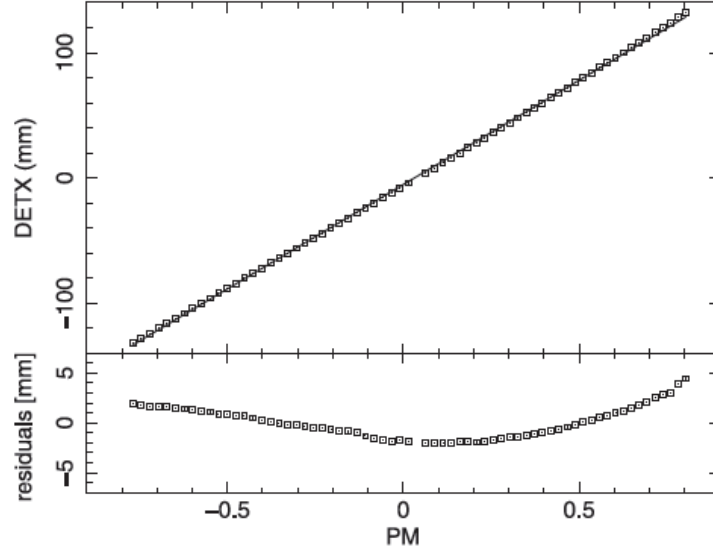


Figure 3.3: Relation between the position at which X-ray is absorbed along the anode wire (DETX) and the position-measure parameter derived from the PHA ratio, PM (Mihara et al., 2011). The data in the top panel is fitted with a linear function (solid line), and the bottom panel shows the residuals.

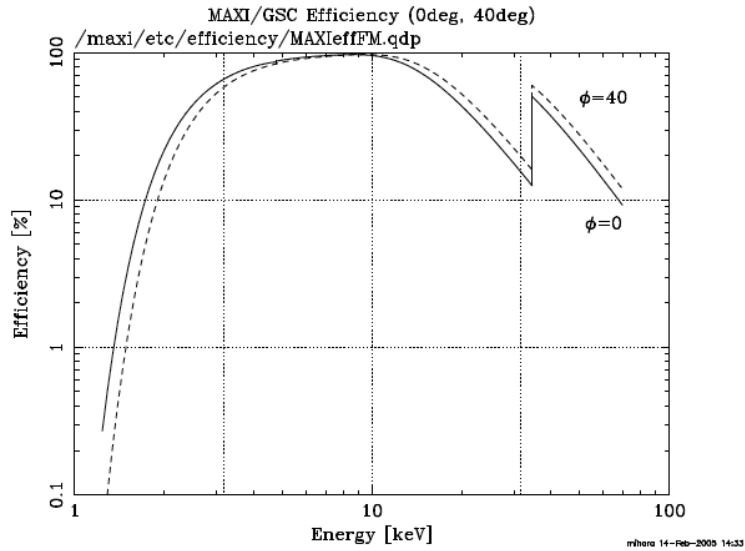


Figure 3.4: A detection efficiency of the MAXI/GSC. The solid line is at the incident angle $\phi = 0^\circ$ and the dashed line is at $\phi = 40^\circ$.

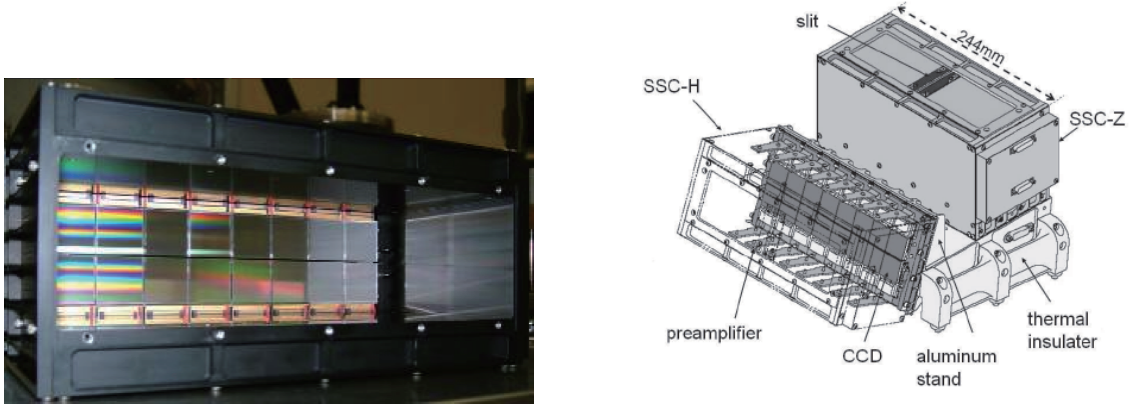


Figure 3.5: (left) The picture of the SSC. The sixteen of CCDs are aligned. (right) An exploded view of the SSC.

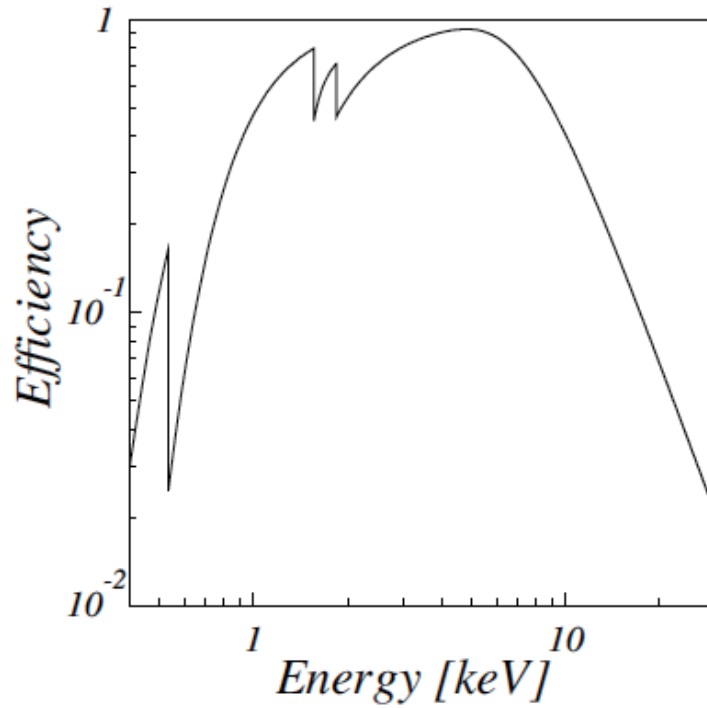


Figure 3.6: A detection efficiency of the MAXI/SSC.

Although the CCD can detect two dimensional image, in normal operation a "parallel sum mode" is applied, when one dimensional information is sacrificed and a fast read-out is made possible.

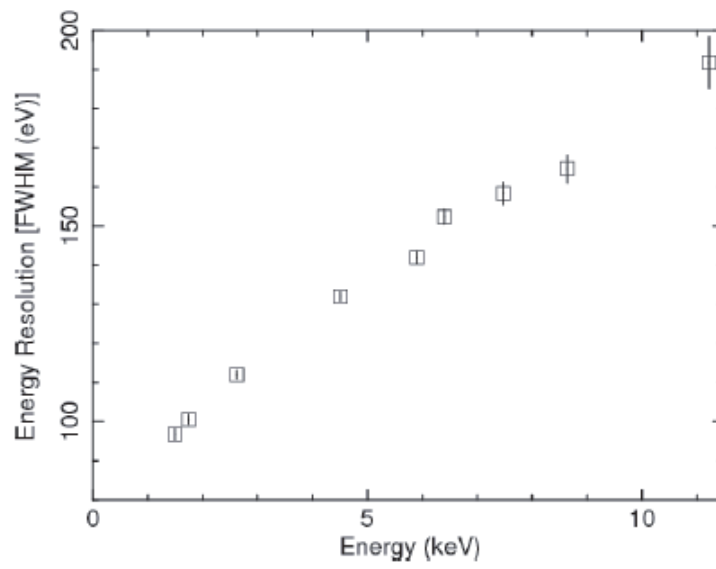


Figure 3.7: Energy resolution of the MAXI/SSC-H as a function of the X-ray energy (Tomida et al., 2011).

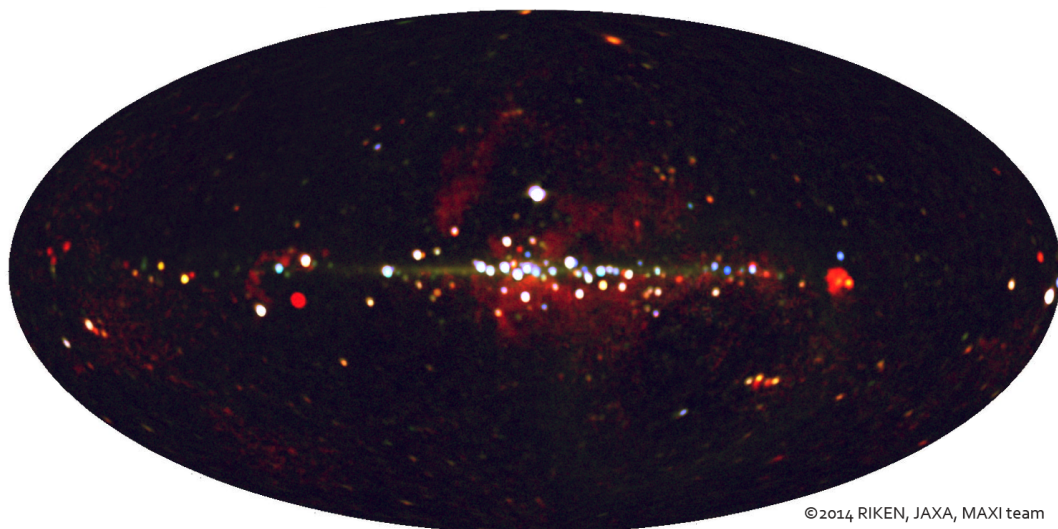


Figure 3.8: The all-sky image obtained by the MAXI/GSC and SSC, accumulated for four and a half years, from 2009 to 2013. The colors, red, green and blue, are corresponding to the X-ray energy bands, 0.7 – 2, 4 – 8 and 8 – 16 keV, respectively.

The parameters of the both cameras are summarized in table 3.1.

Table 3.1: The specifications of the MAXI/GSC and SSC.

	Gas slit camera (GSC)	Solid state slit camera (SSC)
Detector	One-dimensional position-sensitive X-ray detector (Xe+CO ₂ 1%)	X-ray CCD (1024× 1024 pixel)
Energy range	2 – 30 keV	0.5 – 12 keV
Total detection area	5350 cm ²	200 cm ²
Energy resolution	16% (6 keV)	145 eV (5.9 keV)
Field of view	160° × 1.5°	90° × 1.5°
Localization accuracy	0.1°	0.1°
Time resolution	0.1 msec	5.8 sec

Figure 3.8 shows the all-sky image by the MAXI/GSC and SSC, accumulated for four and a half years.

Chapter 4

Observation of Cyg X-1 with MAXI

Contents

4.1	Light Curve	35
4.2	Definition of spectral states	38

4.1 Light Curve

From the MAXI home page ¹, we downloaded one-day bin and 90-minute bin archival data of Cyg X-1. These archival data were selected on the condition that X-ray incident angle to a camera is smaller than 38 ° and scan times of the source and the background are both longer than 15 s. The source events are extracted from a 1°.6 radius circle with a center at the source position. The background is extracted from an annular region with 3°.0 outer radius and 1°.6 inner radius around the source region (figure 4.1). In the light curve, the flux is already corrected to photons considering detector response and exposure time on the assumption of Crab-like spectrum.

Energy spectra of the GSC and SSC were processed by the MAXI on-demand data web page ² (Nakahira, 2013). In this page, we can extract the images, light curves and spectra of both the MAXI/GSC and SSC with an arbitrary size for the source and background region. We selected circular sky-regions with its radius of 2°.0 and 3°.0 for a source and background analyses, respectively. Figure 4.2 shows an example of the spectra of the on-source, background and background-subtracted source spectrum.

Figure 4.3 shows one-day bin light curves of Cyg X-1 obtained with the GSC from 2009 August 15 (MJD = 55058) to 2016 January 17 (MJD = 57404), in three energy bands (2–4 keV, 4–10 keV and 10–20 keV). Time histories of two kinds of hardness ratios (HR), $I(4\text{--}10\text{ keV})/I(2\text{--}4\text{ keV})$ and $I(10\text{--}20\text{ keV})/I(4\text{--}10\text{ keV})$, are also plotted.

¹<http://maxi.riken.jp/top/index.php?cid=1&jname=J1958+352>

²<http://maxi.riken.jp/mxondem/>

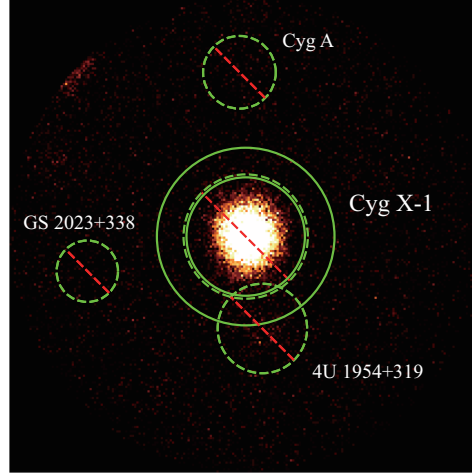


Figure 4.1: The MAXI/GSC image in 4 – 10 keV band of Cyg X-1. The circles with green solid lines show the source and background region of Cyg X-1. The dashed circles are contaminating sources.

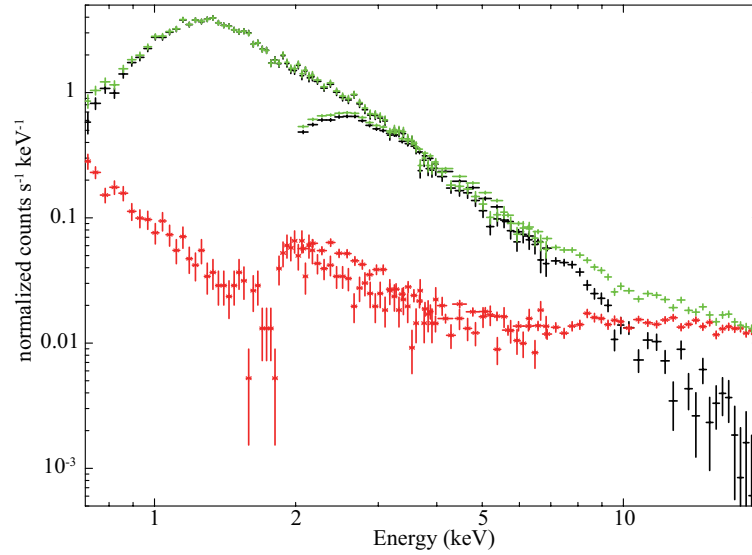


Figure 4.2: An example of the energy spectra of Cyg X-1. The green, red and black data correspond to the on-source, background and background-subtracted source spectrum spectra, respectively.

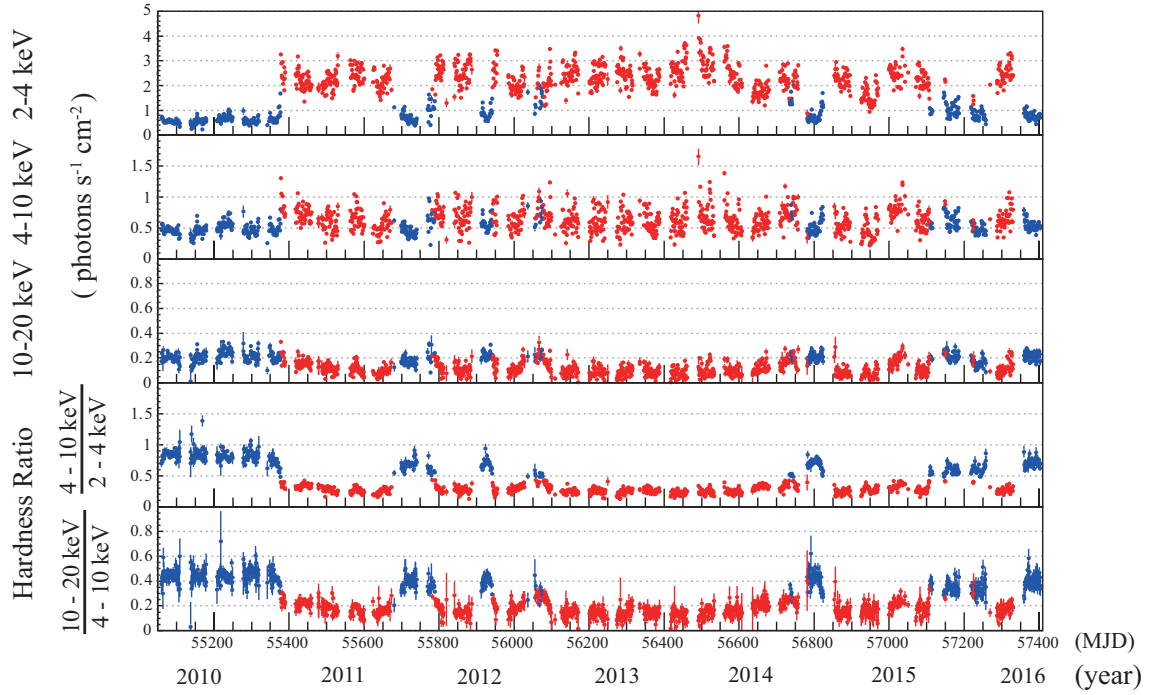


Figure 4.3: One-day bin light curves and HR histories of Cyg X-1 obtained with the MAXI/GSC. From the top to bottom panels, the 2–4 keV, 4–10 keV and 10–20 keV intensities, and the $I(4\text{--}10\text{ keV})/I(2\text{--}4\text{ keV})$ and $I(10\text{--}20\text{ keV})/I(4\text{--}10\text{ keV})$ ratios are plotted. The blue and red data points indicate the LHS and HSS periods, respectively. Data points with large error bars, due to high background counts, were omitted.

