Overview of Spectral Change in NS-LMXB

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ABSTRACT

Neutron Star (NS)-Low Mass X-ray Binaries (LMXBs) are historically divided into two classes called Z and atoll sources, according to the shape of their color-color diagrams. Z sources (including Sco X-1, Cyg X-2, etc.) are always very bright close to Eddington luminosity, and show three distinct states named as Horizontal, Normal and Flaring branches (HB, NB and FB). Some of atoll sources are transient and sometimes switch the states between low/hard and high/soft states. After the discovery of the bright transient NS-LMXB XTE J1701−462, which followed the spectral states of both Z and atoll sources, it is confirmed that these two types of NS-LMXBs are determined mainly by the mass accretion rate. However, XTE J1701−462 repeatedly showed all three Z states many times during the gradual outburst decay, and the physical origins are still unclear how Z sources change the three branches of HB, NB and FB (almost) independent from the mass accretion rate. We present the recent observational results of the high/soft state of the atoll source 4U 1608−522, and explain the detail behaviors of physical parameters, which may relate to the three states of Z sources.

KEY WORDS: binaries: general — stars: neutron — X-rays: stars

1. Spectral States of NS-LMXBs

Neutron Star (NS)-Low Mass X-ray Binaries (LMXBs) are bright and they are observed from the beginning of X-ray astronomy. To classify their behavior, color-color diagrams (CCDs) are used and they are divided into two classes called Z and atoll sources (Hasinger et al. 1989). Z sources have a luminosity close to the Eddington limit (~10^{38} erg s^{-1}), while atoll ones are transients from quiescent to $\lesssim$ Eddington luminosity. As shown in Figure 1, with increasing the accretion rate $\dot{M}$, atoll sources show low/hard and high/soft states, which are historically called as island and banana states, respectively. Z sources are named as they show three states called Horizontal, Normal and Flaring branches (HB, NB and FB). However, the differences of the three Z states are physically not understood yet. Among Z sources, there are two sub classes called Cyg-like and Sco-like, since Cyg X-2 and Sco X-1 are their representatives. Cyg-like Z sources take "Z" shape in the CCDs, while Sco-like ones show "ν".

Since the recent bright transient NS-LMXBs (e.g., XTE J1701−422 and MAXI J0556−332) showed both Z (Cyg-like and Sco-like) and atoll behaviors during their outbursts, it is thought that atoll sources become Z ones when $\dot{M}$ becomes higher (Lin et al. 2009; Sugizaki et al. 2013). These transients also repeated the three Z states many times during the gradual outburst decay. It suggests that the three Z states are (almost) independent from $\dot{M}$, although many previous researches assumed that the Z behavior was mainly controlled by the mass accretion rate.

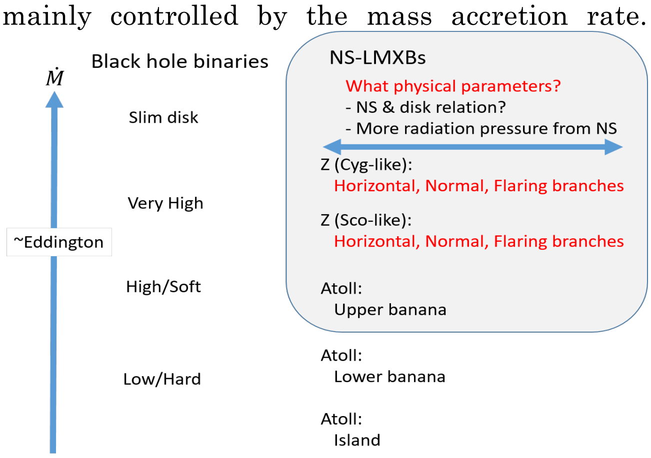

Figure 1. States of NS-LMXB compared with those of black hole binaries. This paper is about the high/soft state shown in grey.

Compared with black-hole binaries (Figure 1), which have very high or slim-disk states according to $\dot{M}$ over the Eddington limit, it is unclear for NS-LMXBs how physically different each of HB, NB and FB is and what causes the transitions among them at the (almost) constant $\dot{M}$.

In this paper, we summarize observational results of the high/soft state of NS-LMXB and propose the physical interpretations.

2. 4U 1608–522 (atoll source): Outflow and disk fluctuation

The emission of NS-LMXB in the high/soft state is normally well represented by the combination of the emission from the accretion disk and NS surface (or boundary layer). The former is sum of the black body emission from different temperatures at different radii (= the multi-color disk). The latter can be approximated by a single-temperature black body (Mitsuda et al. 1984; Makishima et al. 1989).

We also used this "diskbb+bb" model in xspec in the spectral analysis of the high/soft (upper banana) state of an atoll source 4U 1608−522 observed by Rossi X-ray Timing Explorer (RXTE) satellite (Takahashi et al. 2011). Assuming the black body emission, we obtain the luminosity and temperature, and estimate the emission radius. As a result, we realized the luminosity of the NS surface (L_{NS}) relatively decreases as that of the accretion disk (L_{disk}) increases (i.e., L_{NS}/L_{disk} decreases from ~0.6 to 0.4 as the total luminosity increases from ~1×10^{37} to 4×10^{37} erg s^{-1}). This implies that the ~20% fraction of the accretion matter does not accrete onto the NS surface. Such a behavior can be explained by the existence of an outflow, which is probably caused by the radiation pressure of $L_{NS} + L_{disk}$ (Figure 2).

