Spectral Variability of LMC X-1 with SUZAKU

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Abstract

We report a study of the spectral variation in the soft state with Suzaku observation of the black hole binary LMC X-1. We found intensity-correlated variations in the spectral hardness ratio on a timescale of $10^4$-$10^5$ sec. The variation is explained by $\sim 10\%$ changes in the Comptonized emission, possibly accompanied by those in the narrow iron line. Assuming that the timescale corresponds to the viscous timescale in a standard accretion disk, the origin of the variation is considered to be located at distant region above $\sim 100 R_g$ from the black hole.

Key words: accretion, accretion disks — black hole physics — X-rays: individual (LMC X-1)

1. Introduction

LMC X-1 is one of persistently luminous X-ray black hole (BH) binaries accompanying an O type star. Although the spectral state has been steady in soft state, this object is a good sample to study the variation of coronal emission because of present variable power-law (PL) component (e.g. Ruhlen et al. 2011). Steiner et al. (2011) reported clear iron line from LMC X-1 spectra observed with Suzaku and a positive correlation between iron line flux and Compton scattering fraction with RXTE observation, which suggests that the coronal emission and iron line emission arose at the same region. In this paper, we reanalyzed the Suzaku data and confirmed the iron line change from a stretch of the observation in order to estimate the variation timescale.

2. Observation

Suzaku (Mitsuda et al. 2007) observed LMC X-1 on 2009 July 21 UT 18:38 through July 24 21:29 at “XIS nominal” pointing position. The total exposure time is $\sim 110$ ksec. In the following spectral analysis, we used an energy range of the 1.4–10 keV for the XIS spectrum and 13–50 keV for the HXD-PIN spectrum where the calibrations of the energy responses were well established.

3. Analysis

Figure 1 (left) shows the background-subtracted light curves. We can see sinusoidal fluctuations with a timescale of $\sim 10^4 - 10^5$ s. That amplitude becomes stronger in the higher energy band. Figure 1 (right) shows the hardness ratio in 6-10 keV to 4-6 keV against 4-10 keV count rate with time bine size of 5760 s. In order to evaluate the $10^4-10^5$ s spectral variation, we divided the data into hard phase (HP) and soft phase (SP), as the hardness ratio in 6-10 keV to 4-6 keV is higher and lower than the average of 0.25 (dashed line in 1), respectively. Figure 2 shows spectral ratio in 5-8 keV from fitting by the power-law + Gaussian model for HP, SP and difference, plotted except for the Gaussian contribution.

Although the Gaussian parameters are consistent in the error range of 90% confidence, the significance of the line derived from the $F$ test in differential spectrum is high enough ($F = 6.55$; d.o.f = 26 for PL only and 24 for PL + Gauss; probability $5.3 \times 10^{-3}$). Thus the presence of the iron line and its variation could be significant.

For the spectral fitting, we considered the simple physical situation that a part of the disk photon is Compton-upscattered at coronae and the coronal emission irradiates the disk and is reflected. A simpl model and an ireflect model in XSPEC were employed for fractional Compton upscattering and for reflection with an ionized matter, respectively. For the disk emission model, we test two cases of standared MCD model of diskbb (Model1) and relativistic model of bhspec (Davis et al. 2005) (Model 2). Figure 3 shows the deconvolved $\nu F_\nu$ spectra and residuals from the best-fit model. The best-fit parameters are shown in table 1. In both models, the disk component was stable between two phases. The application of relativistic effect makes disk component slightly broaden and gives a better fit to the observed spectra than model1. The bhspec requires spin parame-
Table 1. Best-fit parameters for each phase.

