ACCRETION DISK SPECTRA OF THE BRIGHTEST ULTRALUMINOUS X-RAY SOURCE IN M82

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ABSTRACT

Emission spectra of hot accretion disks characteristic of advection-dominated accretion flow (ADAF) models are investigated for comparison with the brightest ultraluminous source, X-1, in the galaxy M82. If the spectral state of the source is similar to the low-luminosity hard state of stellar mass black holes in our Galaxy, a fit to the Chandra X-ray spectrum and constraints from the radio and infrared upper limits requires a black hole mass in the range of \( 9 \times 10^4 \text{\( M_{\odot}\) to} 5 \times 10^5 \text{\( M_{\odot}\).} \) Lower black hole masses (\( \leq 10^4 \text{\( M_{\odot}\)} \)) are possible if M82 X-1 corresponds to the high-luminosity hard state of Galactic black hole X-ray binary sources. Both of these spectrally degenerate hot accretion disk solutions lead to an intermediate-mass black hole interpretation for M82 X-1. Since these solutions have different spectral variability with X-ray luminosity and predict different radio/infrared emission, they could be distinguished by future off-axis Chandra observations or simultaneous sensitive radio/infrared detections.

Subject headings: black hole physics — galaxies: individual (M82) — X-rays: galaxies

1. INTRODUCTION

Ever since the discovery of ultraluminous X-ray sources (ULXs) in external galaxies with the Einstein satellite (see Fabbiano 1989), much attention has focused on their nature, since they represent a class of abnormally bright X-ray sources (\( \sim 10^{39} \text{\( -\) } 10^{41} \) ergs s\(^{-1}\)). The existence of temporal variability on a time of scales in this subpopulation suggests that these systems are accreting objects. For recent reviews, see Miller & Colbert (2004) and Miller (2005). Within this framework, ULXs have been considered as either stellar mass black holes accreting at super-Eddington rates or intermediate-mass black holes (IMBHs) accreting at sub-Eddington rates (see Colbert & Mushotzky 1999; Makishima et al. 2000). For stellar mass black holes, super-Eddington luminosities (by a factor of 10) can be produced from optically thick, slim accretion disks (Watarai et al. 2001). Alternatively, apparently super-Eddington luminosities can result in circumstances where significant beaming of radiation can occur (King et al. 2001; Begelman 2002; Körding et al. 2002), with enhancement factors ranging from less than 5 for funnel-shaped disks (see Misra & Srim 2003) to \( \sim 100 \) for a beamed relativistic jet (see Körding et al. 2002). In both descriptions, the effect is directionality dependent and is maximal for face-on viewing. We note that the theoretical models that invoke beaming do not address the spectrum of ULXs, as the primary focus is toward providing an understanding of the luminosity. In the IMBH interpretation, the challenge is to provide an understanding for the formation of such massive black holes.

In addition to their high X-ray luminosities, hints as to their nature should also be revealed by their emission spectra. Spectral transitions, similar to those seen in Galactic black hole systems, have been reported in NGC 1313 X-1 (Colbert & Mushotzky 1999) and two sources in IC 342 (Kubota et al. 2001). Analysis of XMM-Newton data revealed the presence of a cool accretion disk component (\( kT_{\text{in}} \sim 0.1 \text{\( -\) } 0.5 \text{\( \text{keV}\)} \)) in NGC 1313 X-1, X-2 (Miller et al. 2003), and M81 X-9 (Miller et al. 2004), which suggested that these sources harbor IMBHs. However, Gonçalves & Soria (2006) have argued that such soft spectral components depend on the complexity of the fitting model. Indeed, the spectra of ULXs have been fitted by a variety of empirical and physical models, including an absorbed power law, a multitemperature disk blackbody, spectral cutoffs, and/or a combination of the above. While an absorbed power law can adequately represent most (but not all) of the spectra observed by Chandra, spectral fits of bright ULXs observed by XMM-Newton often require a spectral break or cutoff above 2 \( \text{\( \text{keV}\)} \) (Stobbart et al. 2006). In general, the spectra of ULXs reveal a diversity of spectral shapes, suggesting that the sources identified as ULXs are a heterogeneous class and/or exhibit various spectral states. Thus, a detailed spectral study of a single source may offer better evidence of the presence (or absence) of IMBHs.

