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X-ray observations of the intermediate-mass black hole in M82

Hironori Matsumoto
Department of Physics, Kyoto University, Kyoto 606-8502, Japan

Abstract

M82 X-1, which is the brightest X-ray source in M82, is a strong candidate for an intermediate mass black hole of 10^3 – 10^6 $M_\odot$. Since M82 X-1 is much brighter than ultra-luminous X-ray sources (ULXs), we call it a hyper-luminous X-ray source (HLX). We analyzed the ASCA spectra of M82 X-1 by using the multi-color disk (MCD) blackbody model, and found that the MCD model can describe the spectra of M82 X-1 as well as those of ULXs. Not only the bolometric luminosity ($L_{\rm bol}$) but also the innermost disk temperature ($T_{\rm in}$) of M82 X-1 is higher than those of ULXs. The most striking feature is that there is no correlation between $T_{\rm in}$ and $L_{\rm bol}$, while there is a positive correlation between those of ULXs. A lower limit on the mass of M82 X-1 obtained by assuming that $L_{\rm bol}$ is sub-Eddington is much larger than an upper limit obtained by assuming that the innermost disk radius ($R_{\rm in}$) is larger than the gravitational radius of a black hole (BH). These characteristics are not consistent with theoretical models such as a standard accretion disk model with a Kerr BH, a slim disk model, and a beaming model, all of which might be able to explain ULXs. This may suggest either that some important processes we overlook play an important role in such luminous objects, or that the HLX is a different kind of object from ULXs.

1.1 Introduction

The ASCA spectrum of M82 consists of soft, medium, and hard components (Tsuru et al. 1997). By monitoring M82 with ASCA, we found that the luminosity of the hard component in the 0.5 – 10 keV band changed between 4.5×10^{40} erg s^{-1} and 1.6×10^{41} erg s^{-1} at various time scales from a few hours to a month, while the soft and medium components showed no evidence for time variability (Matsumoto & Tsuru 1999; Ptak & Griffiths 1999). Although the soft and medium components clearly originate in hot gas due to starburst activity, the origin of the hard component was not clear.

We then observed M82 with the Chandra HRC twice, and found that the ASCA hard component comes from M82 X-1, which is the brightest X-ray source in M82 (Kaaret et al. 2001; Matsumoto et al. 2001). Considering its peak luminosity ($\sim 10^{41}$ erg s^{-1}) and its off-center position ($\sim$ 170 pc away from the dynamical center of M82), M82 X-1 is a strong candidate for an intermediate mass black hole (IMBH) of $10^3 - 10^6$ $M_\odot$.

Since M82 X-1 is much brighter than enigmatic ultra-luminous X-ray sources (ULXs) (e.g. Makishima et al. 2000), we call it a hyper-luminous X-ray source (HLX). To investigate the emission mechanism of M82 X-1, we analyzed the ASCA spectra of M82 X-1, and compared the HLX M82 X-1 with the ULXs.

Throughout this paper, errors and uncertainties refer to 90% confidence limits. We assumed that the distance to M82 is 3.9 Mpc (Sakai & Madore 1999).

1.2 Analysis and Results

ASCA observed M82 ten times from 1993 to 1996, and we analyzed the data of all observations. Detailed descriptions about the observations and the data reductions are given in Matsumoto & Tsuru (1999).

We fitted the ASCA spectra with a 2 RS + MCD model described as

$$N_{\rm H}^{\rm whole} \times ({\rm RS}^{\rm soft} + N_{\rm H}^{\rm medium} \times {\rm RS}^{\rm medium} + N_{\rm H}^{\rm hard} \times {\rm MCD}^{\rm hard}), \tag{1.1}$$