<table>
<thead>
<tr>
<th>Model 1</th>
<th>N_H [10^{21} cm^{-2}]</th>
<th>T_in [keV]</th>
<th>R_in [km]</th>
<th>Γ</th>
<th>f_{scat} [0.9-1]</th>
<th>R_{eff} [10^{14} cm]</th>
<th>ξ</th>
<th>χ^2/d.o.f.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hard Phase</td>
<td>4.24^{+0.16}_{-0.19}</td>
<td>0.807 ± 0.010</td>
<td>60.8^{+1.8}_{-1.6}</td>
<td>3.02^{+0.07}_{-0.09}</td>
<td>0.185^{+0.016}_{-0.018}</td>
<td>1.09^{+0.22}_{-0.20}</td>
<td>34.1^{+10.4}_{-14.0}</td>
<td>180.96/97</td>
</tr>
<tr>
<td>Soft Phase</td>
<td>3.55^{+0.18}_{-0.17}</td>
<td>0.807^{+0.010}_{-0.012}</td>
<td>60.8^{+1.7}_{-1.8}</td>
<td>3.16^{+0.12}_{-0.13}</td>
<td>0.147^{+0.026}_{-0.025}</td>
<td>1.16^{+0.38}_{-0.36}</td>
<td>13.5^{+14.8}_{-16.4}</td>
<td>138.24/97</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Model 2</th>
<th>N_H [10^{21} cm^{-2}]</th>
<th>L/L_{Edd}</th>
<th>a_+</th>
<th>Γ</th>
<th>f_{scat} [0.9-1]</th>
<th>R_{eff} [10^{14} cm]</th>
<th>ξ</th>
<th>χ^2/d.o.f.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hard Phase</td>
<td>4.72 ± 0.14</td>
<td>0.136 ± 0.001</td>
<td>0.86 ± 0.01</td>
<td>2.94^{+0.07}_{-0.08}</td>
<td>0.166^{+0.025}_{-0.024}</td>
<td>0.85^{+0.10}_{-0.09}</td>
<td>36.6^{+12.6}_{-14.9}</td>
<td>156.63/97</td>
</tr>
<tr>
<td>Soft Phase</td>
<td>4.83^{+0.17}_{-0.16}</td>
<td>0.138^{+0.001}_{-0.002}</td>
<td>0.85 ± 0.02</td>
<td>3.07^{+0.14}_{-0.13}</td>
<td>0.133^{+0.015}_{-0.014}</td>
<td>0.88^{+0.04}_{-0.05}</td>
<td>10.8^{+10.5}_{-10.0}</td>
<td>130.69/97</td>
</tr>
</tbody>
</table>

Notes. The errors are 90% confidence level for single parameter.


Fig. 1. (a) Background-subtracted light curves of the XIS FI in 0.5-2 keV, that in 2-4 keV, that in 4-6 keV, that in 6-10 keV, and of the HXD-PIN in 13-50 keV. (b) Hardness ratio in 6-10 keV to 4-6 keV against 4-10 keV count rate. Dashed line denotes average value of hardness ratio of 2.5.

4. Discussion

According to the alpha disk model (Shakura & Sunyaev 1973), a viscous time scale of accretion flow is given as

\[ t_{\text{vis}} = \alpha^{-1} \Omega^{-1} (H/r)^{-2} \]

where \( \alpha \) is a viscous parameter, \( \Omega \) is the Keplerian angular speed of rotation, \( H \) and \( r \) is a scaleheight and radius of the disk, respectively. We can derive a radius of the origin of the variation regarding the observed time scale of 10^4 – 10^6 s as viscous timescale \( t_{\text{vis}} \). As shown in figure 4, if any reasonable value of \( t_{\text{vis}} \geq 0.01 \) and \( \alpha \geq 0.1 \) are chosen, the region becomes above \( \sim 100 R_g \) (hatched region in figure 4).

References

Mitsuda, K., et al., 2007, PASJ, 59, S1
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Fig. 2. Spectral ratio to the best-fit model (power-law + Gaussian) for hard phase (upper panel), soft phase (middle panel) and difference (bottom panel), showing except the Gaussian contribution.

Fig. 3. Left: (a) Unfolded spectra of LMC X-1 from the best-fit for Model 1. Black and red plots (and lines) denote the spectra (and best-fit models) for HP and SP, respectively. (b) Residuals between the data and best-fit models for HP. (c) Same plots for SP. Right: The same as the left panel, but Model 2.

Fig. 4. Relation between disk thickness and viscous region. Upper line denotes case of \( \alpha=1 \) and \( t_{\text{vis}}=10^{14} \) s. Middle line denotes case of \( \alpha=1 \) and \( t_{\text{vis}}=10^{15} \) s. Bottom line denotes case of \( \alpha=0.1 \) and \( t_{\text{vis}}=10^{4} \) s.