In attempting to distinguish between the accreting stellar mass and IMBH models, detailed calculations of the emission spectrum from an accretion disk surrounding the black hole are required. Specifically, a fitting of both the luminosity and spectrum of a source is necessary to quantitatively confront the theoretical models with observations. Among the ULXs, the bright ULX source X-1 in M82 is a very promising candidate for this purpose because its luminosity has been measured to be as high as \( 1.6 \times 10^{41} \) ergs s\(^{-1}\) (Pak & Griffiths 1999). The early XMM-Newton spectral (Fiorito & Titarchuk 2004; Agrawal & Misra 2006) and temporal observational results (Strohmayer & Mushotzky 2003) may not be conclusive because recent Chandra observations (taken on 2005 February 4–5) by Kaaret et al. (2006) revealed that there are two bright, nearly X-ray sources, which would be contributing to the XMM-Newton flux. We note that the observation of Kaaret et al. (2006) was taken such that M82 X-1 was off axis, and hence the data were not affected by pile-up effects. This allowed, for the first time, an unambiguous (i.e., with possibly little contamination) measurement of the source spectral properties. The spectrum of the brightest X-ray source, X41.4+60, is well described by a power law with photon index of \( \Gamma = 1.67 \pm 0.02 \), with an isotropic luminosity in the 2–10 \( \text{\( \text{keV}\)} \) energy range of \( 2.4 \times 10^{40} \) ergs s\(^{-1}\). Hereafter we use the name M82 X-1 to denote X41.4+60.

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It is reasonable to hypothesize that the hydrodynamic and radiative models invoked for explaining the spectra of stellar mass black holes could also be applicable to systems with IMBHs. It is well known that observationally stellar mass black hole systems exhibit different spectral states, denoted as quiescent, hard/low, intermediate, soft/high, and very high (or steep power law) states (see McClintock & Remillard 2006 for a review). These states are distinguished by their spectral and timing properties. For example, in a typical hard state, the X-ray spectrum is well described by a power-law form with $\Gamma = 1.5-2.1$, and the radio emission is relatively strong. On the other hand, the X-ray spectrum is much steeper in the soft state, with $\Gamma = 2.1-4.8$ and no detectable radio emission. With respect to their timing properties, the integrated power spectrum is usually strong in the hard state and often exhibits a quasi-periodic oscillation (QPO). This is in contrast to the timing properties in the soft state, where the power spectrum is very weak and QPOs are not observed. It is possible that the spectral states of ULXs can be similarly described. This idea has been invoked in the study of ULXs by Winter et al. (2006), and what is more, similar state transitions to those in stellar mass black holes have been detected for two ULXs in NGC 1313 (Feng & Kaaret 2006).

The spectrum of M82 X-1 unambiguously resembles the low/hard state of Galactic black hole X-ray binary systems, which is much harder than that of the very high state. Therefore, it is possible that M82 X-1 can be explained in terms of emission from an advection-dominated accretion flow (ADAF), since such accretion flows have been successfully applied to understand the properties of the hard state of these binary systems (McCIntock & Remillard 2006). Thus, this source is an ideal candidate to investigate whether, indeed, these systems can also be described by ADAF solutions and to test the hypothesis that they harbor IMBHs. Moreover, there are radio and infrared observations of this region that, as is described in a later section, place further constraints and consistency checks on these models.

