Towards a Unification of the Hard and the Soft states of LMXBs

Ko Ono¹, Shunsuke Torii¹, Soki Sakurai¹, Zhongli Zhang¹
Kazuhiro Nakazawa¹ Kazuo Makishima¹

¹ Department of Physics, The University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-0033
E-mail(OK): ono@juno.phys.s.u-tokyo.ac.jp

Abstract

Sakurai et al. (2012) revealed that the spectra of Aquila X-1 in the hard state can be explained by a blackbody emission from the NS surface Comptonized by an electron corona around the neutron-star, plus an optically-thick disk emission. This model though with much different parameters, was originally developed to explain the soft state of many low-mass X-ray binaries. The model was applied successfully to Suzaku and RXTE data of the high luminosity LMXB GS 1826-238 in the hard state, and Suzaku data of 4U 1608-52 in the soft and the hard state. The obtained fitting parameters confirmed that these sources were in the soft state, or in the hard state, which were close to the state boundary. Attempting to unify the two states, the data of GS 1826-238, 4U 1608-52 and Aql X-1, as well as other sources, were plotted on a diagram of the Compton y-parameter vs. the (electron temperature)/(seed photon temperature) ratio. On this diagram, LMXB appears to form a single continuous locus across the two states.

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

1. Introduction

A low-mass X-ray binary (LMXB), which consists of a neutron star (NS) and a low-mass star (< 1 $M_\odot$), has two spectral states: the soft state and the hard state. The spectrum of an LMXB in the soft state appears mainly in the soft X-ray band below ~10 keV, and is understood as a superposition of a blackbody radiation from the NS surface and a multi-color-blackbody radiation from the standard accretion disk around the NS.

The spectrum of an LMXB in the hard state shows a power-law-like shape with a photon index of ~ 2, extending up to ~100 keV. The high sensitivity of Suzaku over a broad energy band contributed significantly to our understanding of the hard state. Sakurai et al. (2012, 2014) revealed that the hard state is understood as a standard accretion disk emission, plus a blackbody radiation from the NS surface Comptonized by the subsequent coronal stream. Although this model composition is the same as that of the soft state, the model parameters, particularly the Comptonization strength, are rather different.

In order to understand the LMXB in both states in a unified way, we studied two LMXBs which are relatively close to the state boundary. Our main interest is to understand how the spectral parameters, particularly of the corona, change depending on the luminosity.

2. Observation and Data Reduction

We analyzed archived Suzaku and RXTE data of two LMXBs, GS 1826-238 and 4U 1608-52, which are located at a distance of 7 kpc¹ and 4.1 kpc², respectively. The dates of three observations are summarized in table 1. We excluded type I bursts of GS 1826-238 and derived simultaneous spectra of the Suzaku and RXTE. Three spectra of 4U 1608-52 were derived from the three Suzaku data sets.

Table 1. Suzaku data sets utilized in the present work. Obs. date indicates month and date. GS 1826-238 was observed in 2009 and 4U 1608-52 in 2010.

<table>
<thead>
<tr>
<th>Source</th>
<th>GS 1826</th>
<th>4U 1608</th>
</tr>
</thead>
<tbody>
<tr>
<td>Obs. date</td>
<td>10/21</td>
<td>3/11</td>
</tr>
<tr>
<td>Exposure (ks)</td>
<td>103</td>
<td>26</td>
</tr>
<tr>
<td>$L$ (10³⁶ erg/s)</td>
<td>15</td>
<td>58</td>
</tr>
</tbody>
</table>

3. Spectral Analysis

3.1. GS 1826-238

Figure 1a shows XIS0, HXD-PIN, HXD-GSO and PCA spectra of GS 1826-238, acquired simultaneously. We fitted them with an XSPEC model diskBB, plus nthcomp (Zdziarski et al. 1996; Zycki et al. 1999) which expresses Comptonized photons, where we used a blackbody model as a seed photon source. We allowed different temperatures between the diskBB and the seed blackbody. The fitting was successful and gave $\chi^2_d(\nu) = 1.6(157)$. 

- 204 -
Figure 1b and 1c show the Suzaku (XIS3 and HXD-PIN) spectra of 4U 1608-52 on 2010/3/11 and 3/15, respectively, both acquired in the soft state. Figure 1d is the XIS3, HXD-PIN, and HXD-GSO spectra of 4U 1608-52 on 2010/3/18, when the source was in the hard state.

We fitted the three spectra of 4U 1608-52 with the same model as used for GS 1826-238. In the 2010/3/11 data, a Gaussian was added to account for the Fe-K line. The fit was all successful, yielding typically $\chi^2$ $\sim$ 1.1 or less. Compared to the soft state, the hard-state spectrum is characterized by a retreated inner-disk edge (from $\sim$ 20 km to $\sim$ 53 km), an increased Compton $T_e$ (from $\sim$ 5 keV to $\sim$ 15 keV), and a flattening in the Compton continuum slope $\Gamma$ (from $\sim$ 4 to $\sim$ 2.2). These agree with Sakurai et al. (2012, 2014).

4. Discussion

In order to explain the LMXB in a unified way, we made a diagram of the $y$ parameter versus a new parameter $Q \equiv T_e/T_{bb}$ (Makishima et al. 2014), where $T_e$ is the coronal temperature and $T_{bb}$ is the seed blackbody temperature. While $y$ expresses degree of Comptonization, $Q$ the balance between ion heating and photon cooling of the Comptonizing corona.

As shown in figure 2 (top), LMXB including the sources we analyzed appear to form a single continuous locus. The soft and hard states occupy regions of $Q \leq 6$ and $Q \geq 8$ respectively. Therefore, $Q$ can specify the spectral states uniquely. Furthermore, the spectral parameters are suggested to evolve continuously across the state boundary, event though the change must be very quick therein.

5. Conclusion

We analyzed four archived data sets (mainly from Suzaku but also incorporating RXTE) of two LMXBs, GS 1826-238 and 4U 1608-52. All the spectra were successfully reproduced with a model which consists of an optically thick disk emission and a blackbody Comptonized by corona. The results have been compiled in a unified way on a $(Q, y)$ diagram.

References
Sakurai, S. et al. 2012 PASJ, 64, 72
Sakurai, S. et al. 2014 PASJ, 66, 10
Makishima, K. et al. 2014, this volume