Investigation on The X-ray Spectra of the ULX NGC 5204 X-1 in Quest of the slim disk signatures

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Introduction

The existence of ultraluminous X-ray sources (ULXs) have been identified since the late of 1980s in nearby spiral galaxies, with typical X-ray luminosities of 10^{39}-10^{40} ergs s^{-1} (Fabbiano 1989). Their location is significantly far from the nucleus region of their host galaxy and thus ruled out the possibility of being active galactic nuclei (AGNs) of low luminosity. On the other hand, ULXs are too luminous, far exceeding the luminosity of neutron stars.

It still remains an open question if the ULXs really contain **intermediate mass black holes (IMBHs)**, or if they are simply **super-critical accretors onto stellar-mass black holes**. The former have gained so much favor at present.

Objective

There is an evidence that ULXs are associated with a spreading wave of star formation which supports the idea that most of the ULXs, in particular those located in star-forming galaxies are high-mass X-ray binaries that somehow exceed its Eddington limit (King 2004). One of the models supporting this idea is the slim disk model (Watarai, Mizuno & Mineshige 2001; Ebisawa et al. 2003). The observed high disk temperatures which is the most severe problem regarding ULXs can be explained by the slim disk model around a stellar-mass black hole.

To reveal the true origin of the ULXs spectra, we investigate the XMM-Newton EPIC spectra of the nearest and brightest example of ULXs, NGC 5204 X-1.

Data and Methods

Data

The ULX, NGC 5204 X-1, whose X-ray luminosity is about (2–6) x 10^{39} ergs s^{-1}, is located ~ 15 arcsec from the center of a nearby, 4.8 Mpc distance, Magellanic-type galaxy (Roberts & Warwick 2000).

We use the XMM-Newton data which were obtained in two observations (table 1).

Observation ID	Date (yyyy-mm-dd)
0142770101	2003-01-06
0142770301	2003-04-25

Table 1. Observational data.

Data for the analysis were extracted from the pipeline product event lists using the XMM-Newton SAS version 6.5.0 tools. Following Roberts et al. 2005, the pn data were filtered and left only events with flag = 0 and pattern ≤ 4. MOS data were filtered for pattern ≤ 12 and the #XMMEA_EM flag. No time filter is needed for the first observation because the background count rate was consistently low (< 10 count s^{-1} in the pn detector). On the other hand, background flaring was heavily observed in the second observation, and excluding the background rate that exceed 30 count s^{-1} in the pn resulted in the loss of ~50 per cent of the data. Here we therefore focus on the first observation data.

Methods

We first try the standard spectral model of disk blackbody (DBB) + power-law (PL) following Roberts et al. 2005, supporting the IMBH idea.

Next, we try to fit the data by the generalized MCD model, the so called p-free disk model, alone assuming effective temperature profile of $T_{\mathrm{eff}} \propto r^{-p}$. The p-free model is quite useful for discriminating slim disks with $p = 0.5$ from the standard disk with $p = 0.75$ (Watarai et al. 2000).

Results

IMBH supporting model (Figure 1)

We first tried the standard spectral model of DBB + PL and found a good fit to the data. The low temperature apparently support the IMBH interpretation of ULXs, in agreement with Roberts et al. (2005).

Stellar-mass black hole supporting model (Figure 2)

Next, we tried to fit the data by p-free disk model alone. Surprisingly, we also obtained a good fit. The obtained $p = 0.50 \pm 0.03$ is just the value predicted by the theory of supercritical accretion (slim disk), rather than $p = 0.75$ expected by the standard disk model.

Model Parameter	Value
N_{H} kT_{in} Norm. Γ χ^2/dof	*IMBH supporting model* $(0.45 \pm 0.72) \times 10^{21}$ 0.30 ± 0.02 2.34 ± 0.77 1.73 ± 0.078 469.3/475
N_{H} kT_{in} p Norm. χ^2/dof	*Stellar-mass black hole supporting model* $(0.52 \pm 0.042) \times 10^{21}$ 2.87 ± 0.54 0.50 ± 0.03 $(3.01 \pm 0.05) 10^{-4}$ 523.4/476

Table 2. Spectral fitting results.