Table 4.1: Spectral states of Cyg X-1 during the MAXI observation.

data	spectrum	start	end	duration
No.	state	MJD	MJD	day
1	hard	55058	55376	318
2	soft	55378	55673	295
3	hard	55680	55788	108
4	soft	55789	55887	98
5	hard	55912	55941	29
6	soft	55943	56068	125
7	hard	56069	56076	7
8	soft	56078	56733	655
9	hard	56735	56741	6
10	soft	56742	56757	15
11	hard	56781	56824	43
12	soft	56854	57107	253
13	hard	57108	57114	6
14	soft	57148	57150	2
15	hard	57151	57223	72
16	soft	57223	57226	3
17	hard	57226	57259	33
18	soft	57269	57331	62
19	hard	57359	57404~	45~

The state of Cyg X-1 can be recognized by the values of the HR. Since the start of the MAXI observation in 2009 August, Cyg X-1 was in the LHS for about ten months. At around MJD = 55378, the source caused a transition to the HSS, and then it stayed for another ten months. After several times of state transitions, it has been mainly in the HSS since MJD = 56078.

4.2 Definition of spectral states

As shown in the HR histories in figure 4.3, Cyg X-1 exhibited distinct LHS and HSS. Since the two HR histories have the same trend, we hereafter use the $I(4\text{--}10\text{ keV})/I(2\text{--}4\text{ keV})$ ratio, which has better statistics. The top panel of figure 4.4 shows a hardness-intensity diagram. Thus the two states are clearly separated. The bottom panel in figure 4.4 shows a histogram of the HR, which exhibits two clear peaks corresponding to the HSS and LHS. We fit the histogram with two gaussian functions and determined their mean values and standard deviations. Then we defined the boundaries of each state as 3σ from the gaussian center, i.e. $\text{HR} < 0.43$ for the HSS and $0.48 < \text{HR}$ for the LHS. From figure 4.3

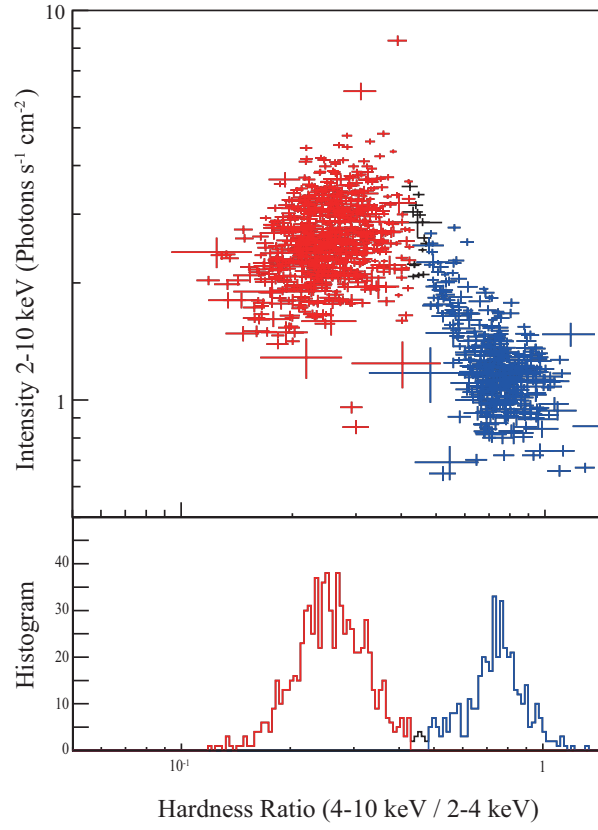


Figure 4.4: The hardness-intensity diagram (top panel) and the histogram of the 4–10 keV vs. 2–4 keV HR (bottom panel). Blue and red data points specify the LHS and the HSS, respectively, while black points were taken during transitions.

and 4.4, the periods of the two states have been obtained as listed in table 4.1.

Chapter 5

Long-Term variations in the low/hard and the high/soft states

Contents

5.1	Power Spectra	41
5.1.1	Definition of NPSDs	41
5.1.2	Sampling and gap effects	41
5.1.3	Estimation of the sampling and gap effects	42
5.1.4	Estimation of the Poisson noise	44
5.1.5	Results (1): using the longest data length	46
5.1.6	Results (2): using shorter data lengths	48
5.2	Energy Spectra	53
5.3	Summary and short discussion	57
5.3.1	Summary of data analysis	57
5.3.2	Comparison with short-term variability	60
5.3.3	Spectral variation	61

In this section, the long-term variation of Cyg X-1 is investigated by analyzing the light curve and the energy spectrum. To know the difference of the variability between the LHS and HSS, the long-term power spectrum are calculated using data more than several ten days. We calculated the normalized power spectrum (NPSD) from the uneven and discrete longtime data including data gaps. The long-term spectral variation is also analyzed. Based on our results, we discuss the origin of the long-term variation.

5.1 Power Spectra

5.1.1 Definition of NPSDs

The X-ray light curve with 90-minute bin was converted to the PSD by the discrete Fourier transformation as,

$$F_c(f) = \frac{2}{N} \sum_{j=1}^N y_j \cos(2\pi f \Delta t \times j), \quad F_s(f) = \frac{2}{N} \sum_{j=1}^N y_j \sin(2\pi f \Delta t \times j), \quad (5.1)$$

where y_i is the intensity (photons $\text{s}^{-1} \text{cm}^{-2}$) at the i -th bin, N is the number of data after filling the gaps as described in subsection 5.1.2, and Δt is a time interval of 5400 s, which is the regular sampling time of the MAXI public data, f is the frequency which is an integer multiple of $\Delta f = \frac{1}{T}$ and T is the total time span of the observation. The factor of $2/N$ is employed so that $F_c(f)$ and $F_s(f)$ represent the amplitude of the cosine and sine components, respectively, regardless of N . The PSD is the sum of squares of F_c and F_s as,

$$P(f) = \frac{T}{2} \{F_c^2(f) + F_s^2(f)\}. \quad (5.2)$$

By multiplying with a factor of $T/2$, the derived PSD becomes independent of T , and has a unit of (RMS^2/Hz). The PSD is normalized by the square of the average intensity following Miyamoto et al. (1994). It is called an Normalized PSD (NPSD).

5.1.2 Sampling and gap effects

The MAXI data are not completely regular-sampled. Sometimes data gaps are caused by sun avoidance, high particle background regions, small dead regions at the scan poles which move with the precession period of the orbit of the ISS, and other effects. The treatment of these data gap affects the result of the PSD (hereafter gap effects). Furthermore, the derived PSDs are strongly affected by aliasing effects (hereafter sampling effects), because MAXI measures the intensity of an X-ray source only for $40 \sim 70$ s, every 5400 s period. That is, each data point is a very short snapshot, with a long interval to the next (or from the preceding) sampling. As a result, the MAXI light curves are generally sensitive to source variations not only on time scale longer than 5400 s, but also to these in between $40 \sim 70$ s and ~ 5400 s.

In the following subsections, we describe the estimation and correction of these effects and derive a “transfer function” for the calculated PSD to the best estimation of the intrinsic PSD. Also, we estimated the power of the poisson noise. PSDs obtained from the observed data are divided by the transfer function thus obtained, in order to correct for the gap effects and the sampling effects. Prior to this division, we subtract the Poisson noise, which is estimated by a numerical simulation (subsection 5.1.4).

5.1.3 Estimation of the sampling and gap effects

Simulation of a MAXI/GSC light curve

To estimate effects of the data gaps and the sampling windows in our Cyg X-1 observation with the MAXI/GSC, we make a simulated light curve in units of (counts s⁻¹ cm⁻²), whose PSD has a form of Af^{-1} , since the PSD of Cyg X-1 can be approximated by a power law with an index of -1 (Reig et al., 2002; Churazov et al., 2001). The normalization A is chosen to be close to what has actually been observed with the MAXI/GSC. Let us assume first that the observation is continuous with each data bin having a length Δt , and set it equal to a typical source transit time, $t_{\text{scan}} = 54$ s. According to the method described in Isobe et al. (2015) and Timmer and Koenig (1995), the count rate a_i at the i -th bin is generated as

$$a_i = \frac{2}{\sqrt{N\Delta t}} \sum_{j=0}^{N_F-1} \{c_i(f_j) + s_i(f_j)\} \quad (\text{counts s}^{-1} \text{ cm}^{-2}), \quad (5.3)$$

$$c_i(f_j) = R_{\cos,j} \cos(2\pi f_j t_i), \quad s_i(f_j) = R_{\sin,j} \sin(2\pi f_j t_i),$$

$$t_i = i\Delta t \quad (i = 0, \dots, N-1), \quad f_j = j\Delta f \quad (j = 0, \dots, N_F-1).$$

Here N is the total time-bin number, of the order of 5×10^5 (300d / 54s), $N_F = N/2$ is the number of PSD bins, Δf is the width of each PSD bin [$\Delta f = 1/(N\Delta t)$], $R_{\cos,j}$ and $R_{\sin,j}$ are independent gaussian-distributed random numbers with their mean values 0 and their standard deviations $\sqrt{Af_i^{-1}}$, while $c_i(f_j)$ and $s_i(f_j)$ are the corresponding Fourier components. The DC component, c_0 , is chosen so as to reproduce the average source count rate. The factor $\frac{2}{\sqrt{N\Delta t}}$ is the coefficient arising from the inverse Fourier transformation. Thus, $\{a_i; i = 1, 2, \dots, N\}$ provides a simulated light curve, but without including the Poisson error.

To simulate the Poisson noise, a Poisson distributed random number b_i is generated at the i -th bin as

$$b_i = p(a_i \cdot (S \cdot t_{\text{scan}}) + \bar{B}) \quad (\text{counts}). \quad (5.4)$$

Here $p(x)$ means a Poisson distributed random number with the mean value of x , S (cm²) is the average effective area per scan, $a_i \cdot (S \cdot t_{\text{scan}})$ represents the simulated signal counts, and $\bar{B}$ denotes the average background counts per transit of a source. We ignore scan-by-scan scatter in S , t_{scan} , and $\bar{B}$. From this b_i , we subtract $\bar{B}$, and divide the result by $S \cdot t_{\text{scan}}$, to obtain a simulated data point Y_i as

$$Y_i = (b_i - \bar{B}) / (S \cdot t_{\text{scan}}) \quad (\text{counts s}^{-1} \text{ cm}^{-2}). \quad (5.5)$$

An example of the light curve obtained in this way is shown in figure 5.1.

We simulate one hundred light curves composed of continuous 54-s bins, with a total real observation time of 318 d which is the longest observation segment in the LHS (data No.1-all in table 5.1). These 100 light curves with 54-s bin were Fourier transformed into PSDs, which were averaged to give the PSD shown in black in figure 5.2. It recovers the assumed $\propto f^{-1}$ shape.

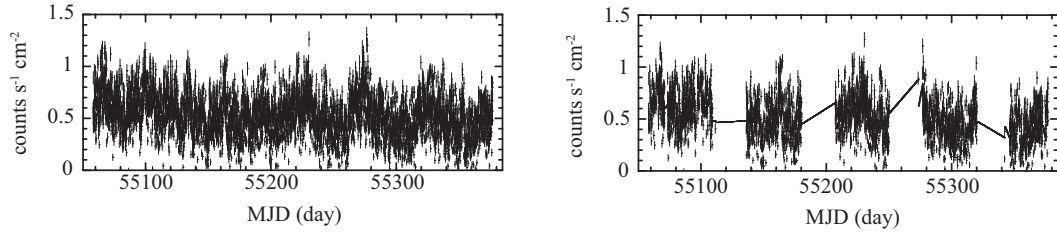


Figure 5.1: The left figure is a simulated light curve calculated with equation (5.5). The right one is after applying the data gaps and filling them by linear interpolations. The sampling time is $\Delta t = 5400$ s.

Sampling effect

The MAXI exposure for a celestial object is far from being continuous. A MAXI light curve consists of discrete snap-shot scans, which are separated by $\Delta t = 92\text{min} \simeq 5400\text{s}$ and lasting for $\sim t_{\text{scan}}$ each. In such sparse-sampling observations with $t_{\text{scan}} \ll \Delta t$, significant alias appears in the high frequency end (subsection 3.2.2 in Kirchner (2005)).

To estimate the sampling effects, we retained one every 100th bin, and discarded the remaining 99 data points. Analysis of these sparse light curves yielded the red PSD in figure 5.2. The red points have more power than the black one towards the Nyquist frequency. This is because the power from 10^{-4} to 10^{-2} Hz, which was smeared out in the black PSD by averaging over the original 100 data points, now appears in frequencies below 10^{-4} Hz. This excess represents the alias power.

Gap effect

Next, to simulate the observational gaps, the sparse (5400s bin) light curves were multiplied with exactly the same sampling windows as in the actual data (data No.1-all). An example is given in figure 5.1 (right). We interpolated each gap with a linear line, which connects the pre-gap intensity (averaged over 5 data points) and the post-gap value (also averaged over 5 data points) (Sugimoto et al., 2014). All the light curves were Fourier transformed. The obtained PSDs were averaged, and are shown in figure 5.2 in blue. Since we interpolate the data gap by a linear function, variation in the higher frequency range was suppressed. The alias effect is still present.

Correction by a Transfer function

The bottom panel of figure 5.2 shows the ratio of the PSD calculated from the sparse and gap-applied light curves, mimicking the actual observation, to the original PSD. This is to be called the transfer function. We corrected the sampling and gap effects in the MAXI/GSC observation, by dividing the PSD calculated from the real data by this transfer function.

To evaluate systematic errors associated with the transfer function, we also performed similar simulations by changing the PSD index to -2 and -0.5 . As expected, the transfer function became flatter for the PSD index -2 (~ 1 at 10^{-5} Hz), while more deviated from unity (~ 5 at 10^{-5} Hz) when the PSD index is set at -0.5 . However, these effects are limited to frequencies above $\sim 10^{-5}$ Hz.

5.1.4 Estimation of the Poisson noise

The observed data are subject to statistical fluctuations, or Poisson noise. Since this component is independent of the intrinsic source variability, the derived raw PSDs are considered to be a direct sum of the intrinsic and Poissonian contributions. Although the Poisson noise would usually be a constant, this is not true in the present case, because of the data gaps, background variations, and other practical effects. We hence estimate the Poisson-noise contributions to the PSDs by a numerical simulation.

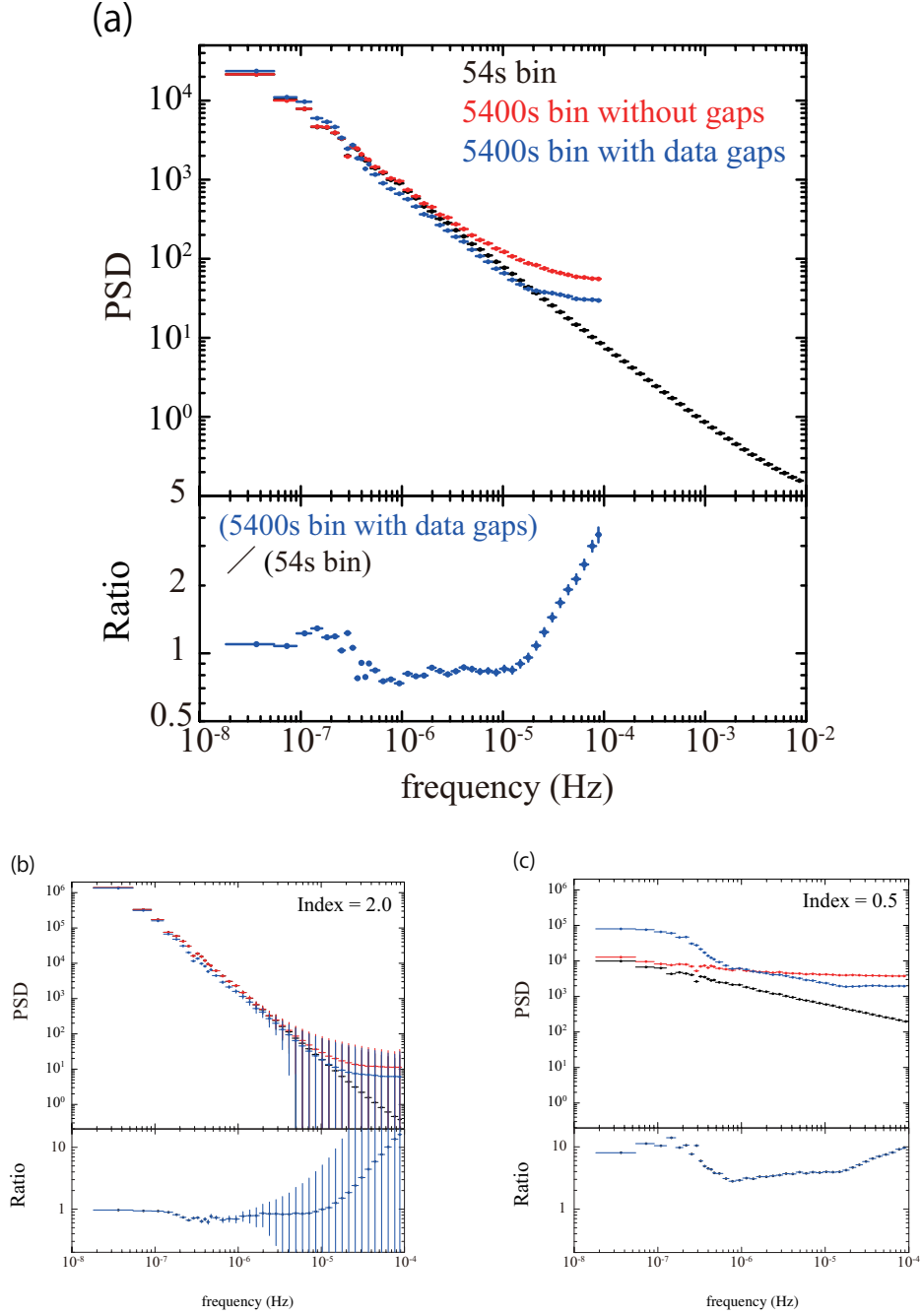


Figure 5.2: (a) Simulations of the alias effects and sampling effects on the PSD with the index of -1 . The black data are the PSD calculated from 100 fake light curves, each continuous with a bin width of 54s. The red one is the PSD calculated after sparse sampling (once every 5400s), to the original light curves, and blue one further considering the data gaps that are present in the read data. The bottom panel shows the transfer-function, obtained by the dividing the blue PSD by the black one. (b)(c) Same simulations as (a), but the PSD indices are set at -2 and -0.5 , respectively.