where $N_{\rm H}$ is the absorbing column density, and RS is a thin thermal plasma model (Raymond & Smith 1977), and MCD is a multicolor disk blackbody (MCD) model (Mitsuda et al. 1984; Makishima et al. 2000). The MCD model is a good approximation to X-ray emission predicted by a standard accretion disk model (Shakura & Sunyaev 1973), and is characterized by the innermost disk temperature ($T_{\rm in}$) and the bolometric luminosity ($L_{\rm bol}$). The innermost disk radius ($R_{\rm in}$) can be calculated from them. We fixed the parameters of the soft and medium components other than their normalizations to the best-fit values of Tsuru et al. (1997): $N_{\rm H}^{\rm whole} = 3.0 \times 10^{21}{\rm cm}^{-2}$, $N_{\rm H}^{\rm medium} = 0.0 \times 10^{21}{\rm cm}^{-2}$, $kT^{\rm soft} = 0.32$ keV, $kT^{\rm medium} = 0.95$ keV, He = C = 1.0 cosmic, N = 0.0 cosmic, O = 0.063 cosmic, Ne = 0.15 cosmic, Mg = 0.25 cosmic, Si = 0.40 cosmic, S = 0.47 cosmic, Ar = Ca = 0.0 cosmic, and Fe = Ni = 0.049 cosmic. Free parameters are thus the normalizations of the soft, medium, and hard components, $N_{\rm H}^{\rm hard}$, and $T_{\rm in}$.

The 2RS + MCD model can describe the ASCA spectra quite well. The obtained parameters are $kT_{\rm in} = 1.70 - 2.91$ keV, $L_{\rm bol} \cos i = 1.8 - 7.4 \times 10^{40}$ erg s^{-1}, and $R_{\rm in}\sqrt{\cos i} = 64 - 205$ km, where i is the inclination angle of the disk.

1.3 Discussion

Assuming $L_{\rm bol}$ is sub-Eddington, the mass of M82 X-1 must be larger than $490(\cos i)^{-1}$ $M_\odot$. We also estimated an upper limit on the mass to be $7(\cos i)^{-0.5}$ $M_\odot$ by assuming that $R_{\rm in}$ is larger than the last stable orbit around a Schwarzschild black hole (BH), which is $3R_{\rm s} = 6GM/c^2$. Then, we face a serious problem that the upper limit is much smaller than the lower limit. This problem is essentially the same as the "too hot accretion disk problem" seen in ULXs (Makishima et al. 2000); the $kT_{\rm in}$ of ULXs ($1 - 2$ keV) is too high to be reconciled with their BH mass required to explain their luminosity. The problem of ULXs may be solved by invoking a Kerr BH, since the last stable orbit is $0.5R_{\rm s}$ (Makishima et al. 2000). However, even if we assume a Kerr BH, the upper limit on the mass of M82 X-1 is $42 \cos^{-0.5} i$ $M_\odot$, which is still much smaller than the lower limit.

Figure 1 is the X-ray H-R diagram of M82 X-1 and ULXs (Makishima et al. 2000;