In this paper, we focus on the calculation of the theoretical spectrum of M82 X-1 and present a detailed emission spectrum from a hot accretion disk model, as applied to ULXs. A number of calculations have been carried out for a range of black hole masses, mass accretion rates, and other input parameters, with the goal of fitting the observed X-ray spectrum, as well as the isotropic X-ray luminosity (since beaming is unimportant in such models), to provide constraints on the properties of the system. In the next section, we provide a description of the accretion disk model, which forms the basis of our study, and the parameters used to fit the spectrum. The numerical results of the detailed emission spectrum are presented for a range of black hole masses and mass flow rates in the disk, and compared to the observed spectrum of M82 X-1 in $\S$ 3. Finally, we discuss the implications of our results and conclude in the last section.

2. MODEL DESCRIPTION

The origin of the X-ray emission characterizing the hard state is very likely due to the Comptonization process of soft photons by thermal electrons in a hot accretion-disk corona (see e.g., Zdziarski [2000] and Zdziarski & Gierliński [2004] for reviews). Such a corona may be produced during the process of magnetic reconnection above the standard thin disk (Liang & Price 1977; Galeev et al. 1979). However, this process is poorly understood, and detailed models have yet to be developed. Moreover, Esin et al. (2001) show that in the case of XTE J1118+480, the EUV data requires that the standard thin disk must be truncated at a certain radius. On the other hand, a hot corona is a natural consequence of an ADAF (Narayan et al. 1998), which is dynamically well described, and hence its astrophysical applications can be examined in detail.

In this paper, we concentrate on the ADAF model. Narayan (1996) and Narayan et al. (1996) first proposed to apply the ADAF to the hard state of stellar mass black holes. Subsequently, Esin et al. (1997) presented detailed calculations applied to Nova Musae 1991. Yuan et al. (2005) further developed the Esin et al. (1997) model by taking into account the presence of outflows in ADAFs (Blandford & Begelman 1999) and by including a jet component, which appears to be always present in the hard state (Fender 2006).

Briefly, the hard spectral state can be described in terms of an accretion flow consisting of two components, namely a standard thin disk external to a transition radius $r_t$, and an ADAF (or luminous hot accretion flow; see Yuan et al. 2007 for details) interior to it. We assume that only a fraction of the mass flow rate at $r_t$ accretes onto the black hole, with the remainder ejected in the form of an outflow. The strength of this outflow is described by a parameter $s_0$. The possible existence of this outflowing material was hypothesized in analytical work (Narayan & Yi 1994; Blandford & Begelman 1999) and has been confirmed in numerical simulations (Stone et al. 1999; Hawley & Balbus 2002; Igumenshchev et al. 2003). Following Yuan et al. (2005), we assume that $M(r) = M_0$ for $r \geq r_t$, and

$$\frac{d \ln M(r)}{d \ln r} = s(r), \quad r < r_t,$$

where

$$s(r) = s_0 \max(f(r), 0),$$

and $s_0$ is independent of $r$. Here, the advection term $f(r)$ is defined as the ratio of the rates of energy advection to viscous heating. When $M$ is very low, $f(r) = 1$ and $s(r) = s_0$. In this case, equation (1) gives us the usual form, $M = M_0(r/r_t)^{\alpha}$ (e.g., Blandford & Begelman 1999), where $M_0$ is the accretion rate at $r_t$. In the innermost regions, some fraction of the inflowing material is assumed to be redirected to flow in the vertical direction as a jet. We denote the mass loss rate in the jet as $M_{\text{jet}}$. The X-ray emission in the hard state in this model originates from the thermal Comptonization of seed photons associated with synchrotron emission in the ADAF. We note that there are other possible sources of seed photons, such as the soft photons from the standard thin disk exterior to $r_t$ or possibly the existence of cold clumps within the hot accretion flow, which may be important in some cases (see $\S$ 3 and 4). The temperature of the thin disk for $r > r_t$ is determined by the local viscous dissipation and the nonlocal irradiation from the inner ADAF. The optical radiation and infrared/radio emission in the hard state arise mainly from this thin disk and the jet, respectively.

