Spectral states in NS-LMXBs observed with MAXI/GSC and Swift/BAT

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Abstract

We review the spectral states in NS-LMXBs observed with MAXI/GSC and Swift/BAT. The spectral state transitions (soft/hard) were seen in the NS-LMXB transients. This was caused by the instability in a standard accretion disk. Sensitive observations with GSC and BAT showed outbursts even with small peak luminosities and shorter durations. Such "mini-outbursts" were observed in four sources; 4U 1636−536, 4U 1705−44, 4U 1608−52, and GS 1826−238 (Asai et al. 2015). We understand it as a "purr-type" of disk instability predicted by Mineshige and Osaki (1985), whereas the large normal outburst is named as a roar-type. There are several atoll NS-LMXBs, which are persistent and always in the soft state. Although the hardness ratio (HR) in GSC and BAT observations is always low (i.e. soft state), the HR distributed in two (higher/lower) groups. The higher group contains 4U 1820−30 and 4U 1735−44, while the lower group contains GX 3+1, GX 9+1, GX 13+1, and GX 9+9. We interpreted the difference to come from the size of the Comptonized cloud. The high HR was resulted from a large Comptonized cloud, which might be dammed at the Alfvén radius by rather high magnetic fields (Asai et al. 2016). In the brightest NS-LMXB (Z sources), there are three branches; Horizontal Branch (HB), Normal Branch (NB) and Flaring Branch (FB). Although the differences of HB and NB in the spectral and timing properties indicated some changes in the geometrical structure, the physical understanding is still controversial. We suggest that the difference of HB and NB might be explained by existing of the disk evaporation.

Key words: accretion, accretion disks — X-rays:neutron — X-rays:binaries

1. Introduction

Low mass X-ray binaries with a weakly magnetized neutron star (NS-LMXB) are divided into two main subclasses (Z sources and Atoll sources) based on their behavior on the color–color the diagram and hardness–intensity diagram (Hasinger & van der Klis 1989). Z sources are generally bright and sometimes become close to the Eddington luminosity (L_E). On the other hand, Atoll sources are generally less bright, $L \leq 0.5\ L_E$. The NS-LMXBs show two kinds of X-ray spectra depending on their X-ray luminosities. In the high luminosity($> 10^{37}$ erg/s) it is dominated by blackbody components, and called the soft state. On the other hand, in the low luminosity($< 5 \times 10^{36}$ erg/s) it is dominated by a Comptonized component, and called the hard state. Z sources are usually in soft state, whereas some of Atoll sources exhibit spectral state transitions (soft or hard).

The present study focuses on the properties of the spectral state of Z sources and Atoll sources. The analyzed data are MAXI (Matsuoka et al. 2009)/GSC (Gas Slit Camera: Mihara et al. 2011; Sugizaki et al. 2011) [1] and Swift (Gehrels et al. 2004)/BAT (Burst Alert Telescope: Barthelmy et al. 2005) [2]. The obtained count rates of GSC and BAT were converted to luminosities by assuming a Crab-like spectrum (Kirsch et al. 2005) and the distances listed in table 1. The assumption of Crab-like spectrum is acceptable in the hard state, because the energy spectrum is dominated by the Comptonized emission approximated by a power law with the photon index of 1–2. On the other hand, in the soft state, the energy spectrum is dominated by the thermal emission. The obtained luminosity by assuming Crab-like spectrum is underestimated in the 2–10 keV band, but is overestimated in the 15–50 keV band. As a result, the hardness ratio (HR) of two energy bands is overestimated by 2.0 times (see Asai et al. 2015 for detail). Therefore, we handle only the relative difference.

In this paper, first, we introduce two kinds of spectral state transitions, normal outburst and mini outburst

*1 <http://maxi.riken.jp/>.
*2 <http://heasarc.gsfc.nasa.gov/docs/swift/results/transients/>.

(Asai et al. 2015). Next, we show two groups in a soft state of Atoll sources, and then propose that the difference would come from the surface magnetic field of a neutron star (Asai et al. 2016). Finally, we discuss the difference between Horizontal and Normal branch (HB and NB) of Z sources. We suggest that the difference might be explained by the disk evaporation.