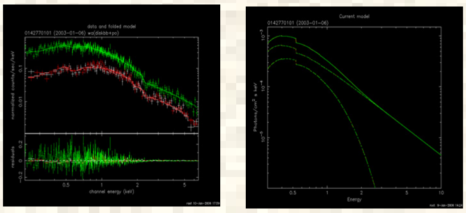

Figure 1. Best-fitting spectra using DBB + PL model. Left: the data and best-fitting in the upper part and the fit residuals in the lower part. Right: the model.

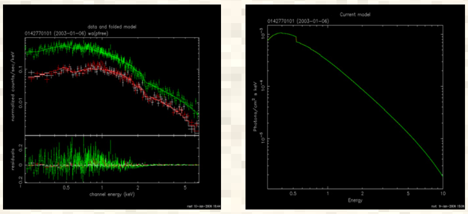

Figure 2. Best-fitting spectra using p-free model. Left: the data and best-fitting in the upper part and the fit residuals in the lower part. Right: the model.

Discussion

Following Makishima et al. (2000), the bolometric luminosity of an optically thick accretion disk can be written as

$$L_{\mathrm{bol}} = 2\pi D^2 f_{\mathrm{bol}} (\cos i)^{-1}$$

with i is the inclination and D is the distance. This L_{bol} is related to the maximum disk color temperature T_{in} and the innermost disk radius R_{in} as

$$L_{\mathrm{bol}} = 4\pi (R_{\mathrm{in}}/\xi)^2 \sigma (T_{\mathrm{in}}/\kappa)^4$$

where $\kappa \sim 1.7$ is the ratio of the color temperature to the effective temperature, or “spectral hardening factor”, and $\xi = 0.412$ is a correction factor reflecting the fact that T_{in} occurs at a radius somewhat larger than R_{in}. Hence, the innermost disk radius is

$$R_{\mathrm{in}} = \xi \kappa^2 (L_{\mathrm{bol}} / 4 \pi \sigma T_{\mathrm{in}}^4)^{1/2}$$

We may identify R_{in} with the radius of the last stable Keplerian orbit. Thus, we may in general write

$$R_{\mathrm{in}} = 3R_{\mathrm{s}}$$

by which we can determine the black hole mass.

The bolometric luminosity can also be written as

$$L_{\mathrm{bol}} = \eta L_{\mathrm{E}}$$

where L_{E} is the Eddington limit for a body of mass M.

Therefore, using T_{in} and f_{bol} from the fitting results, we can determine the value of R_{in} and η.

IMBH supporting model

Fitting the data with the standard spectral model of DBB + PL, with $f_{\mathrm{bol}} = 1.74 \times 10^{-12}$ ergs cm^{-2} s^{-1}, we obtained $R_{\mathrm{in}} = 1.8 \times 10^3 (\cos i)^{-1/2}$ km. The derived mass value is $200 (\cos i)^{-1/2} M_{\mathrm{sun}}$, which is within the IMBH regime. We also obtained, $\eta = 0.08 (\cos i)^{-1/2}$.

Stellar-mass black hole supporting model

As for p-free model, with $f_{\mathrm{bol}} = 1.58 \times 10^{-1/2}$ ergs cm^{-2} s^{-1}, we obtained $R_{\mathrm{in}} = 18.8 (\cos i)^{-1/2}$ km and thus the derived mass is $2.12 (\cos i)^{-1/2} M_{\mathrm{sun}}$, which is within the stellar-mass black hole regime. In this case, we obtained $\eta = 6.83 (\cos i)^{-1/2}$.

Conclusions

- The spectra of ULX NGC 5204 X-1 can be well fitted with the standard spectral model of DBB + PL. The low temperature results in the derived mass within the range of IMBH regime.
- Using p-free model, surprisingly we also obtain a good fit with $p \sim 0.5$, just the value predicted by the slim disk theory, that is, NGC 5204 X-1 should shine at about (or above) the Eddington luminosity, indicating that its black hole mass is about 10 M_{sun}.
- The slim disk theory model is likely to explain the origin of the ULXs spectra for the model can explain the observed super-Eddington luminosities, hard energy spectra, and spectral variations of ULXs.
- The ULX is likely to harbor a stellar-mass black hole which is not unexpected from the standard stellar evolution scenario.

References

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