The determination of the emission spectrum from the accretion disk model requires specifying a number of input parameters. In addition to the mass of the black hole, $M$, and mass accretion rate $M_0$, the viscous parameter $\alpha$, the “magnetic” parameter $\beta$ (describing the strength of the magnetic field), the fraction of viscous dissipation that directly heats electrons, $\delta$, the transition radius $r_t$, and $s_0$ must be chosen. Among these parameters, the values of $\alpha$, $\beta$, and $\delta$ are determined by the microphysical processes associated with the magnetohydrodynamic (MHD) driven turbulence in the disk. We assume that these parameters do not differ appreciably among different sources, including supermassive black hole sources, Galactic X-ray binaries, ULXs, and M82 X-1 in particular. The MHD numerical simulations of accretion flows and previous
ADAF modeling of several well-studied sources constrain their values to a narrow range (e.g., Hawley & Krolik 2001; Yuan et al. 2003). Based on extensive calculations covering a wide range of values, the spectral results are insensitive to the particular choices. Hence, we fix their values as $\alpha = 0.3$, $\beta = 0.9$, and $\delta = 0.5$. The value of the transition radius $r_s$ is unimportant for the determination of the X-ray spectrum and mainly affects the optical/UV spectrum, where data are currently lacking. Its value is therefore unimportant for our study, and we set $r_s = 100r_g$, where $r_g \equiv 2GM/c^2$. The most important parameters affecting our modeling are the remaining three parameters, i.e., $M$, $M_\text{d}$, and $s_0$. The values of $M$ and $M_\text{d}$ are completely unknown, and obtaining estimates for their values is our primary goal. Although a value of the remaining parameter, $s_0$, has been inferred from the ADAF modeling of sources such as Sgr A* and XTE J1118+480 (Yuan et al. 2003, 2005), we do not restrict $s_0$, instead allowing it to vary in a range as wide as possible. Thus, in order to obtain a satisfactory fit to the X-ray spectrum, these three parameters are varied.

In order to explain the radio emission (see below), a separate jet component is required in addition to the accretion flow, as in the case of Galactic black hole X-ray binaries (e.g., Yuan et al. 2005; Fender 2006). We use the internal shock scenario, which is widely adopted in the study of gamma-ray burst afterglows, to calculate the jet emission (Yuan et al. 2005 for details). Briefly, internal shocks within the jet occur due to collisions of shells with different velocities. The shocks accelerate a fraction of the electrons into a power-law energy distribution. The energy of the electrons and the strength of the magnetic field after the shock are determined by two parameters, $e_\text{e}$ and $e_B$, which give the fraction of the shock energy transferred into the accelerated electrons and the (amplified) magnetic field, respectively. The radiative transfer in the jet is calculated to obtain the emitted spectrum. We would like to emphasize, however, that large uncertainties exist in the jet model, and its solution is not unique. Fortunately, the jet emission is usually negligible in the X-ray band (see Fig. 1) and thus will not affect the result of our paper.