The aim of this simulation is to construct light curves that would be observed if Cyg X-1 had a constant intensity throughout. This has been carried out in the following steps.

- 1 We start from calculating the mean intensity $\bar{y}$ of Cyg X-1 in a specified energy band, as an average over the 5 years of the MAXI data.
- 2 The signal counts to be observed at the i -th scan of “non-varying Cyg X-1” can be expressed as $\bar{y}(S \cdot t_{\text{scan}})_i$, where the effective area S and the source transit time t_{scan} are the same as in subsection 5.1.3.
- 3 The total counts to be detected in the i -th scan can be expressed as $\bar{y}(S \cdot t_{\text{scan}})_i + \alpha_i B_i$, where B_i is the background which was estimated scan-by-scan and was already utilized in section 4.1 to derive the light curves in figure 4.3, while α_i is a correction factor for the effective area in the i -th scan.
- 4 The above quantity is randomized into $b_i \equiv p(\bar{y}(S \cdot t_{\text{scan}})_i + \alpha_i B_i)$ in the same way as in section 5.1.3. Then, $\{b_i\}$ represent the simulated raw counts data, before the background subtraction, to be detected in this fake observation.
- 5 From this randomized counts b_i , we subtract $\alpha_i B_i$ in the same way as in section 4.1, and divide the result by $(S \cdot t_{\text{scan}})_i$, to obtain the simulated light curve $\{Y_i\}$ which should be observed from “non-varying Cyg X-1”. The procedure is summarized as

$$Y_i = (b_i - \alpha_i B_i) / (S \cdot t_{\text{scan}})_i \quad (\text{counts s}^{-1} \text{ cm}^{-2}) . \quad (5.6)$$

We produced the simulated light curves $\{Y_i\}$ 100 times, and calculated their PSDs in the same manner as for the actual data. In comparison with the actual 4 – 10 keV PSD of Cyg X-1 in the HSS (black), the 4 – 10 keV PSD thus simulated and averaged over the 100 runs is shown in figure 5.3 in red. Since the source intensity has been assumed to be constant, the red PSD is considered to represent pure Poisson fluctuations. While this PSD is approximately flat on long time scales ($< 10^{-7}$ Hz) as expected for white noise, it decreases towards higher frequencies. This is because the data gaps were filled with linear lines which do not contain statistical fluctuations: the Poisson noises are diluted on time scales shorter than those of the data gaps. In any event, the estimated Poisson-noise contribution is $< 15\%$ of the signal PSD at all frequencies analyzed here, and particularly below a few percent at $< 10^{-6}$ Hz.

5.1.5 Results (1): using the longest data length

For both the LHS and HSS, we calculated NPSDs from the light curves in the three energy bands, 2 – 4 keV, 4 – 10 keV and 10 – 20 keV. In calculations, the longest span of data was used for each state, i.e. 318 days for the LHS and 477 days for the HSS. These data segments are shown in table 5.1 (as No.1-all) and table 5.2 (as No.8-all), respectively, together with other shorter segments available.

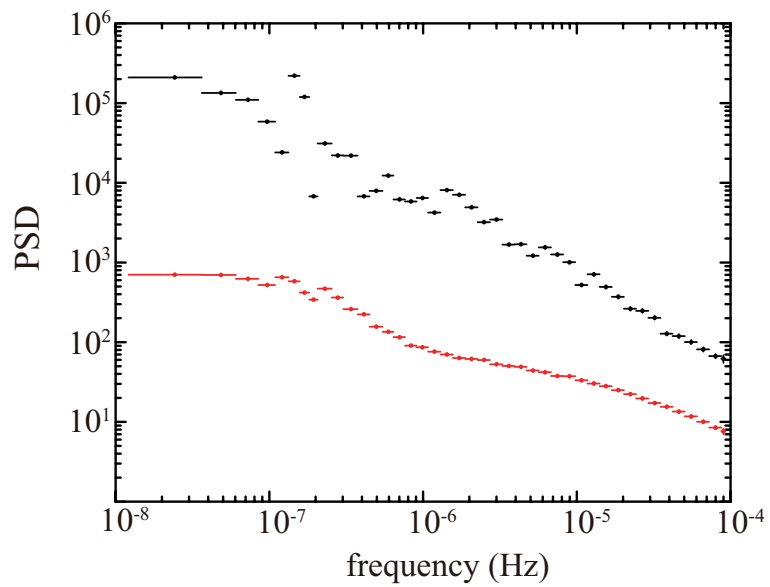


Figure 5.3: The simulated 4–10 keV Poisson-noise contribution (red), compared with the 4–10 keV PSD actually observed from Cyg X-1 in the HSS (black).

Only the GSC data were used, because the SSC data are much more sparse than those of the GSC. In the HSS, the selected span is shorter than Data No.8 in table 4.1 because short data bunches at the beginning and the end of the span were removed. After subtracting the Poisson noise and correcting for the gap and the sampling effects (section 5.1.2), we obtained NPSDs down to 3×10^{-8} Hz as shown in figure 5.4. The error of each data point was obtained by propagating errors of the observed light curve. The NPSDs extend roughly with a power law shape down to 3×10^{-8} Hz, but they scatter largely in the low frequency ($\leq 3 \times 10^{-7}$ Hz) region.

5.1.6 Results (2): using shorter data lengths

By shortening the data length to be used in a Fourier transform by equation (5.1), we can produce a larger number of NPSDs, and take their average. The NPSD obtained in this way is expected to suffer smaller statistical errors, although it lacks the information in the lowest frequencies. Thus, the data span was restricted to 40 and 43 days for the LHS and the HSS, respectively, to cover a frequency range down to $\sim 3 \times 10^{-7}$ Hz at the sacrifice of the $3 \times 10^{-8} - 3 \times 10^{-7}$ Hz range. By doing so, the fraction of data gaps was reduced from ~ 50 % to ~ 10 %. As listed in table 5.1, six data segments were extracted for the LHS, and eight data segments in table 5.2 for the HSS. Then, we converted these data segments individually into NPSDs, and took their averages, separately over the LHS and HSS. The obtained ensemble-averaged NPSDs are shown in figure 5.5, where the vertical error bars represent the NPSD scatter (standard deviation) within each ensemble. In figure 5.5, ordinate employs power times frequency, instead of power itself.

As expected, the NPSDs in figure 5.5 are less scattered even in the low frequency range below 10^{-6} Hz, and show similar structures in all the energy bands, although they could still be subject to some structures including shallow dips around 3×10^{-6} Hz, and the weak tendency of flattening below 3×10^{-7} Hz. As shown by a simulation in section 5.1.3, the possible flattening is unlikely to be caused by the data gaps. Instead, it could be within the scatter of NPSDs, considering that the effect is seen in only the lowest-frequency data points in both states. We also note that the energy dependence in figure 5.4 and 5.5 is slightly different. Especially, the normalization of the 4 – 10 keV NPSD in the HSS in figure 5.4 is higher than that in figure 5.5. Considering the ensemble-averaging procedure involved in the NPSDs in figure 5.5, we regard them as better representing the Cyg X-1 variability than those in figure 5.4.

As seen in figure 5.5, the NPSD slope does not appear to depend significantly either on the spectral state or the energy band. To confirm this suggestion, we fitted the individual NPSDs with a power law, over a frequency range of 10^{-6} and 9.2×10^{-5} Hz. Then, the 18 NPSDs before taking ensemble averages (6 segments times 3 energy bands) in the LHS gave an average slope and the associated RMS scatter as -1.35 ± 0.29 , whereas the 24 HSS ones (8 segments times 3 energy bands) gave -1.29 ± 0.23 . Therefore, the NPSD slope is consistent with being independent of the state. In addition, slope differences among the 3 energy bands are at most within the scatter of ~ 0.3 (in the LHS) and ~ 0.2 (in the HSS).

Figure 5.5 reveals two more important properties. One is that the NPSD normalizations in the

Table 5.1: Data segments used in calculating NPSD in the LHSs.

data	start	end
No.*	MJD	MJD
1-all	55058	55376
1-1	55060	55100
1-2	55138	55178
1-3	55209	55249
1-4	55277	55317
3-1	55700	55740
11-1	56781	56821

* : “ I - J ” denotes the J -th segment in the I -th data. “ I -all” means as the segments in the I -th data number.

Table 5.2: The same as table 5.1 but for the HSS.

data	start	end
No.	MJD	MJD
8-all	56130	56607
2-1	55487	55530
2-2	55623	55666
8-1	56201	56244
8-2	56273	56316
8-3	56418	56461
8-4	56564	56607
8-5	56637	56680
12-1	56926	56969

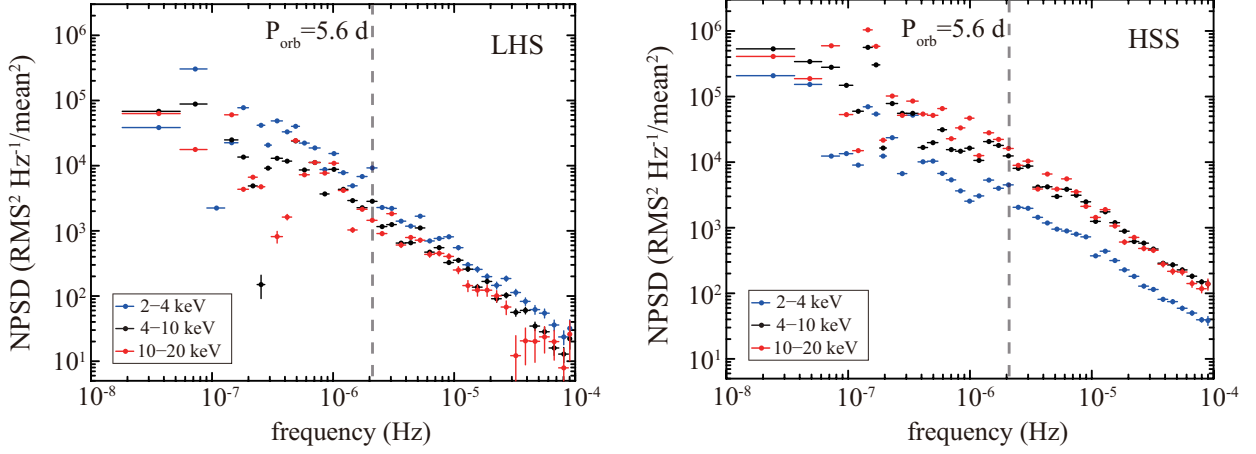


Figure 5.4: NPSDs of Cyg X-1 in the LHS (left) and in the HSS (right), each calculated using the longest data span (No.1-all in table 5.1 and No.8-all in table 5.2). The blue, black and red points represent NPSDs in the 2 – 4 keV, 4 – 10 keV and 10 – 20 keV band, respectively. The vertical line at 2×10^{-6} Hz indicates the 5.6-day orbital period.

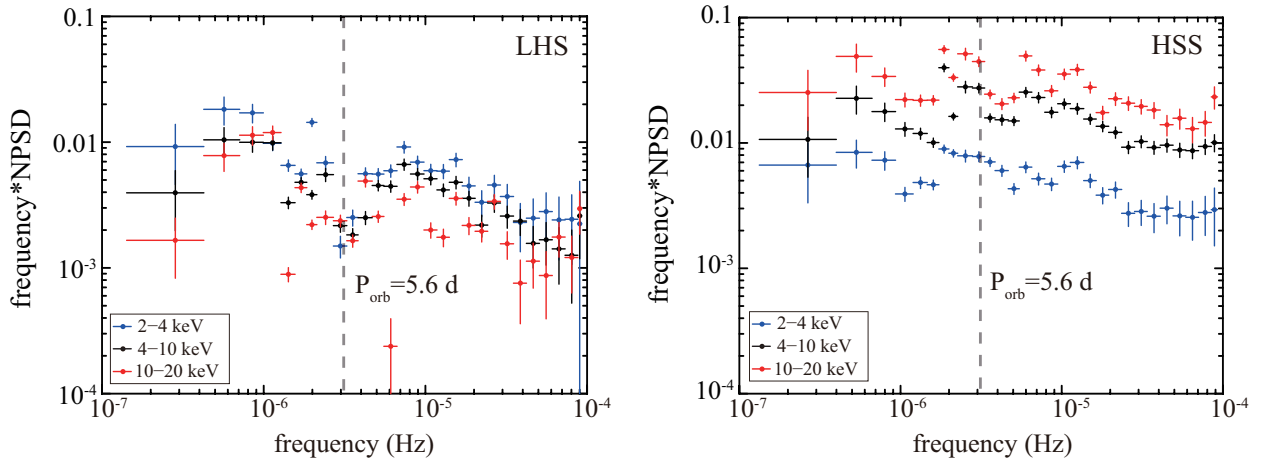


Figure 5.5: The NPSDs calculated over shorter data segments (40 d × 6 for the LHS and 43 d × 8 for the HSS), and averaged. Here, the NPSDs are shown after multiplying with the frequency.

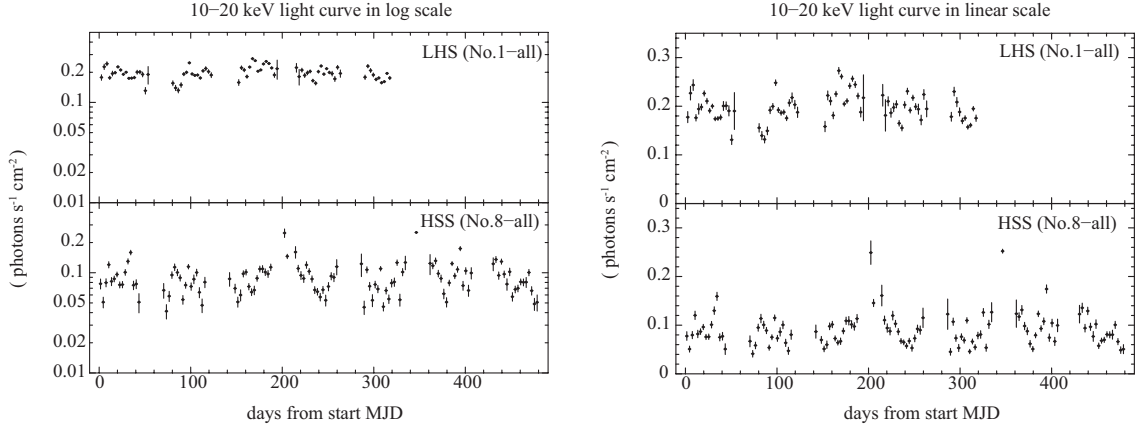


Figure 5.6: (left) Expanded 10 – 20 keV light curves (three-day bin) of Data No.1-all and No.8-all, representing the LHS and the HSS, respectively. Ordinates are logarithmic. (right) The same as left, but with linear scales. Data No.1-all and data No.8-all are shown the LHS and HSS, respectively. The data No. is indicated in top panel, and the corresponding MJDs are listed in table 5.1 and 5.2.

HSS are significantly energy dependent, increasing towards higher energies, whereas those in the LHS show a much weaker and opposite trend. The other is that Cyg X-1 is much more variable, at least above 4 keV, on the relevant time scales while it is in the HSS than in the LHS. To quantify these properties, we integrated the 6 (3 energy bands times two states) ensemble-averaged NPSDs from 10^{-6} to 9.2×10^{-5} Hz, and derived individually the fractional RMS variation η as,

$$\eta = \sqrt{2\Delta f \sum_{i=1}^{N_F} NPSD(f_i)}, \quad (5.7)$$

where N_F is the number of data points in each NPSD. The results, given in table 5.3, indeed confirm the above inferences: the fractional RMS variation in 10 – 20 keV in the HSS ($\eta = 0.70$) is larger than that in the LHS ($\eta = 0.21$). This property can be read directly from the light curve in a logarithmic scale presented in figure 5.6, left. Meanwhile, when plotted in a linear scale (figure 5.6, right), the absolute amplitude of variability is similar between the LHS and HSS. These two properties can be explained as follows. The 10 – 20 keV value of η is $0.70/0.21 \sim 3.3$ times higher in the HSS than in the LHS, while the average 10 – 20 keV intensities (as read from figure 5.6, right) in the HSS is $0.089/0.19 \sim 0.47$ times that in the LHS. Therefore the absolute amplitude of variations in the HSS should be $3.3 \times 0.47 = 1.55$ times that in the LHS. This is close to unity, though not exactly the same.

In the LHS, a peak corresponding to the orbital period of 5.60 d is clearly seen in the low energy band (2 – 4 keV) at 2.06×10^{-6} Hz. However, it is not clear in the other two energy bands in the LHS, in agreement with the Ginga/ASM results by Kitamoto et al. (2000). In the HSS, the orbital period is not clearly seen in any energy band.

Table 5.3: The fractional RMS η of NPSDs from 10^{-6} to 9.2×10^{-5} Hz.

Spectral state	LHS			HSS		
Energy band (keV)	2-4	4-10	10-20	2-4	4-10	10-20
η	0.31 ± 0.09	0.24 ± 0.05	0.21 ± 0.04	0.31 ± 0.09	0.53 ± 0.12	0.70 ± 0.29

Figure 5.7 shows our 4 – 10 keV NPSDs in both states, in comparison with previous works with RXTE data by Cui et al. (1997), Pottschmidt et al. (2003), and Reig et al. (2002). In both states, our results at 10^{-4} Hz locate on simple extrapolations of the NPSDs obtained previously by the RXTE/PCA in the frequency region above 10^{-3} Hz. The figure reconfirms and visualizes the higher variability in the HSS, already presented in table 5.3. The NPSD in Reig et al. (2002), which is obtained by the RXTE/ASM, is located between the two states of the present work. This difference is presumably because their data include some of the HSS and the transition periods, although the main part is in the LHS.

