THE SPECTRAL AND TEMPORAL PROPERTIES OF AN ULTRALUMINOUS X-RAY SOURCE IN NGC 6946

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ABSTRACT

We report variability of the X-ray source, X-7, in NGC 6946, during a 60 ks Chandra observation when the count rate decreased by a factor of ~1.5 in ~5000 s. Spectral fitting of the high and low count rate segments of the light curve reveal that the simplest and most probable interpretation is that the X-ray spectra are due to disk blackbody emission with an absorbing hydrogen column density equal to the Galactic value of $2.1 \times 10^{21}$ cm$^{-2}$. During the variation, the inner disk temperature decreased from $\sim 0.29$ to $\sim 0.26$ keV while the inner disk radius remained constant at $\sim 6 \times 10^8$ cm. This translates into a luminosity variation from $3.8 \times 10^{39}$ ergs cm$^{-2}$ s$^{-1}$ and a black hole mass of $\sim 400 M_\odot$. More complicated models like assuming intrinsic absorption and/or the addition of a power-law component imply a higher luminosity and a larger black hole mass. Even if the emission is beamed by a factor of ~5, the size of the emitting region would be $\sim 2.7 \times 10^9$ cm, implying a black hole mass $\sim 180 M_\odot$. Thus, these spectral results provide strong evidence that the mass of the black hole in this source is definitely $\gg 100 M_\odot$ and more probably $\sim 400 M_\odot$.

Subject headings: accretion, accretion disks — galaxies: individual (NGC 6946) — X-rays: binaries

1. INTRODUCTION

Chandra observations of nearby galaxies, have confirmed the presence of nonnuclear X-ray point sources (Kaaret et al. 2001; Matsumoto et al. 2001; Zezas & Fabbiano 2002), which have luminosities $>10^{39}$ ergs s$^{-1}$ and hence have been called ultraluminous X-ray sources (ULXs).

Since these sources radiate at a rate greater than the Eddington luminosity for a 10 solar mass black hole, they are believed to harbor a black hole of mass $10 M_\odot < M < 10^2 M_\odot$ (Colbert & Mushotzky 1999; Makishima et al. 2000), where the upper limit is constrained by the argument that a more massive black hole would have settled into the nucleus due to dynamical friction (Kaaret et al. 2001). If this interpretation is true, then these black holes have mass in the intermediate mass range between those of stellar mass black holes found in Galactic X-ray binaries and those associated with active galactic nuclei and hence are called intermediate-mass black holes (IMBHs). For a review see Miller et al. (2004) and Miller (2005).

The creation of such black holes (Portegies Zwart & McMillian 2002; Taniguchi et al. 2000; Madau & Rees 2001), and the process by which they sustain such high accretion rates (King et al. 2001), are largely unknown and when understood are expected to make radically shifts in the present paradigms of stellar and binary evolution and the history of the universe. On the other hand, alternate models for ULX challenge our present understanding of accreting systems such as super-Eddington disks (Beigelman 2002) or emission that is beamed from a geometrically thick accretion disk (King et al. 2001). For the latter case, it has been argued that such thick “funnel” shaped disks enhance the observed flux by just a factor of few (Misra & Sriram 2003). Thus, it is important to ascertain whether ULX do indeed harbor IMBH or not.

Since a more direct measure of the mass such as spectroscopic mass function measurement of the binary, is not possible for ULX, indirect evidences have to be used. One such way is to look for similarities in the spectral and temporal properties of ULX and black hole X-ray binaries. There are theoretical indications that the nature of the accretion flow should depend on the Eddington ratio $L/L_{Edd}$ rather than on the actual values of the bolometric luminosity $L$ and the Eddington limit $L_{Edd}$. Thus, a ULX should display similar spectral and temporal characteristics as a black hole X-ray binary accreting at a similar $L/L_{Edd}$ even though the masses of the black holes are different.