Table 1. Distances used in this paper

Name	Distance (kpc)	Ref.*
Atoll sources		
Aql X-1	5	(1)
4U 1608−52	4.1	(2)
4U 1636−536	6	(1)
4U 1705−44	7.4	(1)
4U 1735−44	8.5	(2)
4U 1820−30	7.6	(1)
GX 3+1	4.5	(3)
GX 9+1	5	(1)
GX 9+9	5	(4)
GX 13+1	7	(1)
GS 1826−238	7	(1)
XTE J1709−267	8.8	(1)
Z sources		
Cyg X-2	7.2	(1)
GX 17+2	12.6	(5)
GX 340+0	11	(4)
Sco X-1	2.8	(1)
GX 5−1	9.2	(4)
GX 349+2	5	(4)

∗ (1) Liu et al. (2007), (2) Galloway et al. (2008), (3) Kuulkers and van der Klis (2000), (4) Christian and Swank (1997), (5) Lin et al. (2012).

2. Two kinds of spectral state transitions

We define the spectral state with MAXI/GSC (2–10 keV) and Swift/BAT (15–50 keV). First, we make the histograms (number of days) of the BAT/GSC hardness ratios (HRs) of the seven NS-LMXBs (4U 1636−536, 4U 1705−44, 4U 1608−52, GS 1826−238, Aql X-1, XTE J1709−267, and 4U 1820−30). We basically adopted the HR of the lowest point between the two peaks as the threshold between the soft and hard states (see table 2 in Asai et al. 2015). Figure 1 shows the GSC light curve, BAT light curve, and HRs (BAT/GSC) of 4U 1705−44. In this figure, the threshold separate the data points into soft and hard states.

From the light curve, we noticed that the soft states are separated into two luminosity classes. Comparing with the average luminosity of soft state, one is above

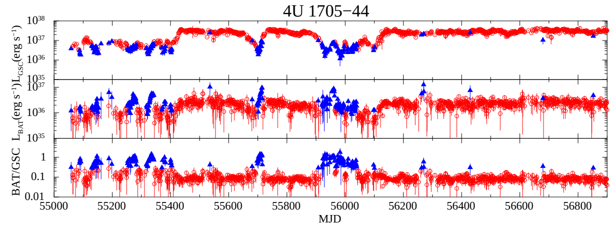

Fig. 1. One-day light curves (LC) of 4U 1705−44 shown as an example. Top: GSC LC in the 2–10 keV band. Middle: BAT LC in the 15–50 keV band. Bottom: the hardness ratios (HRs) (BAT/GSC). Vertical error bars represent 1 σ statistical uncertainty. Circles and triangles represent data of soft and hard states, respectively. See Asai et al. (2015) for other sources.

ten to 10^{37} erg s^{-1}, the other is below this value. So, we calculated the average 2–10 keV luminosities of the soft and hard states using the thresholds of the HR for seven sources. The soft states of all seven sources are separated into two luminosity classes. If the average luminosity in the soft state is below $\sim 10^{37}$ erg s^{-1}, the X-ray variability (repeated small increase) is called "mini-outbursts," whereas outburst with average luminosity above $\sim 10^{37}$ erg s^{-1} is called "normal outburst." The mini-outbursts were characterized by smaller amplitudes and shorter duration than those of normal outbursts. Such mini-outbursts were observed in the four sources (4U 1636–536, 4U 1705–44, 4U 1608–52, and GS 1826–238). We consider that the light curve of mini outburst is similar to the calculated light curve for a "purr-type" of disk instability predicted by Mineshige and Osaki (1985).

Normal outbursts in NS-LMXBs are usually interpreted by the disk instability model like the outburst of dwarf novae. In this model, local disk instabilities (S-shaped curves in the surface density and mass accretion rate diagram) are caused by the partial ionization of hydrogen and helium. The theoretical disk instability model of Mineshige and Osaki (1983, 1985) predicts both large-amplitude outbursts (roar type) and small-amplitude variability (purr type). The former is considered to correspond to normal outburst, but no correspondence has been found for the latter. Here, we propose that purr-type outbursts correspond to mini-outbursts, because the characteristics (small-amplitude and short duration) of both types are quite similar.

The main difference between two types (roar type and purr type) is α parameter of the standard disk. The α parameter is usually considered to depend on the disk temperature. In order to explain a normal outburst, two S-curves with a different α values are used. As a result, the width of the middle branch of S-curve is extended. This means that the instability can propagate through the whole disk, and then outburst occurs. This is a roar type. In the case of one S-curve, the width