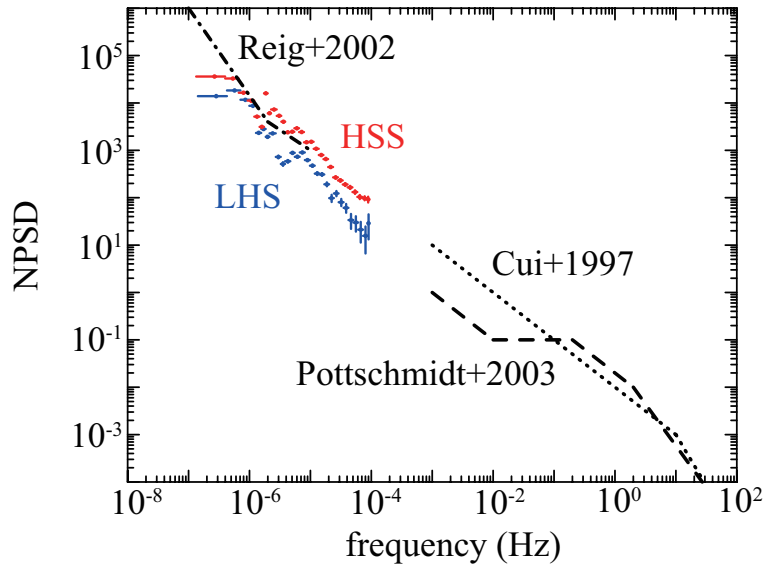


Figure 5.7: A comparison of the MAXI 4 – 10 keV NPSDs in the LHS (blue) and the HSS (red), with the previous works. The dashed line is the 2 – 13 keV NPSD in the LHS by Pottschmidt et al. (2003), the dotted line is that in the HSS in 2 – 13 keV by Cui et al. (1997), and the dot-dashed line is that by Reig et al. (2002) where the most data are in the LHS.

5.2 Energy Spectra

In order to investigate the spectral components that are responsible for the observed long-term variations, we analyzed energy spectra of Cyg X-1 obtained with the MAXI/GSC and SSC. We used the same periods as in the PSD analysis, i.e. from MJD = 55058 to MJD = 55376 for the LHS, and from MJD = 56130 to MJD = 56607 for the HSS. The SSC data, available only for about one third of the time, were also incorporated.

In section 5.1, we found that the long-term variability of Cyg X-1, particularly in the HSS, is significantly energy dependent. To reconfirm the implied spectral variation in this frequency range, we divided the observed data into bright and faint periods by comparing the individual one-day GSC

intensities in 2 – 20 keV with their 15-day running averages. Since the 15-day time scale corresponds to a frequency of 8×10^{-7} Hz, this procedure means an extraction of time variations longer than 8×10^{-7} Hz. Then, eight spectra in total were produced; the GSC and SSC data in the bright and faint periods, from the LHS and HSS. The background-subtracted eight MAXI spectra obtained in this way are shown in figure 5.8. Thus, as expected, the HSS spectra are much softer than those of the LHS, in good agreement with the general understanding of the spectral states. For reference, these spectra include periods of increased low-energy absorption (seen as dips in the 2 – 4 keV light curves, see figure 2.15) in subsection sec:dip, which often appear for $\sim 15\%$ of the orbital phase.

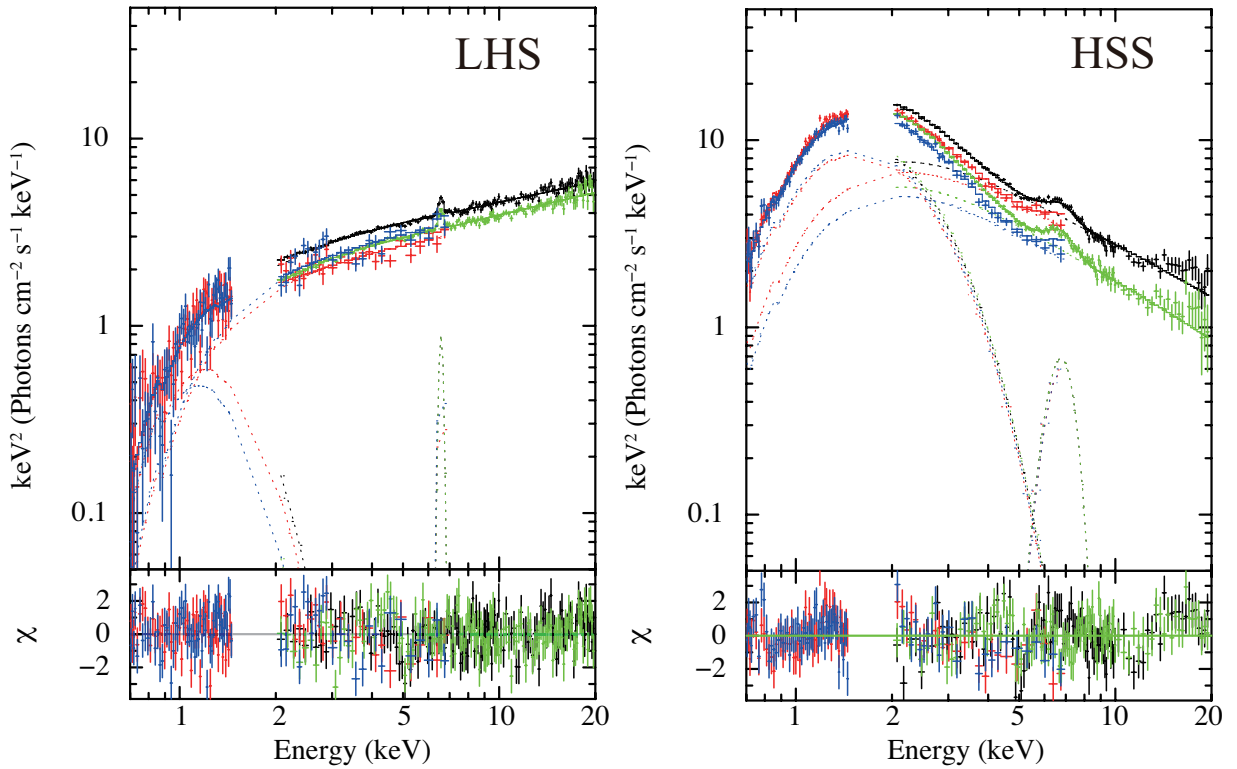


Figure 5.8: Background-subtracted unfolded MAXI spectra in the LHS (left), and the HSS (right). Red and black indicate the bright-period data of the SSC and GSC respectively, while blue and green indicate the faint periods of the SSC and GSC, respectively. The model is $phabs*(diskbb+nthComp+gaussian)$, with the parameters listed in table 5.6. The 1.5 – 2 keV energy range is ignored in the fitting. The dotted lines represent contributions of the three components. The bottom panels are residuals from the model.

To better visualize the intensity-correlated spectral changes in figure 5.8, we present, in figure 5.9, the ratios of the GSC spectrum in the bright period to that in the faint period. The SSC data are not

shown here, because the errors are large. In the LHS, the ratio decreases slightly with energy, whereas the HSS ratio increases significantly towards higher energies. To quantify these spectral results and examine their consistency with table 5.3, we calculated the ratio R of the photon flux in the bright period F_b to that in the faint period F_f , and showed the results in table 5.4. We may express R as,

$$R = F_b/F_f = (\bar{F} + \Delta F)/(\bar{F} - \Delta F), \quad (5.8)$$

where $\bar{F} \equiv \frac{F_b + F_f}{2}$ is the average photon flux in the specified energy band and $\Delta F \equiv \frac{F_b - F_f}{2}$ denotes the variable part. In this formalism, the fractional RMS variation can be given as,

$$\eta' \equiv a\Delta F/\bar{F} = a(R - 1)/(R + 1), \quad (5.9)$$

where a is an appropriate numerical factor of order unity, which can be approximated as energy independent. This a was introduced because the variation η of equation (5.7) calculated from NPSD can be different, by a constant factor, from that derived by equation (5.9). The derived values of η' are also shown in table 5.4, where $a = 2.9$ has been adopted. Thus, the values of η' agree, within errors, with η in table 5.3 which is based on the PSD analysis.

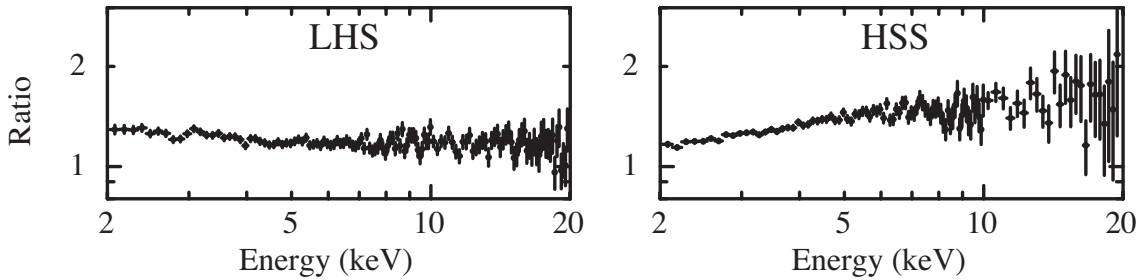


Figure 5.9: Ratios of the GSC spectra in the bright period to that in the faint period, in the LHS (left panel), and in the HSS (right panel).

To understand the physical origin of the behavior seen in figure 5.9, as well as in table 5.3 and 5.4, we proceeded to simultaneous model fitting to the 2 – 20 keV GSC spectrum and the 0.7 – 7 keV SSC spectrum. The 1.5 – 2 keV range of the SSC was excluded to avoid the known systematic uncertainty in the effective area (Tomida et al., 2011). First, we employed a model composed of a multi-color disk (*diskbb*) model (Shakura and Sunyaev, 1973; Mitsuda et al., 1984) for the low-energy part, and a power law (*powerlaw*) as a hard tail. This model has often been used in the previous studies of BH X-ray binaries including Cyg X-1 (e.g. Dotani et al. (1997)). The photo-electric absorption model (*phabs*) with abundances by Anders and Ebihara (1982) and the Fe-K emission line model (*gaussian*) were incorporated. The model then becomes *phabs* × (*diskbb* + *powerlaw* + *gaussian*) in the Xspec (Arnaud, 1996) terminology; hereafter, we call it *diskbb* + *powerlaw* model. The innermost radius of *diskbb* is derived as $r_{\text{in}} = D\sqrt{N_{\text{diskbb}}/\cos i}$, where N_{diskbb} is the normalization of the *diskbb* model. The distance D from the earth and the inclination angle i from our line of sight were adopted to be

1.86 kpc and 27° , respectively (Orosz et al., 2011). The hydrogen column density N_{H} and the gaussian parameters were constrained to be common between the faint and the bright spectra in each state, but were allowed to differ between the two states.

The fit has been approximately successful, and yielded the best-fit parameters as summarized in table 5.5. Thus, in both states, the *diskbb* parameters are the same, within errors, between the bright and faint spectra. In the LHS, the *powerlaw* index is steeper in the bright spectrum than in the faint one, while the opposite trend is found in the HSS. These are consistent with the spectral ratio shown in figure 5.9. The r_{in} value for the LHS is consistent with that from a previous work (Yamada et al., 2013a). On the other hand, that for the HSS is smaller than that reported, e.g., in Dotani et al. (1997) (even after corrections for the distance and the mass), presumably because the luminosity in the present result is roughly half those in typical HSS observations made previously (Zhang et al., 1997).

Referring to equation (5.9), we calculated η' from the model spectra and also from the *powerlaw* component only, and show the results in table 5.4. A comparison of the two values of η' , reveals that the overall source variability in > 4 keV is determined solely by the power law variation, in agreement with the spectral decomposition in figure 5.8 (right). In the $2 - 4$ keV band, in contrast, the overall η' is reduced to $\sim 60\%$ of the *powerlaw* variability; this effect is readily attributed to the presence of the stable disk component. In addition, table 5.4 reveals slight increase of η' (both total and *powerlaw*) from the 1020 keV to $4 - 10$ keV bands. The behavior of η' agrees with that of η in table 5.3 and means that the *powerlaw* slope slightly hardens as it gets stronger, as visualized in figure 5.9 (right) and quantified in the fitting results in table 5.5. This finding is not necessarily consistent, however, with previous reports on Cyg X-1 in the HSS (e.g., Jourdain et al. (2014)) and other HSS sources (e.g., Koyama et al. (2015)), that the hard-tail slope is relatively independent of the source intensity. It is possible that the present HSS was somewhat atypical, because the values of $\Gamma \sim 2.9$ we measured is steeper than those ($\Gamma \sim 2.4$; Dotani et al. (1997)) observed from these BH binaries in their typical HSS.

For a further analysis, we replaced the *powerlaw* with a more realistic model *nthComp* (Zdziarski et al., 1996), which represents Compton scattering of some soft photons by hot electrons (*diskbb+nthComp* model). The seed photon source was set to be the *diskbb* component representing the disk emission. Since the electron temperature T_e of the *nthComp* model cannot be determined with our data, we fixed it to a typical value of 100 keV (Sunyaev and Truemper, 1979; Makishima et al., 2008). The best-fit parameters are summarized in table 5.6 and the best-fit models are shown in figure 5.8. The fits are not yet formally acceptable, but the model, as shown in figure 5.8, reasonably reproduces the spectra from 0.7 keV to 20 keV. In this modeling, the disk photons are partially fed into *nthComp*, so that the parameter r_{in} in the *diskbb* model is smaller than the true inner radius which is denoted R_{in} hereafter. This R_{in} was calculated from the sum of 0.01 – 100 keV photon flux of the *diskbb* component, $F_{\text{ph}}^{\text{disk}}$, and that of *nthComp* component, $F_{\text{ph}}^{\text{nth}}$, utilizing the innermost temperature T_{in} of

Table 5.4: The flux ratio R of equation (5.8), and the RMS variation η' of equation (5.9).

Spectral state		LHS			HSS		
Energy band (keV)		2-4	4-10	10-20	2-4	4-10	10-20
Total							
	R	1.25 ± 0.11	1.19 ± 0.07	1.16 ± 0.08	1.17 ± 0.20	1.43 ± 0.24	1.64 ± 0.31
	η'	0.32 ± 0.10	0.25 ± 0.06	0.21 ± 0.08	0.23 ± 0.19	0.52 ± 0.20	0.70 ± 0.23
powerlaw							
	R	1.29 ± 0.12	1.19 ± 0.07	1.16 ± 0.08	1.33 ± 0.16	1.47 ± 0.22	1.64 ± 0.31
	η'	0.37 ± 0.11	0.25 ± 0.06	0.21 ± 0.08	0.41 ± 0.14	0.55 ± 0.18	0.70 ± 0.23

diskbb and the equation by Kubota and Makishima (2004) as,

$$F_{\text{ph}}^{\text{disk}} + F_{\text{ph}}^{\text{nth}} = 0.0165 \left[\frac{R_{\text{in}}^2 \cos i}{(D/10 \text{ kpc})^2} \right] \left(\frac{T_{\text{in}}}{1 \text{ keV}} \right)^3 \text{ photons s}^{-1} \text{ cm}^{-2}. \quad (5.10)$$

The derived values of R_{in} , shown in table 5.6, are indeed larger than r_{in} in table 5.5 (although we do not discuss absolute values of R_{in}). The LHS is characterized by about twice larger R_{in} than the HSS, implying a disk truncation in the LHS as noted before (Makishima et al., 2008; Yamada et al., 2013a). Finally, in either state, the disk parameters (T_{in} and R_{in}) are found to be apparently constant as the source varies.

5.3 Summary and short discussion

5.3.1 Summary of data analysis

Using six years archival data obtained with MAXI, we derived the NPSDs of Cyg X-1 in its LHS and HSS from 10^{-7} Hz to 10^{-4} Hz in the three energy bands. It is of particular importance that the long-term variations in the two states were studied in a unified way using the same instrument, with the same analysis method, and under similar data statistics. In addition, the long-term NPSD in the HSS was obtained for the first time thanks to a fortunate opportunity that Cyg X-1 stayed in the HSS in most of the time since 2010 June. The PSD of the both states in the frequency range between 10^{-5} and 10^{-4} Hz were also provided by our work in the first time.

These results on the HSS are expected to provide some clues to the still unknown origin of the hard-tail component, which is nearly always observed in this spectral state.

In the LHS, the NPSD down to 10^{-7} Hz obeys a power law, and is approximately expressed as an extrapolation of the NPSD above 0.01 Hz (Pottschmidt et al., 2003; Nowak et al., 1999). We found

Table 5.5: The best-fit parameters of the absorbed *diskbb* plus *powerlaw* model.

Model = <i>phabs</i> *(<i>diskbb</i> + <i>powerlaw</i> + <i>gaussian</i>)					
Component	Parameter	LHS/bright	LHS/faint	HSS/bright	HSS/faint
phabs	N_{H}^*	5.8 ± 0.6		4.92 ± 0.12	
diskbb	T_{in} (keV)	0.24 ± 0.02	0.21 ± 0.02	0.50 ± 0.01	0.49 ± 0.01
	$r_{\text{in}}^{\dagger}$ (km)	84_{-22}^{+34}	99_{-26}^{+49}	33_{-5}^{+1}	36_{-5}^{+1}
powerlaw	Index	1.66 ± 0.01	1.62 ± 0.01	2.85 ± 0.03	2.98 ± 0.03
	Norm ‡	2.09 ± 0.04	$1.65_{-0.03}^{+0.04}$	$19.5_{-1.0}^{+1.0}$	16.7 ± 1.0
gaussian	Line E (keV)	$6.66_{-0.16}^{+0.17}$		6.62 ± 0.07	
	Sigma (keV)	0.7 (fixed)		$0.70_{-0.08}^{+0.09}$	
	Norm §	7.2 ± 1.6		$28.3_{-3.2}^{+3.7}$	
fit goodness	$\chi^2_{\nu}(\nu)$	1.38 (420)		1.31 (356)	

* : In a unit of 10^{21} cm^{-2} .