When looking at deviations of the physical parameters after subtracting the average trend, we found two ways of fluctuations independent from $\dot{M}$. One is that L_{disk} (in the soft energy band) decreases and L_{NS} (in the hard energy band) increases simultaneously (Variable Luminosity Branch: VLB). This VLB behavior makes the large movement in the upper banana branch of the CCD. The other is that there are no luminosity changes but only the disk temperature (T_{in}) and radius (r_{in}) fluctuate each other to keep L_{disk} at constant (Constant Luminosity Branch: CLB).

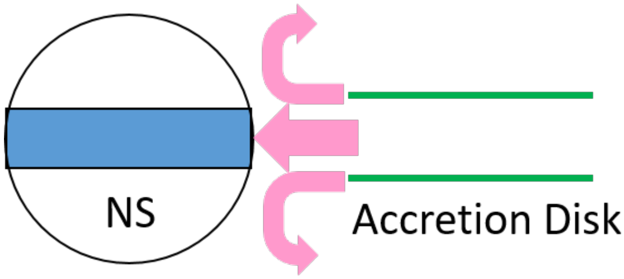

Figure 2. The schematic view of the upper banana state of atoll sources. Some fraction of matter from the accretion disk outflows and does not accrete onto the NS. The emission radius of the NS surface is less than 10 km, and may come from the equatorial region.

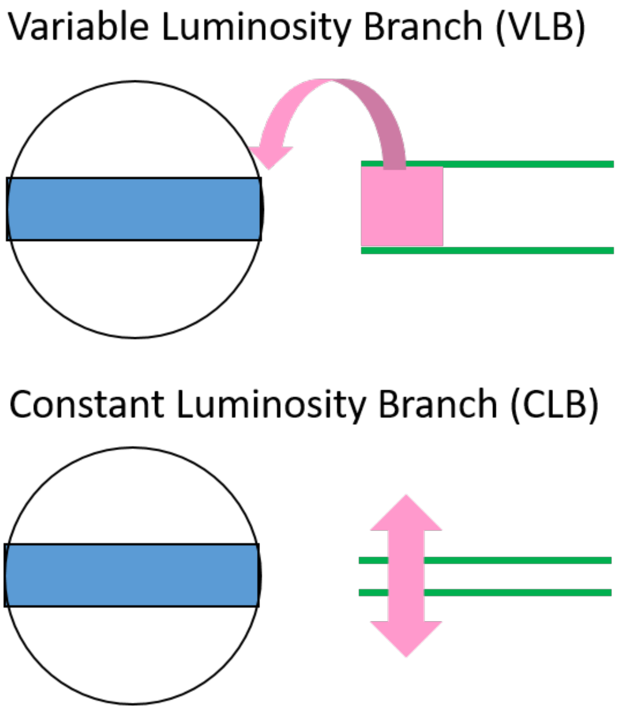

Figure 3. The same as Figure 2 but for the fluctuations independent from the mass accretion rate. Two ways are observed and their luminosities are variable (VLB) or constant (CLB). At VLB, L_{disk} decreases and L_{NS} increases simultaneously. At CLB, T_{in} and r_{in} fluctuate with keeping L_{disk} (and L_{NS}) at constant.

The former VLB suggests some fraction of the disk emission is emitted not at the disk but at the NS surface, as shown in Figure 3. Such an instability might occurred due to photon trapping at the inner edge of the disk (Ohsuga et al. 2002). Then, the matter accretes onto the NS with including the trapped photons, which are later released as the emission from the NS surface additionally. The CLB behavior appears only for the temperature and hence the radius of the accretion disk. This can be explained by the change of the hardening factor, which might be caused by the disk structure (e.g., geometrical thickness).

3. Relation between atoll and Z sources

Considering the atoll sources become Z ones at the higher accretion rate and the above VLB and CLB are independent from the mass accretion rate (after subtracting the average trend), we think that the three states of Z sources, which transitions are also (almost) independent from $\dot{M}$, are related to the VLB and CLB of the atoll ones.

Actually, the movements and positions of the VLB and FB (at least Sco-like) in the CCDs are the same (i.e., the harder flux increases in both states), it is thought that the inner part of the accretion disk drops to the NS without emitting efficiently. The photon-trapping effect can occur more strongly with the higher surface density.

The remaining CLB is the candidate of NB (and HB) of Z sources, when $\dot{M}$ increases. Z sources in NB change only the harder flux (from the NS surface) and keep the softer flux (from the disk) rather stable. The stable disk emission is the same behavior observed in CLB. If CLB changes the geometrical thickness of the accretion disk to explain the behavior of T_{in} and r_{in}, NB might have the thinner disk when it is close to HB and the thicker one when close to FB. The cross-section surface of the disk is suffered from the radiation pressure, and the matter outflows rather than the accretion, if the pressure is large enough. The thicker disk (close to FB) is thought to receive more pressure and the more matter outflows, resulting the less emission from the NS surface, since the accreting matter to the NS deceases. On the other hand, the NS surface emission can be higher with the thinner disk (close to HB).

About HB behavior of Z sources, there are several models (e.g., disk state changes from standard to slim disk), but it should locate the extension of the NB physical explanation.

Furthermore, we need to understand why black hole binaries do not show such three transitions observed in the Z sources.

References

Hasinger, G. et al. 1989, A&A, 225, 79
Lin, D. et al. 2009, ApJ, 696, 1257
Sugizaki, M. et al. 2013, PASJ, 65, 58
Mitsuda, K. et al. 1984, PASJ, 36, 741
Makishima, K. et al. 1989, PASJ, 41, 531
Takahashi, H. et al. 2011, ApJ, 738, 62
Ohsuga, K. et al. 2002, ApJ, 574, 315