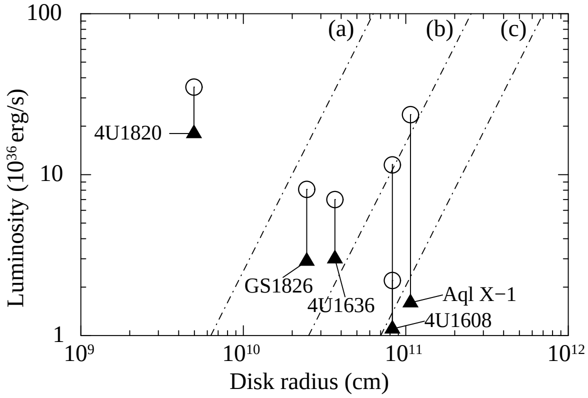

Fig. 2. Average X-ray luminosity in the 2–10 keV band as a function of outer disk radius. Open circles and filled triangles represent data of soft and hard states, respectively. Theoretical lines of (a), (b), and (c) are calculated by equation (53) of Tuchman et al. (1990) ($C = 10^{-4}$). The irradiation temperatures of (a), (b), and (c) are T_{irr} = 10000 K, 5000 K, and 3000 K, respectively.

of the middle branch is narrow, and then the instability propagates only a part of the disk. This is a purr type. We considered that mini outburst occurs when the middle branch is narrow. Tuchman, Mineshige, and Wheeler (1990) reported that the middle branch can become narrow, when the disk is irradiated by the central sources. So, we investigate the status of the outer disk, assuming that the disk temperature is determined by X-ray irradiation. Figure 2 shows the average X-ray luminosities and the outer radius of the accretion disk. Here, the outer radius was assumed as 0.35 of the binary separation (Smak 1982, and see Asai et al. 2015 in detail). For 4U 1820−30, we interpreted the spectral state transition as other type because average luminosity in both soft and hard state are above $\sim 10^{37}$ erg s^{-1} (see Asai et al. 2015 in detail). The left side of (a) indicates a stable region, where S-shape disappears. The right side of (c) is an unstable region, where a normal outburst occurs. In the region between (a) and (b), we observed mini-outbursts. Therefore, we interpreted mini-outbursts were caused by X-ray irradiation.

3. Hard tail emission in Atoll sources

Average hard-tail X-ray emission in the soft state of nine bright Atoll source (Aql X-1, 4U1608−52, 4U1705−44, GX 3+1, GX 9+9, GX 13+1, GX 9+1, 4U 1735−44, 4U 1820−30) are investigated by using the light curves of MAXI/GSC and Swift/BAT. Two sources (4U 1820−30 and 4U 1735−44) exhibit large HR (15–50 keV/2–10 keV: HR > 0.1), while the other sources distribute at HR ≤ 0.1. In either case, HR does not depend on the 2–10 keV luminosity. Therefore the difference of HR is due to the 15–50 keV luminosity, which is Comptonized emission. The Compton cloud is assumed to be around the neutron star. In general, Comptonized emission is considered to be affected by the inclination, origin of seed photon, and electron temperature of Compton cloud. However, we cannot see a clear difference of any parameters between two groups from the results by several authors (see Asai et al. 2016). So, we propose that the difference between the two groups would be due to the size of the Compton cloud. The group with high HR would have large Compton cloud. Next, we consider the location of Compton cloud.

In the soft state, the location for Compton cloud is controversial. Here, let us take into account of the magnetic field of the neutron star. The magnetic field of a neutron star in LMXB is considered to be weak. However, in some cases, the effect of the magnetic field is taken into account. In the soft state, most of the gas in the disk accretes onto the neutron star, because the disk can extend to the neutron star or ISCO. The accretion flow is thermalized on the surface, and the emission from there is Comptonized by the plasma around the neutron star. However, if the magnetic field of the neutron star is relatively strong, the Alfvén radius would be larger than the ISCO. In this case, the accretion flow would be stopped and spread around the Alfvén radius, and then the relatively large Compton cloud would be created.

We calculated the Alfvén radius as a function of luminosity (see figure 7 in Asai et al. 2016). Here, we adopted a gas pressure dominant accretion disk. When L is 10^{37} erg s^{-1}, R_A is larger than ISCO for $B > 1.5 \times 10^8$ G. In this case, the accretion flow would be stopped and spread at the Alfvén radius, and then the relatively large Compton cloud would be created. As a result, the HR would be large (for example HR > 0.09). On the other hand, when $B < 1 \times 10^8$ G, the R_A is smaller than both ISCO and NS surface. In this case, the accretion flow is not affected by the magnetic field, and then most of the gas in the disk accretes onto the NS equatorial region. The HR would be low (for example HR < 0.09). According to increasing the luminosity, R_A becomes smaller and the size of Compton cloud would be smaller.