$\dagger$: The distance is assumed to be 1.86 kpc and the inclination angle is assumed to be 27° (Orosz et al., 2011).

$\ddagger$: In a unit of $\text{photons cm}^{-2} \text{ s}^{-1} \text{ keV}^{-1}$ at 1 keV.

$\S$: In a unit of $10^{-3} \text{ photons cm}^{-2} \text{ s}^{-1}$.

Table 5.6: The best-fit parameters of the model consisting of a *diskbb* and *nthComp* taking account of the photo-electric absorption.

Model = phabs*(diskbb+nthComp+gaussian)					
Component	Parameter	LHS/bright	LHS/faint	HSS/bright	HSS/faint
phabs	N_{H}^*	6.1 ± 0.6		3.6 ± 0.1	
diskbb	T_{in} (keV)	0.23 ± 0.02	0.20 ± 0.02	0.48 ± 0.01	0.47 ± 0.01
	$F_{\text{ph}}^{\text{disk}\dagger}$	47.0	43.2	69.6	72.5
nthComp [‡]	Gamma	1.68 ± 0.01	1.65 ± 0.01	2.81 ± 0.03	2.91 ± 0.04
	$F_{\text{ph}}^{\text{nth}\dagger}$	12.9	10.9	36.3	27.4
gaussian	LineE (keV)	6.65 ± 0.16		6.64 ± 0.07	
	Sigma (keV)	0.7 (fixed)		$0.64^{+0.09}_{-0.08}$	
	Norm [§]	$7.6^{+1.6}_{-1.5}$		$24.5^{+3.1}_{-2.8}$	
inner radius	R_{in}^l (km)	116 ± 15	127 ± 21	54 ± 2	53 ± 2
Luminosity [#]		1.76 ± 0.04	1.50 ± 0.03	2.71 ± 0.02	2.35 ± 0.02
Compton fraction ^{**}		0.87	0.89	0.51	0.41
fit goodness	$\chi^2_{\nu}(\nu)$	1.37 (420)		1.38 (370)	

* : In a unit of 10^{21} cm^{-2} .

†: Photon flux in a unit of photons $\text{cm}^{-2} \text{ s}^{-1}$ in the energy range of 0.01-100 keV.

‡ : The electron temperature T_e is fixed at 100 keV. The spectrum of the seed photon is diskbb and the temperature T_{bb} is fixed at T_{in} .

§ : In a unit of $10^{-3} \text{ photons cm}^{-2} \text{ s}^{-1}$.

l: The distance is assumed to be 1.86 kpc and the inclination angle is assumed to be 27° (Orosz et al., 2011).

: In a unit of $10^{37} \text{ erg s}^{-1}$ and in the energy range of 0.5-100 keV.

** : The fractional luminosity in *nthComp*, which is calculated from the disk luminosity L_{disk} and the Compton luminosity L_{nth} as $\frac{L_{\text{nth}}}{L_{\text{disk}} + L_{\text{nth}}}$.

that the NPSD in the low ($2 - 4$ keV) energy band is slightly larger than those in the $4 - 10$ and $10 - 20$ keV bands (figure 5.4 left, figure 5.5 left and table 5.3).

The newly obtained $10^{-7} - 10^{-4}$ Hz NPSD in the HSS is also approximated by a power law, and on an extrapolation of the NPSD previously obtained in frequencies above 10^{-4} Hz (Churazov et al., 2001; Cui et al., 1997). The NPSD ($\text{RMS}^2/\text{mean}^2 \text{ Hz}^{-1}$) in the HSS is about one order of magnitude larger than that in the LHS in $10 - 20$ keV. This differs from the case of other BH binaries reported by Miyamoto et al. (1993), although their data were limited to higher frequency range above 0.01 Hz. In the HSS, the NPSD from 10^{-7} Hz to 10^{-4} Hz has an energy dependence in such a way that it is $5 \sim 6$ times higher in the $10 - 20$ keV band than that in the low energy band ($2 - 4$ keV). This finding extends the results of energy dependence in $0.2 - 200$ Hz reported by Grinberg et al. (2014). These energy dependences of the long-term variation in the HSS were reconfirmed via the spectral analysis in section 5.2.

5.3.2 Comparison with short-term variability

Since the first discovery by Oda et al. (1971), the aperiodic fast X-ray variation of Cyg X-1 has been investigated by a number of authors (e.g., Negoro et al. (1994), Churazov et al. (2001)), mainly in the LHS and typically over $10^{-3} - 10^2$ Hz frequency range. Similar studies have been performed on other BH binaries as well, including in particular GX 339-4 (Maejima et al., 1984; Miyamoto et al., 1994). Given these, let us briefly compare the present studies with the previous results on the short-term variability of Cyg X-1.

Our results on the LHS has two similarities to the short-term variability in the same state. One is the PSD slope, which is ~ 1.4 over $10^{-7} - 10^{-2}$ Hz and ~ 1 in the $> 10^{-1}$ Hz range (figure 5.7). The other is the energy dependence; on both time scales, η decreases slowly towards higher energies, implying “softer when brighter” characteristic, which Cyg X-1 shows when it is above $\sim 1\%$ of the Eddington luminosity. For example, Grinberg et al. (2014) reported that the $0.125 - 256$ Hz variation of Cyg X-1 in the LHS is about twice higher in $2.1 - 4.5$ keV than in $5.7 - 9.4$ keV, in approximate agreement with our table 5.3. Also, the Suzaku result obtained in the LHS, namely, figure 8b of Makishima et al. (2008), reveals a similar energy dependence. These two resemblances altogether suggest a common mechanism working on these very wide range of time scales. For example, the higher short-term variability in softer energy bands may be a result of spectral softening as individual “shots” develop (Negoro et al., 1994; Yamada et al., 2013b). However, the phenomenon cannot be completely self-similar, since the PSD shows a considerable flattening over the $10^{-2} - 10^{-1}$ range.

The fast variability in the HSS has been considerably less studied than that in the LHS. Nevertheless, we can point out again two similarities between the long-term vs. short-term variations. One is that our NPSD index in the HSS (~ 1.3) is similar to the short-term HSS index of ~ 1 by Cui et al. (1997), as clearly seen figure 5.7. The other is the energy dependence; the slight increase of variability from the $4 - 10$ keV to $10 - 20$ keV ranges (subsection 5.1.6 and section 5.2) is also observed in short-term results by Grinberg et al. (2014). As already described, this “harder when brighter”

property is opposite to the behavior, “softer when brighter”, in the LHS.

5.3.3 Spectral variation

The energy spectrum in the LHS is known to be approximated by a power law with a high-energy cutoff around 100 keV (e.g., Makishima et al. (2008)). This is interpreted by a scenario that an optically-thick standard disk (Shakura and Sunyaev, 1973) is truncated at some distance from the BH and an optically-thin accretion flow (or a corona) is formed around the BH (Esin et al., 1997). High temperature electrons, in the optically-thin corona, up-scatter seed photons presumably from the outer standard disk. In this frame work, the fast hard X-ray variability in the LHS may be explained by considering that the corona covers a variable fraction of the disk (Makishima et al., 2008); when this fraction increases, the source gets brighter, and softer due to the enhanced Compton cooling of the corona. In fact, the MAXI spectrum accumulated over the LHS (figure 5.8 left) was described successfully with the two component model, consisting of a low-temperature *diskbb* (Mitsuda et al., 1984) representing the emission from such a truncated standard disk, and the *powerlaw* or the *nthComp* representing the Compton up-scattered component.

Like in many other reports on BH binaries in the HSS, the MAXI spectrum in the HSS has been expressed by a dominant optically-thick thermal spectrum, accompanied by a *powerlaw* component extending into higher energies. The former is again interpreted by an emission from a standard disk (Shakura and Sunyaev, 1973), which is now considered to extend down to the ISCO around the BH. This is supported by the fact that the obtained inner disk radii in the HSS do not differ significantly between the faint and bright periods. Like the overall hard X-ray emission in the LHS, the hard *powerlaw* component in the HSS could also be a Compton up-scatters component produced by some hot electrons (Cui et al., 1998; Gierliński et al., 1999), but details are still unclear.

In order to better understand the NPSD results, we fitted the spectra by a model composed of a *diskbb*, and the *powerlaw* or the *nthComp*, and studied how the spectrum changes as the source varies on frequencies range below 8×10^{-7} Hz. The obtained results, fully consistent with those from the NPSD studies, can be summarized into the following four points.

- 1 In both states, the *powerlaw* component is responsible for the observed long-term intensity variations, while the disk emission is essentially constant.
- 2 The power law component in the HSS is concluded to be more variable, on this frequency range, than that in the LHS.
- 3 The decreasing variability towards higher energies, observed in the LHS, can be attributed mostly to the “softer when brighter” property of the *powerlaw* component.
- 4 The variability increase with energies in the HSS results from a combination of the two effects, namely, the “harder when brighter” property of the *powerlaw* component in this state, and the presence of the stable disk emission at lower energies.

Similarly high long-term variations were observed also from some BH transients, including GS 1124–684 and GS 2000+25 (Ebisawa et al., 1994; Miyamoto et al., 1994; Terada et al., 2002). When their outburst decline was followed by sparse snap-shot observation with Ginga, the intensity of the disk component changed smoothly, but the power law component varied largely from one observation to the next. Thus, high long-term variability of the hard component in the HSS may be common to all BH binaries, including persistent and transient sources.

Chapter 6

Orbital Modulations in the low/hard and high/soft states

Contents

6.1	Folded Light Curves and Hardness Ratios	63
6.2	Phase resolved Spectral Analysis	65
6.2.1	Spectral ratio	65
6.2.2	Spectral model fitting	65
6.3	Discussion of the orbital modulation	66
6.3.1	Orbital Modulation	66
6.3.2	Density of stellar wind	68
6.3.3	Stellar wind model	71

The non-periodic variation was analyzed in Section. 5. In this section, we focused on the special long-term variation, the binary orbital period. From the observation of the orbital modulation, the information of the gas in the binary system, especially the behavior of the stellar wind from the companion star, is obtained. Although the observation in the HSS covering the 5.6 d orbital phase is obtained by the RXTE/ASM, the result was barely reported (Brocksopp et al., 1999a; Wen et al., 1999; Boroson and Vrtilek, 2010) because the statistic is poor. MAXI firstly succeeded observing Cyg X-1 in the HSS continuously for a year.

6.1 Folded Light Curves and Hardness Ratios

We use the orbital period $P_{\text{orb}} = 5.599829 \pm 0.000016$ d and an epoch of the inferior conjunction of the O-star $T_0 = 41874.207 \pm 0.009$ MJD which were obtained by Brocksopp et al. (1999b). Even if P_{orb} has the maximum error of 0.000016d, the difference of the orbital phase at the MAXI observation term is roughly 0.7% and it is much smaller than the phase bin of 0.1 in our analyses. The folded

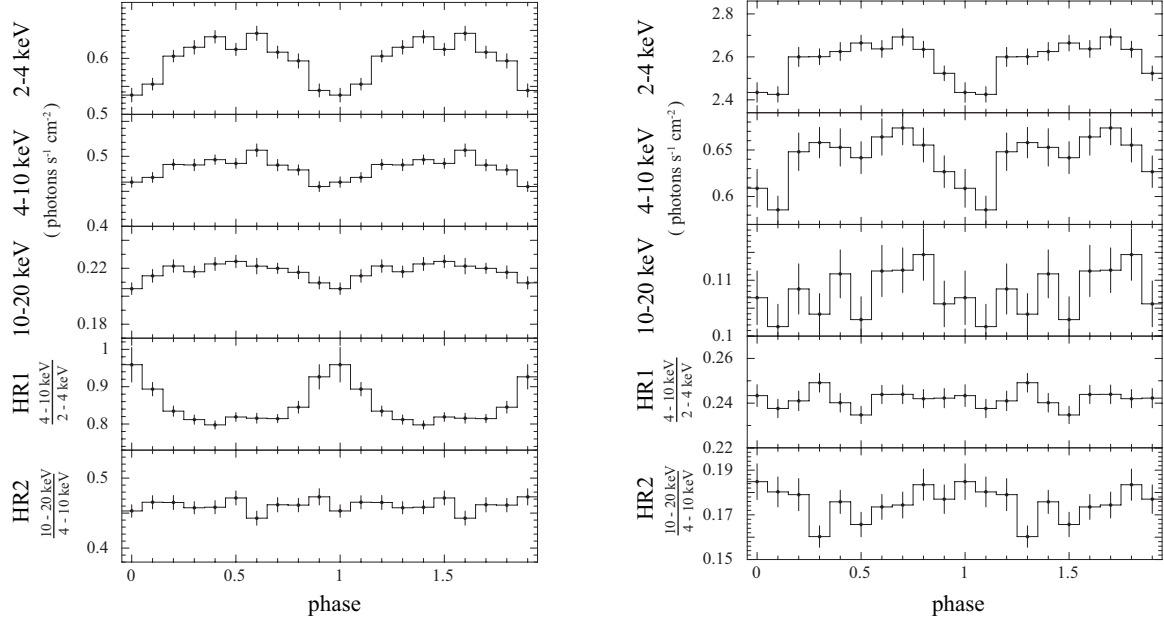


Figure 6.1: Folded light curves and hardness ratios in the LHS (left) and the HSS (right).

light curves and HRs are showed in figure 6.1. The data spans were the same to those of the power spectral analysis. The errors corresponded to standard deviations of the data in each phase. In the both states, the light curves, except for the 10 – 20 keV band in the HSS, showed clear modulation with a minimum around phase 0, which corresponded to a superior conjunction of the BH. It can be recognized that the modulation amplitude of the 2 – 4 keV band in the LHS is larger than others. To evaluate the modulation quantitatively, we fitted sine function to folded light curves and obtained the parameters of the amplitude and the average. Then, a modulation factor, MF , was defined as the ratio of the amplitude and the average. MF s of the three energy bands, in the LHS, are $8 \pm 1\%$ in 2 – 4 keV, $4 \pm 1\%$ in 4 – 10 and $3 \pm 2\%$ in 10 – 20 keV, respectively. Whereas those in the HSS are $4 \pm 1\%$ in 2 – 4 keV and $4 \pm 2\%$ in 4 – 10 keV. The data points in the 10 – 20 keV band in the HSS shows large scattering and we can find only the upper limit of MF of 4%.

The HR1, $I(4 - 10 \text{ keV})/I(2 - 4 \text{ keV})$, in the LHS showed clear hardening around phase 0, whereas it was not seen in the HSS. The HR2, $I(10 - 20 \text{ keV})/I(4 - 10 \text{ keV})$, did not show any significant spectral modulation, in the both states.

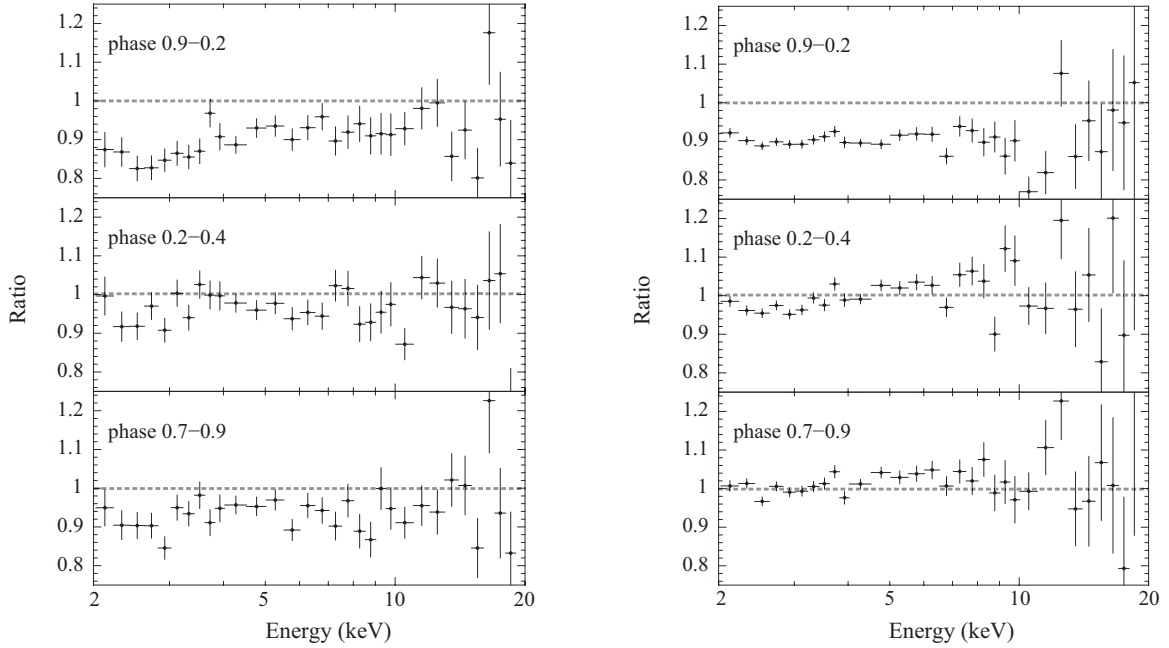


Figure 6.2: Spectral ratios in the LHS (left) and the HSS (right). The spectra in the three phases, 0.9 – 0.2, 0.2 – 0.4 and 0.7 – 0.9 were divided by that in the phase 0.4-0.7, for both states.

6.2 Phase resolved Spectral Analysis

6.2.1 Spectral ratio

We divided the orbital phase into four and extracted the energy spectra of the MAXI/GSC in each phase. The ratios of the spectrum in each phase to that of the spectrum in the phase between 0.4 and 0.7 were presented in figure. 6.2. In the LHS, the ratio of the phase 0.9 – 0.1 clearly showed significant decreasing in the low energy band below 3 keV, suggesting an increasing the photoelectric absorption. However, spectra in the other phases in the LHS, and all the phases in the HSS did not show an enhancement of the modulation in the low energy band, and rather showed a energy independent modulation.