If ULX harbor IMBH, they should display analogs spectral states to X-Ray binaries. Based on such a analogy, Yuan et al. (2007) modeled the X-ray spectrum detected by Chandra of the ULX X-1 in M82, within the framework of advection-dominated accretion flows (ADAFs), which successfully explains the hard state spectra of X-ray binaries. They found that if the source is likened to the low-luminosity hard state, then the black hole mass should be $M \sim 10^3 M_\odot$; else it should be $\sim 10^4 M_\odot$ if the system is to be compared with the high-luminosity hard state. This degeneracy occurs because the observed spectrum during an off axis observation by Chandra (the source is affected by count pileup for normal observations) was a featureless power law, as it should be if it is an analogs to the hard state. XMM-Newton observations of the source reveal a more complex turnover at around $\sim 8$ keV (Agrawal & Misra 2006), which could either be because the spectral state was different during the XMM-Newton observation or that there were serious contamination from nearby sources. However, Stobbart et al. (2006) report that many ULX observed by XMM-Newton do show such high energy turnovers, which makes the comparison with the hard state of black hole binaries ambiguous.

A more robust argument would be provided if a ULX reveals soft-state-like spectral property. In the pure soft state of X-ray binaries, the luminosity is dominated by emission from a standard disk that extends to the last stable orbit. During this state, the high-energy power-law component (which is dominant during the low and intermediate states) contributes $<5\%$ of the total luminosity. The state occurs when the Eddington ratio $>$0.2. During luminosity variations (typically for X-ray novae) the constancy of the inner most radius and its value being always close to the predicted last stable orbit is taken as strong evidence for the correctness of the model. In fact, based on the model, recent attempts have been
made to estimate the spin of black holes by measuring the subtle strong gravity effects of light bending and redshift on the spectra (e.g., McClintock et al. 2006). The analogy to ULX predicts that they should exhibit a similar disk black-body component with a smaller inner disk temperature, due to the larger black hole mass. Indeed, Miller et al. (2003) report the presence of a power-law spectrum with a cool accretion disk component \( \text{\textit{kT}}_{\text{in}} \sim 0.1\text{--}0.5\text{ keV} \) in NGC 1313 X-1 and X-2 corresponding to black hole masses \( M \sim 10^4 M_{\odot} \). A comparison of ULX which show such soft components with X-ray binaries has been undertaken by Miller et al. (2004), who argue that the systematic lower temperatures indicate that the systems harbor IMBH, but also caution for potential weakness of such interpretations. The primary issue is the possibility of incorrect spectral modeling especially of data with low counts (Gonçalves & Soria 2006). The soft component is strongly effected by absorption and errors in the estimation of the column density may crucially affect the results. Another perhaps inconsistent aspect is that for these systems, the power-law component is nearly as luminous as the disk one and hence an analogy has to be made with the rarer very high state (VHS) rather than the more frequent pure soft state. Moreover, since the power-law component is an important contributor to the flux, the modeling of the disk component is suspect to the uncertainties in modeling the power-law one.

The existence of ULX in different spectral states may also be revealed in a systematic spectral study of a large sample of potential sources (Winter et al. 2006). Swartz et al. (2004) fitted the spectra of such a large sample with an absorbed power-law model and found no bimodal distribution on the spectral index. However, using a disk blackbody model, a bimodal distribution was revealed, at least for high-luminosity sources for samples obtained from XMM-Newton (Winter et al. 2006) and Chandra (Devi et al. 2007). One set of high-luminosity sources have temperatures \( kT \sim 0.1\text{ keV} \), while the other have systematically higher temperatures \( kT \sim 1\text{ keV} \). While the higher temperature sources do not seem to have an analogy with black hole binaries, the lower temperature one may be identified as the equivalent of the soft state. For a sample consisting of sources observed by Chandra which were not affected by pileup and which were not located in regions of excessive diffuse emission, Devi et al. (2007) fitted both an absorbed power law and a disk blackbody spectral model to ascertain the dependency of luminosity on the spectral model used. They identified a highly luminous source, X-7, in NGC 6946 as having a soft spectrum and with sufficiently high counts for more detailed studies.

In the next section we report on spectral and temporal analysis of the Chandra observation of this source and summarize and discuss the results in the last section.

2. SPECTRAL AND TEMPORAL PROPERTIES OF NGC 6946, X-7

While the temporal behavior of all the sources examined by Devi et al. (2007) will be presented elsewhere, here we report on the ks variability observed for source X-7, (R.A. = 20°35'0.13" and decl. = +60°9'7.97" [J2000.0]) in NGC 6946. The source is a known variable source (Liu & Mirabel 2005; Lira et al. 2000) and has been called IFO 85 (Colbert & Ptak 2002) and source no. 56 (Holt et al. 2003).