By attributing the difference of the size of Compton cloud to the Alfvén radius, we can estimate the magnetic fields of neutron star. Since HR of 4U 1820−30 and 4U 1735−44 is large, Bs is estimated as $B \geq 2.5 \times 10^8$ G. The upper limit of B is given for other seven sources. These results are consistent with the previous results.

4. Transition between Horizontal Branch and Normal Branch in Z sources

We investigated long-term variations in the hardness-luminosity diagram (HLD) of six Z sources by using MAXI/GSC and Swift/BAT. We confirm the secular motion of the Z-pattern through the HLD in four sources

(Sco X-1, GX 17+2, Cyg X-2, and GX 5−1). Especially, location of the HB and the NB shifted in the time scale of several hundred days. Also, a transition luminosity from HB to NB changed with the shift. We propose a simple model of transition between HB and NB. Since the luminosity is close to the Eddington luminosity, the inner part of the accretion disk is considered to be a radiation-pressure-dominated disk. When the luminosity is even higher, the radiative force overcomes the gravity on the surface of the accretion disk, and the surface starts to evaporate. We interpret that the difference of HB and NB comes from the existence of the evaporation. In the HB, the evaporation does not occur yet, because the luminosity is comparably low. When the source reaches a transition luminosity from HB to NB with the luminosity increasing, the disk evaporation will start. Namely, the evaporation will occur in NB.

The change of transition luminosity with the luminosity decreasing caused the shift of Z-pattern from Cyg-like sources to Sco-like sources. The inner disk radius becomes smaller as the transition luminosity decreases (Lin et al. 2009). Assuming that the large inner disk radius ($\sim$ 20 km) of Z sources represent the Alfvén radius of the neutron star with the surface magnetic field of $\sim 10^9$ G, the change of transition luminosity can be attributed to a gradual change of accretion disk from the radiation-pressure-dominated disk to gas-pressure-dominated disk. At the highest luminosity, the Z-pattern shows Cyg-like with a long HB. At low luminosities, it becomes Sco-like with a short HB. Figure 19 in Lin et al. (2009) shows the change of the inner disk radius at the transition point of HB and NB. The radius increases from Sco-like to Cyg-like. Here we consider the possibility of which the Alfvén radius determines the inner radius. We calculated Alfvén radius is for two special cases. At high luminosity, the disk would be dominated by the radiation pressure [(1)R_A line in figure 3]. On the other hand, the lowest luminosity in Sco-like, the disk would be gas pressure dominated [(2)R_A line in figure 3]. Here, we consider the possibility of disk evaporation. When the radiation pressure overcomes gravitational force, the disk evaporation would occur. So, we also calculated the evaporation radius [(3)R_cr line in figure 3]. When the source is bright (Cyg-like), the inner radius moves along (1)R_A line. This is the HB of Cyg-like. When the mass accretion rate reaches the evaporation line of (3)R_cr, evaporation starts (point P1). After then, the inner radius moves along (3)R_cr. This is the NB of Cyg-like. In a bright Cyg-like, the inner radius is large and the evaporation point is at high luminosity. As a result, the HB is long. In a low luminosity as Sco-like, the disk becomes gas pressure dominate and the Alfvén radius (i.e. inner disk radius) is shown as (2)R_A line. In this case, the HB is short and the transition occurs at lower luminosity (point P2). In summary, we suggest that the difference of HB and NB might be explained by the disk evaporation.

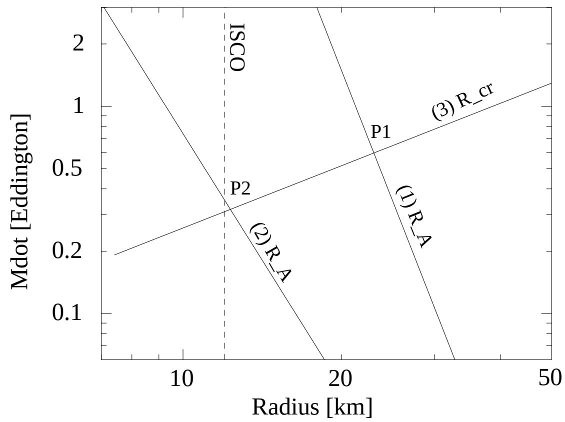

Fig. 3. The Alfvén radius (1) and (2) for $B = 10^9$ G (Campana et al. 1998), and the critical radius (3) (Fukue 2004) as a function of the accretion rate. (1) is for radiation pressure dominated disk [equation (18) in Campana et al. 1998] and (2) for gas pressure dominated disk [equation (14) in Campana et al. 1998].

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