6.2.2 Spectral model fitting

In order to parameterize the spectral modulation, we performed a model fitting of the extracted spectra. We divided the orbital phase into ten phase intervals and extracted ten spectra for each states and for each of the GSC and SSC. The GSC and SSC spectra cover 2 – 20 keV and 0.7 – 7 keV bands, respectively. We employed a model composed of a multi-color disk model (*diskbb*) (Shakura and Sunyaev, 1973; Mitsuda et al., 1984), a power law (*powerlaw*), and *gaussian* as a Fe-K emission

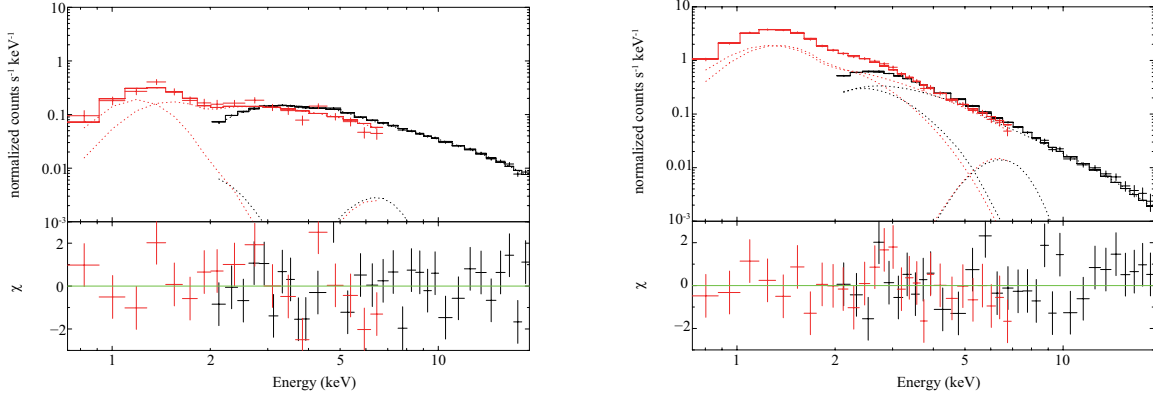


Figure 6.3: Spectra in the 0.0 – 0.1 in the LHS (left) and the HSS (right). The black and the red were the GSC and the SSC spectra, respectively.

line, with a photoelectric absorption (*phabs*). First, we fitted the model to all the spectra, by keeping all parameters to be free. In this case, the errors of the parameters were large and it was difficult to extract modulation properties. Then, we fixed the photon index and the inner disk temperature T_{in} at the mean value of all phases, because they were consistent with a constant according to the orbital phase within their errors. The normalization of *diskbb* was also fixed in the LHS, because they were all not significant and were consistent to be zero. The spectra in the phase 0.0 – 0.1 in the LHS and HSS were represented in figure 6.3, as well as the best fit models. The obtained parameters were shown in figure 6.4.

In the LHS the hydrogen column density N_{H} increased around phase 0, by changing from $5 \times 10^{21} \text{ cm}^{-2}$ to $7 \times 10^{21} \text{ cm}^{-2}$. On the other hand, it in the HSS did not increase around phase 0 and the variation was not more than $1 \times 10^{21} \text{ cm}^{-2}$. The modulation of the unabsorbed *powerlaw* flux was notable in both states, and their *MF*s were $3 \pm 2\%$ and $6 \pm 3\%$ in the LHS and HSS, respectively. The unabsorbed *diskbb* flux in the HSS shows large scattering, which makes difficult to recognize the orbital modulation with the *MF* less than 7%.

6.3 Discussion of the orbital modulation

6.3.1 Orbital Modulation

We first clearly detected the orbital modulation of the X-ray intensity in the HSS, which was an energy independent modulation with the *MF* of roughly 4% up to 10 keV. In the 10 – 20 keV band, data were not in-consistent with the same amount of modulation. On the other hand, in the LHS, an enhanced low energy modulation was notable below 3 keV, overlapping to the energy-independent modulation with *MF* of $\sim 3\%$. A reasonable interpretation is that the stellar wind is almost ionized

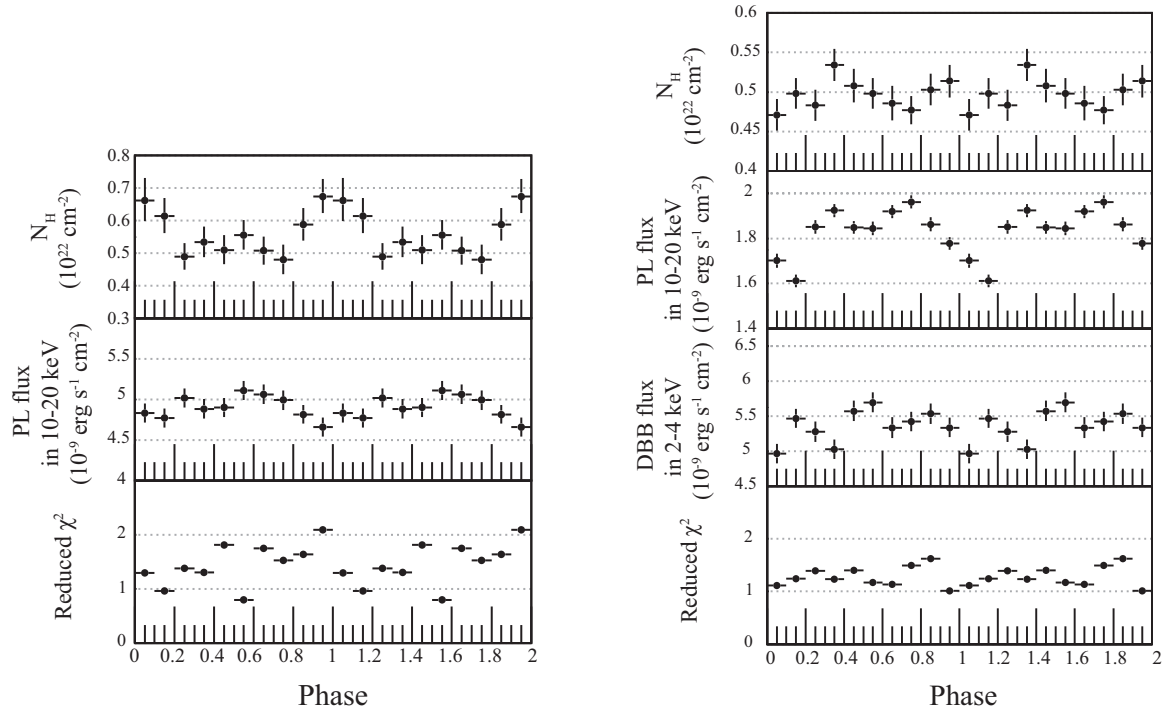


Figure 6.4: The parameter histories in the LHS (left) and the HSS (right). Photon indices and T_{in} were fixed at 1.65 and 0.2 keV in the LHS, and 2.9 and 0.5 keV in the HSS. The disk normalization was fixed at 5×10^5 in the LHS.

and electron scatterings by the ionized wind make the energy independent modulation. In the LHS, however, the wind in the line of sight at the superior conjunction of the BH is not ionized enough and the photoelectric absorption is observed.

This is consistent with the interpretation of the absorption dip of Cyg X-1, which are observed around the phase 0, in the LHS. Our data showed the increase of N_{H} of $2 \times 10^{21} \text{ cm}^{-2}$ around the phase 0 in the LHS. This value was, however, smaller than the previous reports of the absorption dips, for example, $5 \times 10^{22} \text{ cm}^{-2}$ as reported by Grinberg et al. (2015). It is also known that the dip depth and the dip duration have wide variety (Bałucińska-Church et al., 2000) and it does not always occur in the superior conjunction (Kitamoto et al., 1984). The parameter obtained by our MAXI observation should be recognized to be a kind of averaged value of N_{H} , among various snapshot-samplings around the superior conjunction of the BH, with a variety of high density region in their size and density. Feng and Cui (2002) reported that two kind of dips were seen in the LHS. One shows a strong energy-dependent attenuation with spectral hardening, and another shows an energy-independent attenuation. This indicates that the variety also exists in their degree of ionization.

Yamada et al. (2013a) reported a detection of a dip during the HSS of Cyg X-1, which shows a spectral hardening. They reported the detection of the absorption lines of highly ionized irons around the phase 0, and its equivalent width became large during the dip. This indicates that the wind is roughly ionized in the HSS, but some blob-like structure with high density may still enhance the low energy absorption in a short time, and make the “so-called” absorption dip with a spectral hardening. Since our data did not show the increase of the N_{H} around phase 0 in the HSS, we should consider that the “so-called” absorption dip is rare in the HSS.

Using the long observation with MAXI, we could estimate the probability, p_{dip} , of the dip in the orbital phase between 0.95 and 1.05 in the LHS. We assumed the amount of the absorption to be $N_{\text{H}} = 5 \times 10^{22} \text{ cm}^{-2}$ by referring Grinberg et al. (2015). Then, the absorbed flux, in the energy band between 2 keV and 4 keV, was reduced to about a half, from $2.5 \times 10^{-9} \text{ erg s}^{-1} \text{ cm}^{-2}$ to $1.2 \times 10^{-9} \text{ erg s}^{-1} \text{ cm}^{-2}$. In order to explain the observed intensity decrease of 5% by the photoelectric absorption, p_{dip} was estimated to be ~ 0.1 .

6.3.2 Density of stellar wind

The wind properties have been investigated with optical and ultra violet observations (Herrero et al., 1995; Vrtilek et al., 2008; Orosz et al., 2011). In this work, we used wind parameters reported by Vrtilek et al. (2008), and the inclination reported by Orosz et al. (2011). The used parameters are listed in table 6.1. We examined whether the $3 \sim 4\%$ modulation can be explained with electron scattering with the reasonable parameters. If we assume that the wind is spherically symmetric, the wind density, $n(r)$, at the distance, r , from the companion star, can be expressed as,

$$n(r) = \frac{\dot{M}}{4\pi m_{\text{H}} v(r) r^2} \quad (6.1)$$

Table 6.1: Parameters used in calculation.

Parameter	Value	Reference
Mass loss rate ($\dot{M}_0$)	$\sim 5 \times 10^{-6} M_\odot \text{ yr}^{-1}$	(Vrtilek et al., 2008)
Terminal velocity ($v_{\infty,0}$)	$\sim 1400 \text{ km s}^{-1}$	(Vrtilek et al., 2008)
β of the CAK* wind model	~ 0.75	(Vrtilek et al., 2008)
Stellar radius (R_*)	$\sim 1.5 \times 10^{12} \text{ cm}$	(Vrtilek et al., 2008)
Separation of the binary (a)	$\sim 3.0 \times 10^{12} \text{ cm}$	(Vrtilek et al., 2008)
Inclination of the binary (i)	27.1°	(Orosz et al., 2011)

* Castor et al. (1975)

where, $\dot{M}$ is the mass loss rate as the stellar wind, m_H is the mass of the hydrogen atom and $v(r)$ is the wind velocity. If we assume the ionization fraction of Hydrogen to be κ , the electron column density, N_e can be calculated as,

$$N_e = \int_0^\infty \kappa(l)n(l)dl \quad (6.2)$$

where the integral is performed along the line of sight, dl , from the BH to the observer. If we approximate the wind velocity as a constant value with the terminal velocity, v_∞ , and the ionization fraction $\kappa(l)$ is constant as κ_0 , the integral can be reduced as,

$$\begin{aligned} N_e &= \frac{\dot{M}\kappa_0}{4\pi m_H v_\infty} \frac{\pi - \chi}{a \sin \chi} \\ \cos \chi &= \sin i \cos \theta \end{aligned} \quad (6.3)$$

where χ is the angle between the line of sight and the line joining the centers of two stars, represented as $\cos^{-1}(\sin i \cos \theta)$, i the inclination angle and θ the orbital phase. Since the wind condition may change between two states, we introduce a parameter $\eta = \kappa_0 \frac{\dot{M}/\dot{M}_0}{v_\infty/v_{\infty,0}}$, where $\dot{M}_0$ and $v_{\infty,0}$ are the values as listed in table 6.1.

Using parameters listed in table 6.1 and the Thomson scattering cross section, σ_T , we can calculate an optical depth for the electron scattering. The intensity variation can be roughly expressed as; $I = I_0 \exp(-N_e \sigma_T)$, as long as the optical depth is small, where I_0 is the original intensity from near the BH. In figure 6.5, the expected light curves were plotted as well as the observed folded light curves, for the several cases (0.5, 1, 2, 5) of the parameter η . All the curves were adjusted to be one at the peak intensity.

Except for the light curve in the energy range 2 – 4 keV in the LHS, the light curves were able to be simulated with the parameter $\eta = 2.0$ ($N_e \sim 2.5 \times 10^{23} \text{ cm}^{-2}$), in both states. This suggests that the stellar wind parameter, η , does not change between the two states within the precision of our observation. The notable discrepancy was seen around the phase 0 in the LHS. This is considered to be due to the “so-called” absorption dip, which is caused by a large photoelectric absorption. Therefore,

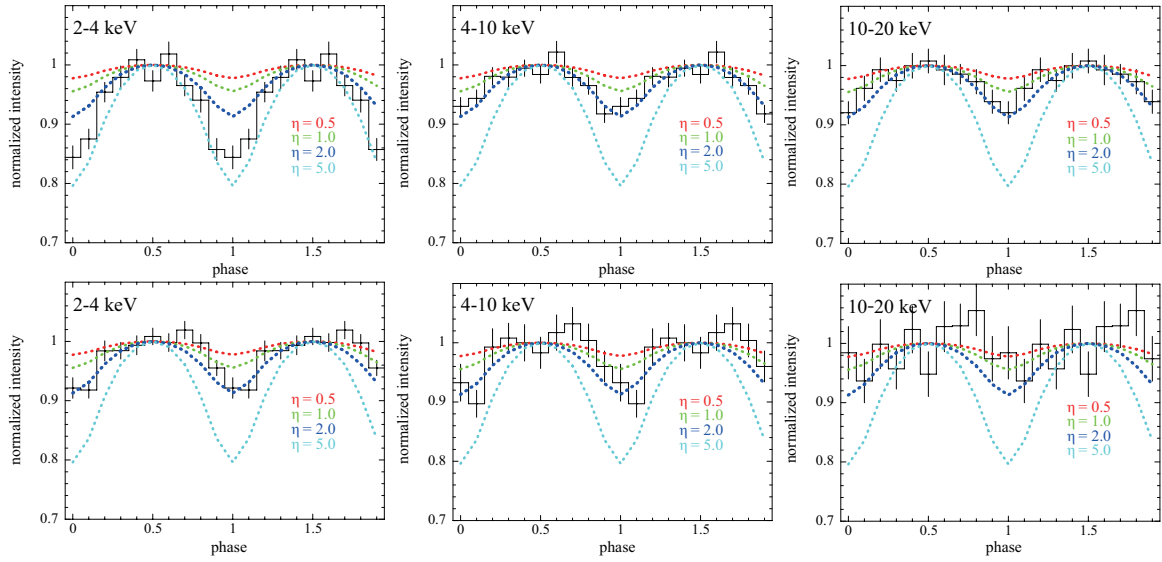


Figure 6.5: The expected light curves for four values of parameter η . The observed folded light curves were also potted. All the light curves were adjusted to be one at the peak intensity.

the difference of the stellar wind condition, between the LHS and HSS, is just the ionization state on the line of sight around the phase 0.

6.3.3 Stellar wind model

The ionization should be due to the photoionization by intense X-rays from near the BH. In such a case, the ionization state can be estimated by the ionization parameter, $\xi = \frac{L_x}{nr^2}$, where L_x is the X-ray luminosity of the compact source, n is the ion density and r is the distance from the compact source (Tarter et al., 1969). According to the calculation of the model 6 and 7 by Kallman et al. (1987), an ionization front of the He can be seen around $\xi \sim 30$. Thus if ξ exceeds 30, the majority of the metal is ionized, but if ξ is less than 30, substantial amount of the metal is not ionized and the absorption by metal becomes notable.

From the fitting result of the energy spectrum, we obtained that the luminosity in $0.7 - 7$ keV was 0.4×10^{37} erg s $^{-1}$, and 2.4×10^{37} erg s $^{-1}$, for the LHS and HSS, respectively. This six times difference of the luminosity should make the difference of the ionization state of the wind, between the two states. On the other hand, we considered that the energy independent intensity modulation is caused by the electron scattering and the parameter η is about 2 for the both states. Although we had an un-known parameter, κ , we assumed that $\kappa = 1$, because we did not observe an orbital modulation of the photo-electric absorption except for the phase 0 of the LHS. Then we could estimate the ionization parameter at the nearest point to the companion star along the line of sight at the phase 0, using the parameters listed in the table 6.1 and the η of 2, as;

$$\xi \sim 500L_{x,38}, \quad (6.4)$$

where $L_{x,38}$ is the X-ray luminosity with an unit of 10^{38} erg s $^{-1}$. Therefore the wind is ionized well at the point in the HSS ($L_{x,38} \sim 0.24$). In the LHS ($L_{x,38} \sim 0.04$), however, a delicate balance between the luminosity and the density leads large variation of the ionization state around the phase 0. Various high density blobs, in an inhomogeneous wind, work as photoelectric absorbers around the superior conjunction of the BH, and cause the various dips in the LHS. In the other phase, most of the wind in the LHS, as well as the HSS, is ionized, and this is consistent to the high resolution observation in the LHS (Miškovíková et al., 2016).

Chapter 7

Discussion

Contents

7.1	Summary of the observation results	72
7.2	Time scale of the variation	74
7.3	Mass accretion rates through optically-thick accretion disk and corona .	74
7.4	X-ray irradiation	75
7.5	Origin of the long-term variation	82

7.1 Summary of the observation results

We analyzed the observational data with MAXI to study the long-term variation of Cyg X-1. The investigation of that in the HSS has succeeded for the first time. We also investigated the difference of the variability between the LHS and HSS by focusing to the following two properties:

1. Aperiodic variability
2. Modulation with the orbital period

For the analysis of the aperiodic long-term variability, we calculated the NPSDs in the frequency range of $10^{-7} - 10^{-4}$ Hz using the three band (2 – 4, 4 – 10 and 10 – 20 keV) data accumulated by MAXI over six years. The following results were obtained.