NGC 6946 was observed by Chandra for an effective time of 59 ks on 2001 September 7 (ObsID 1043). The data reduction and analysis were done using CIAO3.2 and HEASOFT6.2. Using a combination of CIAO tools and calibration data, the source (background) spectrum and light curve were extracted. Spectral fitting was done over the energy range 0.3–8 keV, and spectra were rebinned such that each bin had a minimum of 40 counts. The distance to the source has been estimated to be between 5.1 Mpc (de Vaucouleurs 1979) and 5.9 Mpc (Karachentsev et al. 2000), and hence we adopt here a distance of 5.5 Mpc.

The light curve binned over 2 ks is shown in Figure 1, where a clear transition from high to low count rate is visible. The probability that the count rate was a constant during the observations is \(<2 \times 10^{-10}\). The bottom panel of the Figure shows the hardness ratio versus time binned over 8000 s. The ratio is defined as the ratio between flux in the 0.3–1.0 keV band over that in the 1.0–2.0 keV band. While the higher temperature sources do not seem to have an analogy with black hole binaries, the lower temperature one may be identified as the equivalent of the soft state. For a sample consisting of sources observed by Chandra which were not affected by pileup and which were not located in regions of excessive diffuse emission, Devi et al. (2007) fitted both an absorbed power law and a disk blackbody spectral model to ascertain the dependency of luminosity on the spectral model used. They identified a highly luminous source, X-7, in NGC 6946 as having a soft spectrum and with sufficiently high counts for more detailed studies.

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$N_D \sim 10^{22}$ cm$^{-2}$ but with a large unphysical photon index of $\Gamma > 5$. On the other hand, as shown in Table 1 and illustrated in Figures 2 and 3, an absorbed disk blackbody model with the column density at the Galactic value, provides adequate fits to both segments. The inner radius of the disk $R_{in}$ is computed from the normalization of the disk blackbody component using the distance to the source $D = 5.5$ Mpc, the viewing angle $\cos \ i = 0.5$ and color factor $f = 1.7$. The result and implications are better represented in Figure 4, where confidence region ellipses are shown for the two parameters $R_{in}$ and inner disk temperature $T_{in}$.

The figure reveals that the simplest and more favored interpretation is that the inner disk radius remains constant, while the temperature decreases during the variation. Assuming that $R_{in} \sim 10GM/c^2$, the black hole mass, $M$, can be estimated and confidence ellipses for $M$ and total bolometric luminosity are shown in Figure 5. A black hole mass of $M \sim 400 M_\odot$ is favored for both
sets while the luminosity decreases from $\sim 3.7$ to $\sim 2.8 \times 10^{39}$ ergs s$^{-1}$, corresponding to an Eddington ratio, $L/L_{\text{Edd}} \sim 0.06$.

It is worth emphasizing that the above interpretation is the simplest one which provides acceptable fit to the data and requires the smallest black hole mass. If one allows for intrinsic absorbing column density, the best-fit temperature decreases and the inner radius increases implying a larger black hole mass. For example, a simple model could be that the variation is only due to changes in the intrinsic column density. A model where the column density is allowed to vary, with $R_{\text{in}}$ and $T_{\text{in}}$ same for both segments, indeed gives an acceptable combined $\chi^2/\text{dof} = 36.9/32$, with $N_{\text{H}}$ increasing from $3 \pm 0.4$ to $3.9 \pm 0.4 \times 10^{21}$ cm$^{-2}$ and inner disk temperature $T_{\text{in}} = 0.22 \pm 0.1$ keV. The inner disk radius turns out to be $1.5 \pm 0.3 \times 10^{9}$ cm corresponding to a $\sim 950 M_{\odot}$ black hole. If the column density and temperature are allowed to vary independently for the two segments, $\chi^2/\text{dof} = 29/29$, with $R_{\text{in}} = 1.3 \pm 0.4 \times 10^{9}$ cm corresponding to $M \sim 900 M_{\odot}$. An additional power-law component with photon index $\Gamma = 2.0$ or $\Gamma = 2.7$ does not improve the fit if the column density is fixed at the Galactic value. For $N_{\text{H}} \sim 6 \times 10^{21}$, a disk blackbody and a power-law component with $\Gamma = 2$, provides a good fit to both segments $\chi^2/\text{dof} = 19.9/27$. Here, the variability is due to a change of normalization of the power-law component, while the temperature $T_{\text{in}} \sim 0.13$ keV and $R_{\text{in}} \sim 1.2 \times 10^{10}$ cm remain nearly constant.