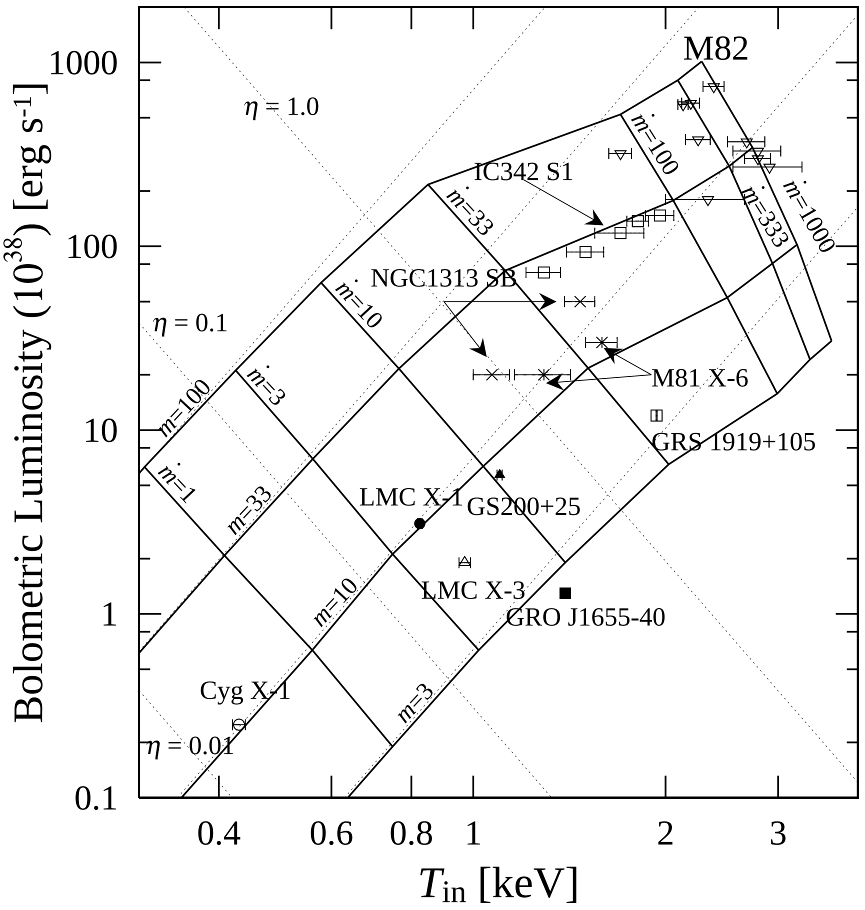

Fig. 1.1. X-ray H-R diagram of M82 X-1 (triangles) and other ULXs (other symbols). Solid lines represent the constant black hole mass ($m = M/M_\odot$) and constant mass accretion rate ($\dot{m} = \dot{M}/\dot{M}_{\rm crit}$) predicted by a slim-disk model. Dotted lines are the same but based on the standard accretion disk theory ($\eta \equiv L_{\rm bol}/L_{\rm Edd}$). We assume face-on geometry ($i = 0°$).

Mizuno, Kubota, & Makishima 2001), which shows the relation between $T_{\rm in}$ and $L_{\rm bol}$. Not only $L_{\rm bol}$ but also $T_{\rm in}$ of M82 X-1 is higher than those of ULXs. The most striking feature is that there is no correlation between $T_{\rm in}$ and $L_{\rm bol}$, while there is a positive correlation between those of ULXs.

If a mass accretion rate is close to or larger than the critical rate ($\dot{M}_{\rm crit} \equiv L_{\rm Edd}/c^2$, where $L_{\rm Edd}$ is the Eddington luminosity), theory predicts that an accretion disk becomes a slim disk (e.g. Abramowicz et al. 1988). Although the MCD formalism was originally developed to approximate X-rays from standard disks, Watarai et al. (2000) found that the MCD model is also a good approximation to X-ray spectra from slim disks, if we limit the energy of the X-rays to the ASCA band (0.5 – 10 keV). Watarai, Mizuno, & Mineshige (2001) then found that the H-R diagram of ULXs can be explained by the slim disk model with constant BH mass and a varying mass accretion rate. The solid lines in Figure 1 show the predictions of the slim disk model. Clearly the slim disk model with constant BH mass is inconsistent with the behavior of M82 X-1.

M82 X-1 may be a beaming object (King et al. 2001). However, if M82 X-1 is a jet source and the jet points toward us, we would expect synchrotron radio emission from the jet. Although there are two radio sources at the position of M82 X-1, they are likely supernova remnants rather than a jet source (Matsumoto et al. 2001). Furthermore, the hard X-ray emission of M82 cannot be fitted by a power-law model (Tsuru 1992; Cappi et al. 1999). We therefore think M82 X-1 is unlikely to be a jet source. Simultaneous X-ray and radio observations will make it much clear.

1.4 Conclusion

The HLX M82 X-1 is a strong candidate for an IMBH, and we analyzed its ASCA spectra using the MCD model. We can estimate the upper and lower limits on the mass of M82 X-1 using the MCD parameters, but the lower limit is much larger than the upper limit. We compared M82 X-1 with ULXs, and found that M82 X-1 shows not only larger $L_{\rm bol}$ but also higher $T_{\rm in}$ than ULXs. Although there is a positive correlation between $L_{\rm bol}$ and $T_{\rm in}$ of ULXs, M82 X-1 does not show such a correlation. These characteristics are not consistent with the theoretical models which might be explained ULXs. This may suggest either that some important processes we overlook play an important role in such luminous objects, or that the HLX M82 X-1 is a different kind of object from ULXs.

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