- The NPSD extends with a single index from 10^{-3} to 10^{-7} Hz, as a power law function, in both the LHS and HSS.
- In the HSS, the NPSD is about one order of magnitude larger than that in the LHS in 10 – 20 keV.
- In the LHS, the fractional RMS variation, η , defined by equation (5.7), weakly decreased towards higher energies. On the other hand, in the HSS, η was found to increase significantly with energy.

- The long-term variation is mostly caused by *powerlaw* component.

From the analysis of the orbital variability in the LHS and HSS, we detected, for the first time, an intensity modulation with the orbital period in the HSS as well as that in the LHS. The following results were obtained.

- In the LHS and HSS, the 5.6 d orbital modulations were seen both in the light curves with roughly 4%, except for the 2–4 keV band in LHS. In both stats, energy independent modulation is found and it is interpreted as the modulation of the *powerlaw* component. This energy independent modulation can be explained by a scattering by the stellar wind, implying that the stellar wind is almost ionized in the both states.
- In 2 – 4 keV of the LHS, the modulation was larger than those in other bands and is about 8%. It means that, in around phase 0, when the line of sight passes through the nearest region of the companion star, we see the gas which is not enough ionized.
- These conditions can be explained by an inhomogeneous stellar wind.

Based on these results, we discuss the accretion model, which can generate the long-term variation in the X-ray intensity, and the origin of the variation.

7.2 Time scale of the variation

Most of the X-rays are radiated from the vicinity of the BH. Also the fluctuating component is mainly the power law component, which is generally considered to be caused by the inverse Compton scattering within $\sim 10r_{\text{S}}$. On the other hand, the time variation newly produced at any radius is considered to be caused by the dynamical or the thermal phenomena, whose time scales are t_{d} and t_{th} , respectively. These time scales can be expressed as (see also section 2.3),

$$\begin{aligned} t_{\text{th}} &= (\alpha\Omega_{\text{K}})^{-1}, \\ t_{\text{d}} &= (\Omega_{\text{K}})^{-1}. \end{aligned} \quad (7.1)$$

Ω_{K} is the Keplerian angular velocity at radius, r , from the BH and α is the viscosity parameter. At $r = 10r_{\text{S}}$, assuming a standard disk with $\alpha = 0.01$ and $M_{\text{BH}} = 15M_{\odot}$, the time scales are calculated as $t_{\text{d}} \sim 10^{-3}$ sec and $t_{\text{th}} \sim 10^{-1}$ sec. Therefore we consider that the long-term variation is produced at large radius and is propagated inward as a variation of the mass accretion rate. Eventually the X-ray radiated from the vicinity of the BH reflects such a time scale. For example considering the thermal phenomenon, it can produce variation of $\sim 10^{-7}$ Hz at the radius $r = 3 \times 10^{12}$ cm ($= 6 \times 10^5 r_{\text{S}}$).

Such variations, however, can propagate toward the center only if their time scales are longer than the viscous time scale, given as $t_{\text{v}} = (\alpha\Omega_{\text{K}})^{-1}(r/H)^2$, where H is the disk half thickness. In an optically-thick and geometrically-thin disk, this t_{v} is much longer than t_{th} and t_{d} because $H \ll r$. Therefore, variations in $\dot{M}$ produced at any outer radii, being strongly dissipated, would not propagate down to the X-ray emitting region, in generally considered accretion disk models, where the standard accretion disk exists at the outer disk in both the states (see section 2.3).

However, if some fraction of $\dot{M}$ streams through a geometrically-thick ($H \sim r$) and optically-thin flow, in which we expect $t_{\text{v}} \sim t_{\text{th}}$, the fluctuations produced at various larger radii can propagate inwards, and cause the X-ray intensity to vary on a wide range of time scales. This idea was invoked by Churazov et al. (2001) to explain the X-ray variations on timescales down to 10^{-4} Hz. We extend this two-flow scenario from the time scale of 10^{-4} Hz to 10^{-7} Hz, where the optically-thin flow starts at $\sim 3 \times 10^{12}$ cm ($\sim 6 \times 10^5 r_{\text{S}}$). The optically-thick part is identified to the standard accretion disk, and the optically-thin part is expected to develop into the Comptonizing corona in a vicinity of the BH. It should be noted that the self similar structure of the accretion disk is suitable to explain the power law type time variation.

7.3 Mass accretion rates through optically-thick accretion disk and corona

Utilizing schematic drawings in figure 7.1, we examine an accretion model of Cyg X-1 that can explain our results. The optically-thick accretion disk (thick black line) is assumed to extend from outer regions inward, but is truncated at a certain radius in the LHS. Meanwhile, in the HSS, it is thought

to extend down to the ISCO. In both states, the optically-thin flow is assumed to extend from an outer region ($\sim 6 \times 10^5 r_S$) to the ISCO. The observed low frequency variations of the mass flow are assumed to be generated at large radii, and propagate through the optically-thin flow to the vicinity of the BH to make the hot corona vary on these long time scales.

After Churazov et al. (2001), let us consider mass accretion rate through the optically-thick disk, $\dot{M}_d$, and through the optically-thin flow, $\dot{M}_c$. The total accretion rate is given as $\dot{M}_t = \dot{M}_d + \dot{M}_c$. We further assume that the Comptonized component in the energy spectrum is mainly powered by $\dot{M}_c$, while the disk emission by $\dot{M}_d$. Let us describe fractional variations in $\dot{M}_c$ and $\dot{M}_d$ as f_c and f_d , respectively, and assume that these quantities depend neither on the frequency nor on the spectral state. Then, the observed normalized power should be proportional to $[(f_c \dot{M}_c)^2 + (f_d \dot{M}_d)^2] / (\dot{M}_t)^2$. When the optically-thick flow is not variable, f_d is equaled to zero.

In the LHS, the optically-thick accretion disk is truncated at a certain radius, and within that radius, only the optically-thin flow exists ($\dot{M}_t = \dot{M}_c$; Churazov et al. (2001)). Then, since the time variation above 0.1 Hz originates only from the optically-thin flow, the normalized power of this range is f_c^2 itself; $\text{NPSD} = f_c^2$. On the other hand, in the frequency less than 10^{-3} Hz the NPSD is roughly $\frac{1}{25}$ of the extrapolation of the NPSD above 0.1 Hz. Therefore $[(f_c \dot{M}_c)^2 / (\dot{M}_t)^2]_{\text{LHS}} = \frac{1}{25} f_c^2$, where $f_d = 0$ is assumed. The suffix LHS specifies the states. Since we assume that f_c is independent of frequency, we obtain $[\frac{\dot{M}_c}{\dot{M}_t}]_{\text{LHS}} \sim \frac{1}{5}$, and hence $[\frac{\dot{M}_d}{\dot{M}_t}]_{\text{LHS}} \sim \frac{4}{5}$.

Similar arguments can be performed on the HSS. In the low frequency region below 10^{-4} Hz, the normalized power of the HSS, $[(f_c \dot{M}_c)^2 / (\dot{M}_t)^2]_{\text{HSS}}$, is about six times larger than that in the LHS, $[(f_c \dot{M}_c)^2 / (\dot{M}_t)^2]_{\text{LHS}} = \frac{1}{25} f_c^2$ (see figure 7.1). Since we assume that f_c does not depend on the states, $[(f_c \dot{M}_c)^2 / (\dot{M}_t)^2]_{\text{HSS}} = \frac{6}{25} f_c^2$. Then, $[\frac{\dot{M}_c}{\dot{M}_t}]_{\text{HSS}} = \sqrt{\frac{6}{25}} \sim \frac{1}{2}$, and hence $[\frac{\dot{M}_d}{\dot{M}_t}]_{\text{HSS}} \sim \frac{1}{2}$. These values are supported by the fact that the luminosity of the disk component is roughly the same as that of the Comptonized component in the HSS (see table 5.6). The inferred fractions of the mass accretion rate through the assumed two flows are summarized in figure 7.2.

7.4 X-ray irradiation

It is not clear that why the corona extends up to very outer region of the accretion disk. In the LHS the mass accretion rate is small, and the radiative cooling is insufficient against the heating in the inner region of the standard disk ($r < 10 r_S$), and hence the disk becomes high temperature. In this region, the radiative pressure P_{rad} is dominant and the disk becomes like a corona (Fukue, 2007). In the outer region, the cooling is dominant, and the disk is usually thought to be the standard disk. In the HSS, the disk is mainly constructed by the standard optically-thick disk, with some corona in $r < 10 r_S$. Galeev et al. (1979), however, proposed a magnetized disk model with variable coronal loops suspended by the magnetic field. The magnetic field is amplified by the differential rotation of the accretion disk, and then, the magnetic loop formed in the disk randomly produces the corona. However, it is not clear whether this process can work in the very outer region of the accretion disk.

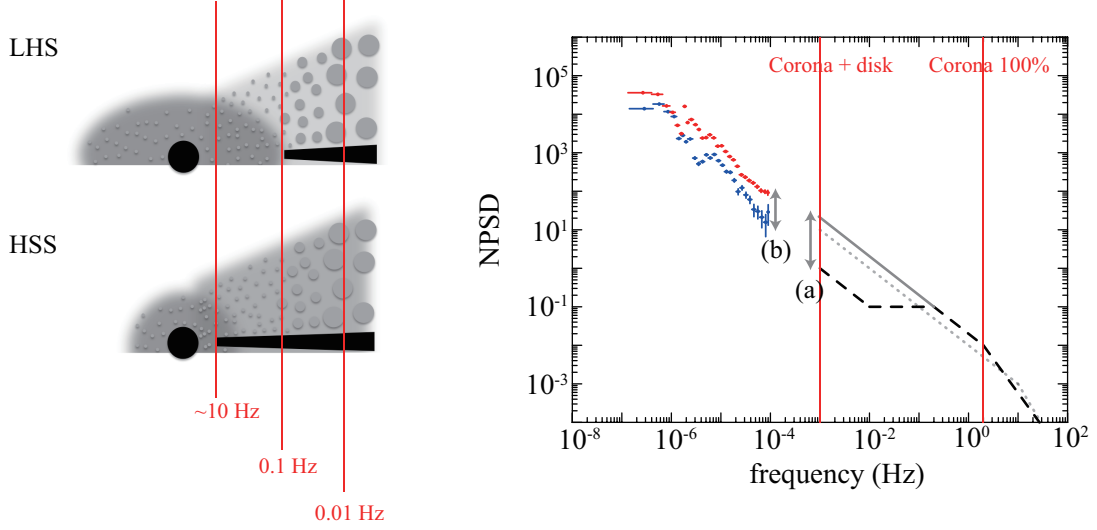


Figure 7.1: Illustrations of accretion models (left) and the NPSD which is same as figure 5.7. Red lines show time-scales which correspond to breaks in the NPSD. (a) Focusing on the NPSD in the LHS in the high frequency, in the frequency less than 10^{-3} Hz (corona + disk), the NPSD is roughly $\frac{1}{25}$ of the extrapolation of the NPSD above 0.1 Hz (corona only). (b) Focusing on the NPSD in the LHS and HSS in the low frequency, below 10^{-4} Hz, the normalized power of the HSS is about six times larger than that in the LHS.

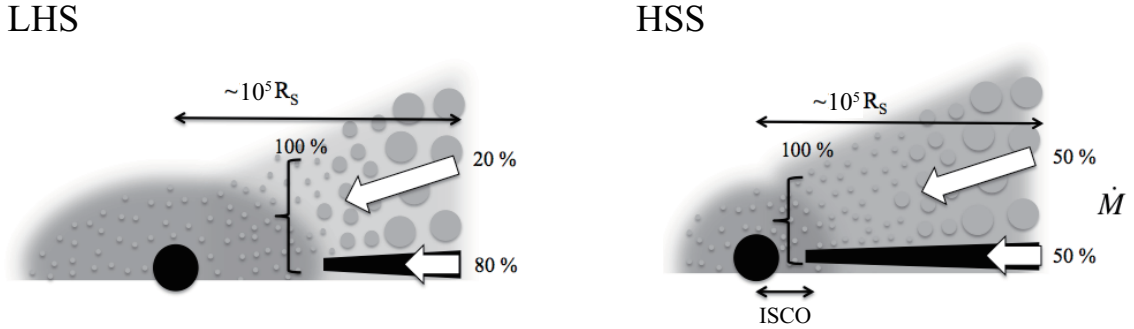


Figure 7.2: Illustrations of accretion models in the LHS (left) and in the HSS (right). The optically-thick accretion disk is shown with a thick black line, which is truncated at a certain radius in the LHS, but extends down to the ISCO in the HSS. In both states, the optically-thin flow extends up to $\sim 10^5 r_s$, while it turns into the Comptonizing corona at small radii. The percentages mean the fractional mass accretion rate in each state.

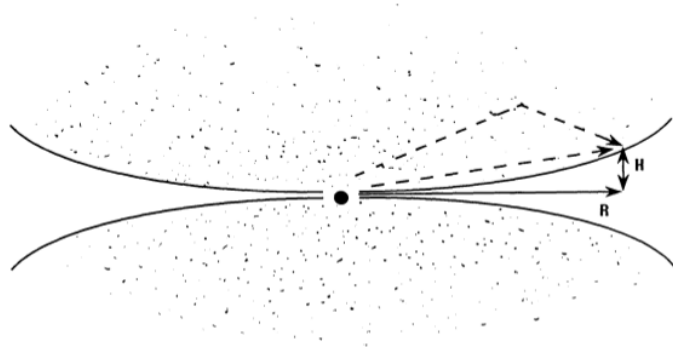


Figure 7.3: A simple schematic of a model of an irradiated accretion disk in figure 1 in Ko and Kallman (1991).

There is another idea for producing the corona where the X-ray irradiation from the vicinity of the BH heats the surface of the disk (Liang and Price (1977); Bisnovaty-Kogan and Blinnikov (1977); Hayakawa (1981), see figure 7.3). This X-ray irradiation model can influence at large radius. In the following, we discuss whether the model can explain our observation.

The effect of the X-ray irradiation is important at large radius in the disk (Hayakawa, 1981; Tuchman et al., 1990; Mineshige et al., 1990; Jimenez-Garate et al., 2002), as explained below. In the standard disk, the energy source is the frictional heat occurring when the mass accretes. The viscous heating rate, Q_{vis} , is expressed in equation (2.8) as,

$$Q_{\text{vis}} = \frac{3GM_{\text{BH}}\dot{M}}{4\pi r^3} \left(1 - \sqrt{\frac{r_{\text{in}}}{r}}\right). \quad (7.2)$$

Here, r is a distance from a central compact star, M_{BH} is the mass of the BH and $\dot{M}$ is the mass accretion rate. Defined that the fraction of energy which is used for heating the disk among the incident X-ray, f , the heating rate by X-ray irradiation Q_{X} is represented as,

$$Q_{\text{X}} = \frac{fL_{\text{X}}}{4\pi r^2} = \frac{f\eta\dot{M}c^2}{4\pi r^2}. \quad (7.3)$$

Here, we defined $L_{\text{X}} = \eta\dot{M}c^2$. Because Q_{X} is proportional to r^{-2} and Q_{vis} is proportional to r^{-3} , it is clear that the X-ray irradiation should be important at large radius from the BH. We assumed the parameters for Cyg X-1, $M_{\text{BH}} = 14.8M_{\odot}$, $\dot{M} = 5 \times 10^{-6}M_{\odot} \text{ yr}^{-1}$, $f = 0.1$ and $\eta = 0.1$. The relationship between r and Q_{vis} and Q_{X} were shown in figure 7.4. Therefore the heating by the X-ray irradiation is dominant in the region $r > 70r_{\text{S}}$, where r_{S} is the Schwarzschild radius.

The surface matter on the X-ray irradiated disk evaporates. The evaporating gas has a high temperature but it will cool down by expansion and a thin-density corona is formed (Tuchman et al., 1990). If the disk has a convection, the irradiation affects not only the surface but also a gas in a

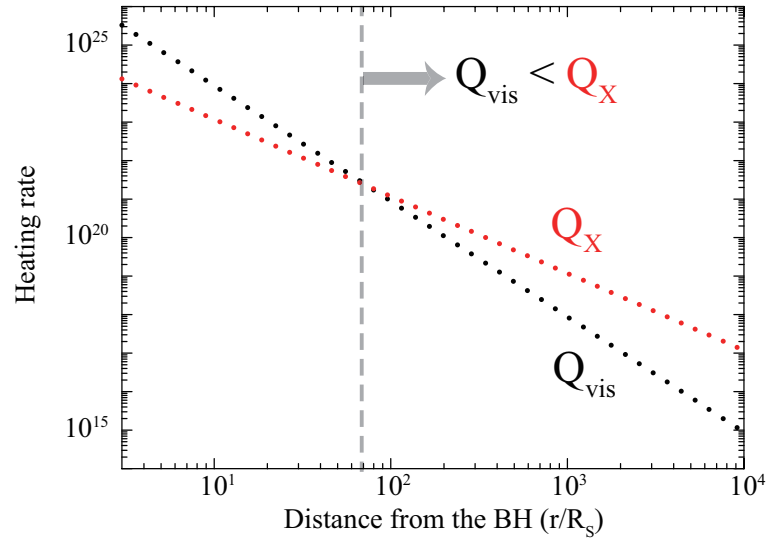


Figure 7.4: The heating rate per unit area Q_{vis} and Q_X . r is divided by Schwarzschild radius.

substantial depth, and such the disk gas efficiently evaporates by the X-ray irradiation, and relatively high-density corona is formed (Ko and Kallman, 1991).