In these more complicated interpretations $R_{\text{in}}$ is significantly larger implying a larger black hole mass.

3. SUMMARY AND DISCUSSION

The X-ray source X-7 in NGC 6946 is located in a region of low diffuse emission and has a count rate which does not cause pileup in Chandra detectors. The light curve of this source reveals a decrease of $\sim 1.5$ in the count rate over 5000 s making it one of the few ULX that have clearly shown variability on ks time-scales (Krauss et al. 2005; Mizuno et al. 2001).

Spectral fitting of the high and low count rate parts of the light curve reveals that a simple model of a disk blackbody emission absorbed by the Galactic column density of $N_{\text{H}} = 2.1 \times 10^{21}$ cm$^{-2}$ can adequately represent both segments. The best-fit temperature varies from 0.26 to 0.29 keV while the inner disk radius remains constant at $\sim 6 \times 10^{8}$ cm. This would imply that the mass of the black hole is $\sim 400 M_{\odot}$ and at a luminosity of $\sim 3 \times 10^{39}$ ergs s$^{-1}$ the system has an Eddington ratio of $\sim 0.06$. Other more complicated spectral fits like assuming intrinsic column density for the source and/or addition of a power-law component results in a larger estimation of inner disk radius and hence a larger black hole mass. Although the luminosity of the source estimated here is only mildly super-Eddington for a 10 solar mass black hole, the low inner disk temperature $\sim 0.3$ keV implies a larger inner disk radius and hence a larger black hole mass $\sim 400 M_{\odot}$. A low sub-Eddington accretion rate on a 10 solar mass black hole could produce the observed low inner disk temperature, but then the predicted luminosity would be significantly less than what is observed. As cautioned by Miller et al. (2004) the source could be a background AGN and the soft component observed is actually the soft excess which is detected in many AGN. These soft excesses can be modeled as blackbody emission at $kT \sim 0.1$ keV similar to the soft component in ULX. While this may be true for some ULX, this is unlikely in this case because here (unlike soft excess of AGN) the soft component totally dominates the luminosity.

If the emission is beamed (King et al. 2001) by a factor $\eta$, the inner disk radius would be overestimated by $\eta^{1/2}$. However, even for extreme geometries Misra & Sridhar (2003) have computed $\eta < 5$. Hence an extreme beaming of $\eta \sim 5$, would imply that $R_{\text{in}} \sim 2.7 \times 10^{8}$ cm corresponding to a black hole mass of $180 M_{\odot}$. The color factor used in this analysis is the standard value of 1.7. Even for the extreme case that there is no color correction, $R_{\text{in}} \sim 2 \times 10^{9}$ cm corresponding to a black hole mass of $130 M_{\odot}$. Thus only in the extremely unlikely case of having no color correction and high beaming factor $\eta \sim 5$ would the black hole mass be $< 100 M_{\odot}$.

A model can be envisioned where the inner disk radius is not at $100 G\, cm^2$ but is at a much larger radius, say, $100G\, cm^2$, with the inner region being highly radiatively inefficient. Then the mass of the black hole could be $\sim 40 M_{\odot}$. However, to produce a luminosity of $\sim 2 \times 10^{39}$ ergs s$^{-1}$ at $100 G\, cm^2$ would require an accretion rate which is 50 times the Eddington value, and it is not clear how the inner region would remain radiatively inefficient at such accretion rates. A more radical model would be that the emission arises from an optically thick sphere of radius $\sim 100 G\, cm^2$ surrounding a $40 M_{\odot}$ black hole, but that would be a serious paradigm shift from our present understanding of accretion flows.

In a contemporary work, Fridriksson et al. (2008) have studied the long-term variability of sources in NGC 6946 using five Chandra observations. They confirm the variability of this source (their source no. 60) for this observation, but not for the others. They detect long-term flux variability for the different observations. Their hardness ratio estimations confirm the soft nature of this source for all the observations.

The results presented here indicate that the black hole mass of this source is $> 400 M_{\odot}$ which may be true for other supersoft X-ray sources and for ULX in general. However, further analysis of data of this and other supersoft sources are required to ascertain whether such temporal and spectral behavior is common among ULX.

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