The temperature of the X-ray irradiated disk is roughly determined by the balance between the plasma heating by the Compton scattering and the cooling by the inverse Compton scattering. Using the average energy of the photon, $\langle E \rangle$, the temperature of the optically thin plasma, kT_{comp} satisfies the following equation;

$$\frac{4kT_{\text{comp}}}{m_e c^2} \langle E \rangle = \frac{\langle E \rangle^2}{m_e c^2}. \quad (7.4)$$

Expressed the photon spectrum as $F(E)$, $\langle E \rangle$ is represented as,

$$\langle E \rangle = \frac{\int E F(E) dE}{\int F(E) dE}. \quad (7.5)$$

When we put the energy spectrum of Cyg X-1 into $F(E)$, kT_{comp} becomes around a few keV ($\sim 10^7$ K). Jimenez-Garate et al. (2002) had detail calculation considering more realistic plasma process, emission lines and a photoelectric absorption (see figure 7.5). The corona temperature becomes $\sim 3 \times 10^6$ K at height/radius ~ 1 around radius of 10^{11} cm, and, at larger radius of $\sim 10^{12.5}$ cm, is rather lower than this temperature.

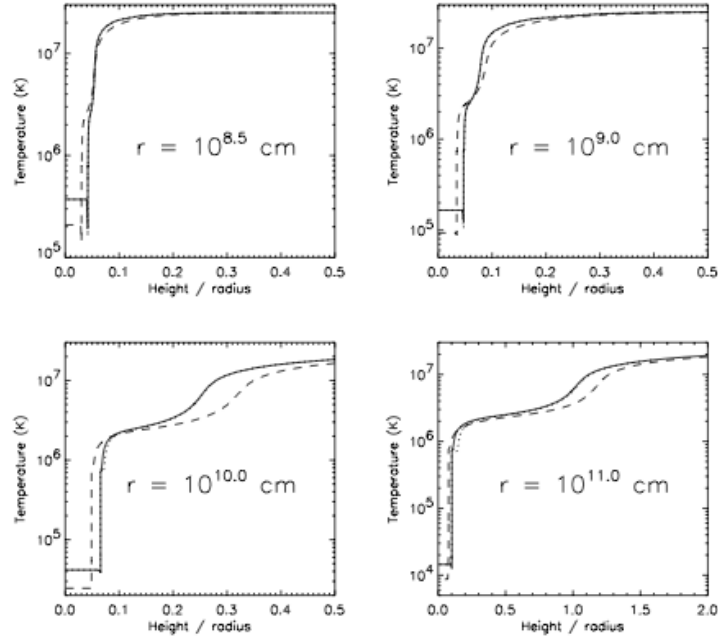


Figure 7.5: The modeled temperature for the normalized disk height (z/r) with various radius r calculated by Jimenez-Garate et al. (2002).

Since the plasma is irradiated by the X-rays from the central region, the plasma get a momentum toward radial direction from photons and might be blown off from the accretion disk, like an accretion

disk wind (Ohsuga and Mineshige, 2011). However, in the case of Cyg X-1, the luminosity is about 10^{37} erg sec $^{-1}$, which corresponds to a few percent of the Eddington luminosity. Therefore the effect of the blowing off is expected to be small, although a part of plasma might be blown away. In addition, we should confirm that the plasma temperature is smaller than the temperature which corresponds to the gravitational binding-energy. The escape radius, r_{esc} , where the gravitational energy equals to the thermal energy of the plasma with its temperature, T , can be calculated as,

$$r_{\text{esc}} = \frac{2GM_{\text{BH}}m_{\text{p}}}{3kT}. \quad (7.6)$$

Here, m_{p} is the mass of a proton and k is the Boltzmann constant. By inserting $M_{\text{BH}} = 14.8M_{\odot}$ and $T = 5 \times 10^6$ K, r_{esc} is obtained as $\sim 5 \times 10^{12}$ cm. Although the plasma, outside of the r_{esc} , can not be confined by the gravity and can spontaneously escape by their thermal motion, the most of the plasma evaporated by the X-ray irradiation in the radius of 5×10^{12} cm forms an optically thin disk.

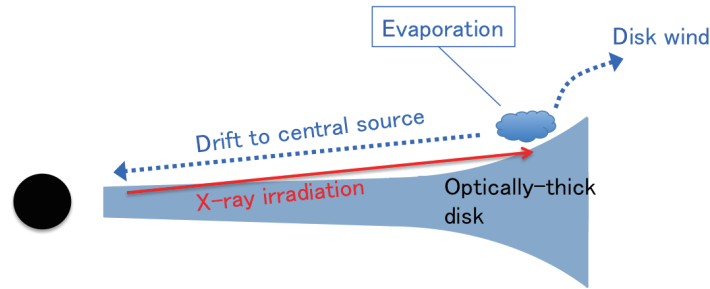


Figure 7.6: The schematic description of the evaporated plasma by the X-ray irradiation. Most of the evaporated plasma forms a thin disk, but a part of it becomes a disk wind.

The mass flow rate through the optically-thin disk can be estimated as follows. Jimenez-Garate et al. (2002) calculated the density distribution as a function of the thickness of the corona (optically-thin disk). Some examples are shown in figure 7.7. At $r = 10^{11}$ cm, the density around $H/r \sim 1$ (i.e. the height is equal to the radius from the compact star) is roughly five order of magnitude smaller than the central density. On the other hand, the radial velocity toward the central object, which can be estimated by $\alpha(H/r)^2$, in the optically-thin disk is roughly four order of magnitude larger than that in the optically-thick standard disk, because H/r is roughly 1 and 0.01 and the viscous parameter, α , is roughly 0.1 and 0.01. Furthermore, H of the corona is hundred times larger than that of the optically-thin disk. Therefore it is expected that the flux flowing in the corona is as same as that in the standard disk. Especially in the HSS, the irradiation from the central region is strong so that the flux along the optically-thin disk probably becomes prominent.

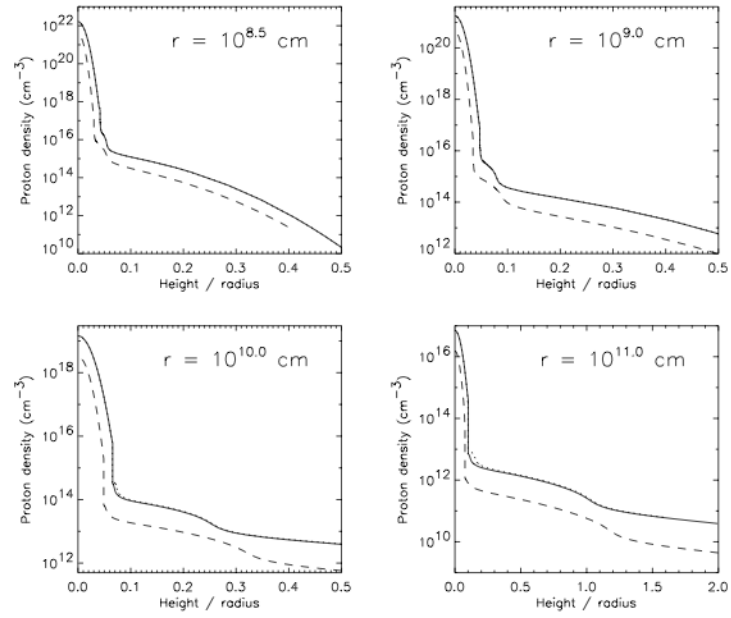


Figure 7.7: The modeled proton density for the normalized disk height (z/r) with various radius r calculated by Jimenez-Garate et al. (2002).

7.5 Origin of the long-term variation

We explained in section 7.2 that, when the corona is formed on the accretion disk for some reasons such as the X-ray irradiation, the variations of the mass accretion rate produced at large radius propagate into an inner region of the accretion disk. And then, X-rays, which are radiated from the vicinity of the BH, fluctuate. In order to create a powerlaw-shaped PSD, variations in various time scales should be mixed and hence variations should be produced at various places in the accretion disk without any particular radius. Here, we discuss what is the origin of the time variation.

Mineshige et al. (1994) proposed a Self-Organized Criticality (SOC), which is a mechanism for creating the powerlaw-shaped PSD in the disk. This model is explained through a sand-pile model (SP model) as an example. The quotation of Mineshige et al. (1994) is written as follows;

“Let us consider a circular table. As sand grains are dropped onto the table one after one to randomly chosen positions on the mountain side, the sand grains will heap up and finally come to construct a sand mountain with an ‘ exposure angle of slope ’. If we still continue to add sand grains, so-called avalanche would occur in the system. The size of the avalanche varies depending on the case.”

They considered that the X-ray is radiated with the energy which the mass accreted by the SP model releases. However, since the relation of the time-scales is estimated as $t_{\text{drift}} \sim t_{\text{vis}} \gg t_{\text{th}} > t_{\text{d}}$, this model also can not create the long-term variation. If the accretion disk is not smooth but clumpy, the time-scale which a blob accretes is represented as,

$$t_{\text{blob}} \sim \frac{r}{\alpha c_s}, \quad (7.7)$$

then the time scale which is proportional to the radius r can be created. It leads the variation having the shape of the power law in the PSD. We consider that, as explained in section 7.4, if there is the corona on the disk, the variation produced at large radius can be propagated inward. Since the SP model by Mineshige et al. (1994) is constructed assuming $r < 10r_s$, it only deals with the short time scale less than a few seconds. We expand this model to outer radius of the disk. If the random drop of the sand grain onto the sand mountain (i.e. accretion disk) by the SP model occurs far from the BH, the disk will be disturbed and an efficient evaporation and a fast mass accretion through the corona is expected.

Cyg X-1 has the wind accretion, and the focused wind model is proposed (Gies and Bolton (1986); Friend and Castor (1982), figure 2.9). The stellar wind from the companion star is focused on the BH and falls onto the accretion disk within the range $9^\circ \sim 23^\circ$ from the axis connecting the BH and the companion star (Friend and Castor, 1982). In this model, the stellar wind having the various amounts of angular momentum arrives at the disk, unlike the Roche lobe over flow.

Furthermore, by the study of the 5.6 d orbital modulation (Sugimoto et al., 2016 in prep.) and previous works of the dips (Kitamoto et al., 1984; Feng and Cui, 2002; Grinberg et al., 2015) it is known that the stellar wind is clumpy and contains blobs. Therefore, we can expect that the blobs hit the disk at the various radii and the disk is disturbed constantly. Sugimoto et al. (2016 in prep.) and Grinberg et al. (2015) reported that the column density of the blob is $10^{22 \sim 23} \text{ H atoms cm}^{-2}$. The size of the

blob is estimated as $10^{8\sim 10}$ cm from the observed dip duration and the assumed velocity (Kitamoto et al., 1984). On the other hand, the surface density of the standard disk is $\Sigma \sim 30 \text{ g cm}^{-2}$ ($\sim 2 \times 10^{25}$ Hatoms cm^{-2}) at the radius $r \sim 10^5 r_S$ (3×10^{11} cm) (Fukue (2007), and see figure 2.5). Furthermore, the orbital velocity of the gas in the accretion disk around the BH is $v_\phi = 10^8 \left(\frac{M_{\text{BH}}}{10 M_\odot}\right)^{1/2} \left(\frac{r}{10^{11}}\right)^{-1/2}$, which is the same order with that of the wind, 10^8 cm s^{-1} (Vrtilek et al., 2008). As a result, the accretion disk suffers disturbances with roughly one percent of the kinetic energy of the Keplerian motion, by hits of the blobs. In this way, we consider that the accretion disk has mass accretion avalanche induced by the random collision of the blobs, like the SP model. Besides, it is expected that the disturbance in the disk temporarily increases the efficiency of the X-ray irradiation by the amplification of the turbulence. Eventually the mass accretion avalanche, produced at a various radius of the accretion disk, is transported to the vicinity of the BH through the optically-thin corona and produces the observed long term variation in the X-ray intensity, with powerlaw-shaped PSD. In conclusion, although it is phenomenological and qualitative, we propose a new picture of the accretion disk shown in figure 7.8.

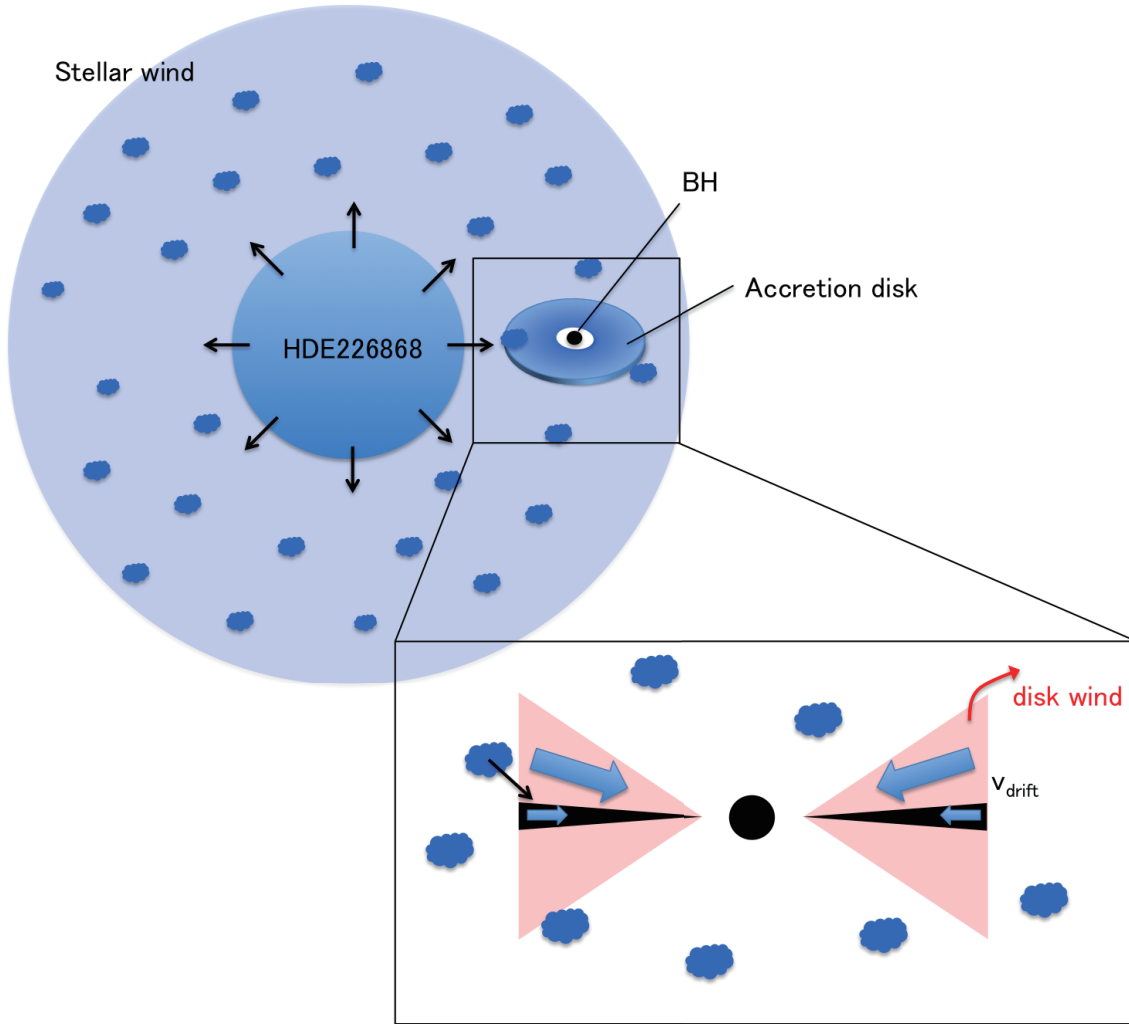


Figure 7.8: The upper schematic shows the grand structure of the binary system of Cyg X-1. Blue clouds scattered in the stellar wind indicate blobs. The inside of the lower square is a magnified drawing of the BH and the accretion disk in side view. Blobs hit and disturb the accretion disk. The drift velocity v_{drift} in the optically-thin flow (the red regions) is faster than that in the optically-thick disk (the black lines).

Chapter 8

Conclusion

The accretion disk around a BH has been intensively investigated by the X-ray observations. However, its large-scale structure is not still understood well. Because the study of the large-scale structure requires long-term observations with more than a week and usually such a long-term observation can not be performed. Only monitoring instruments can provide us such a long-term data, but the quality of the data was not enough to study the accretion disk structure before the MAXI era. MAXI on board the ISS is the first instrument, which can provide us the long-term behaviors of X-ray sources with a good statistics. In this thesis, we succeeded to capture the behavior of the long-term variability with the continuous observation for six years by MAXI.

First, we investigated an aperiodic long-term variation with the NPSD in the LHS and HSS, respectively. We found that the NPSD down to 10^{-7} Hz obeys a power law and is approximately expressed as an extrapolation of the NPSD above 0.01 Hz in the LHS. In the HSS, we newly discovered that the NPSD in the range of $10^{-7} - 10^{-4}$ Hz is also approximated by a power law, and on an extrapolation of the NPSD previously obtained in frequencies above 10^{-4} Hz. In both states, we showed that the *powerlaw* component in the energy spectra is responsible for the observed long-term intensity variations. We also found that the amplitude of the long-term variation in the HSS is larger than that in the LHS.

Next, we studied the orbital modulation with 5.6 d period seen in the light curve and the energy spectrum. The intensity modulation with 5.6 d in its HSS was first discovered by us in the world. We also confirmed the spectral and intensity modulation with the orbital period in its LHS. By comparing the behaviors in both states and by considering the previously reported phenomena, we concluded that the stellar wind from the companion star should be inhomogeneous.

We then proposed a new disk structure. In the LHS, the optically-thin corona should extend to $\sim 10^{12}$ cm, and a standard optically-thick and geometrically-thin disk co-exists in the out side of the certain radius. In the HSS, a standard disk is formed down to the ISCO, the optically-thin corona should co-exist from the vicinity of the BH to the radius of $\sim 10^{12}$ cm. The long-term variation produced at the large radius is transported to the vicinity of the compact star, via the optically-thin

corona, and eventually X-ray intensity of the power law component shows the long-term variation.

Furthermore we discussed the origin of the optically-thin corona and pointed out the importance of the X-ray irradiation. Also, as a cause of the long-term variation, we proposed the effect of the inhomogeneous wind accretion onto the accretion disk.

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