3. EMISSION SPECTRUM OF M82 X-1

3.1. Observed Spectrum

The X-ray data of Kaaret et al. (2006) are described by a power-law spectrum with photon index of $\Gamma = 1.67$ and a 2–10 keV isotropic luminosity of $2.4 \times 10^{40}$ ergs s$^{-1}$. In addition to the data in the X-ray regime, we also include data in the radio and infrared wavelengths in Figure 1. Kaaret et al. (2006) conducted four VLA observations at a frequency of 8.5 GHz, between 2005 January 29 and 2005 February 5. We choose the radio data taken on 2005 February 5, since it is the closest in time (same day) to the Chandra observation. The radio position is offset by $\sim 1''$ relative to the position of the brightest X-ray source (X41.4+60) in M82, and only a marginal detection of a radio flux of $0.5 \pm 0.1$ mJy has been obtained. However, Kaaret et al. (2006) argue that due to the uncertainty of the Chandra X-ray position, the radio and X-ray sources are very likely the same. The corresponding isotropic radio luminosity was found to be $(6.7 \pm 1.3) \times 10^{40}$ ergs s$^{-1}$ for an assumed distance of 3.63 Mpc. An upper limit for the infrared luminosity for M82 X-1 is also shown based on near-infrared observations of the associated star cluster MGG 11 with the 10 m Keck II telescope on 2002 February 23 (McCready et al. 2003). Magnitudes of $13.10 \pm 0.15$ at 1.6 $\mu$m and $12.03 \pm 0.05$ at 2.2 $\mu$m were determined. By de-reddening the spectrum due to extinction, McCready et al. (2003) estimate a light-to-mass ratio $L/M$ of $(3.5 \pm 1.0) \times 10^5 M_\odot$ for MGG 11 at 1.6 $\mu$m. Estimating the mass of MGG 11 to be $(3.5 \pm 0.1) \times 10^5 M_\odot$, they find an infrared luminosity of MGG 11 at 1.6 $\mu$m as $4.7 \pm 0.2 \times 10^{39}$ ergs s$^{-1}$. It should be noted that the infrared observation was not taken simultaneously with the radio and X-ray observations. Since it is difficult to estimate the respective contributions of the stars and of M82 X-1 to the IR flux, we take this value as an upper limit to the luminosity at 1.6 $\mu$m for M82 X-1.

3.2. Calculated Spectrum

From a number of calculations, the numerical results indicate that to fit the X-ray spectrum, including the luminosity and spectral slope, the mass of the black hole in M82 X-1 (and correspondingly the mass accretion rate) must lie in a narrow range. For $s_0 = 0.27$, the most favored value in the case of Sgr A* (Yuan et al. 2003), the mass of the black hole in M82 X-1 is estimated to be $1.8 \times 10^5 M_\odot$, and the corresponding mass accretion rate to be $M_0 = 0.55M_{\text{Edd}}$, where $M_{\text{Edd}} \equiv L_{\text{Edd}}/c^2$ is the Eddington accretion rate.\footnote{Here, the efficiency for the conversion of rest-mass energy to radiation is $L_{\text{ADAF}}/M_0 = 0.009L_{\text{Edd}}/0.55M_{\text{Edd}}c^2 = 0.016$. This value is much smaller than the efficiency of a standard thin disk and is a characteristic feature of an ADAF. The produced spectrum is shown in Fig. 1 by the thin solid line.}

The constraint on the mass of the black hole (and the mass accretion rate) can be obtained from fitting the X-ray spectrum as follows. Noting that the X-ray spectrum of M82 X-1 is produced by the Comptonization process in the ADAF, the spectral slope is determined by the Compton $\gamma$-parameter, which is proportional to the product of the Thompson optical depth and the electron temperature of the accretion flow, with a larger $\gamma$ corresponding to a harder spectrum. As the mass of the black hole is increased (from the favored value of $1.8 \times 10^5 M_\odot$), a smaller $M_0$ would be required to produce the same luminosity. In this case, the Compton $\gamma$-parameter will become smaller due to the decrease of the density of the accretion flow. Therefore, the predicted spectrum would be too soft, as shown by the dashed line in Figure 1. On the other hand, if the mass were smaller, the predicted spectrum would be
too hard, as shown by the dot-dashed line in Figure 1. We note that the results also depend on the value of $s_0$. This is because the produced X-ray spectrum is the sum of the local Comptonization spectrum from different radii of the ADAF, which have different slopes, while the value of $s_0$ controls the fractional contribution of each radius, thus affecting the total spectral slope. For $s_0$ varying from $s_0 = 0$ to 0.4, a satisfactory fit to the X-ray spectrum can be obtained, leading to black hole masses ranging from $M = 9 \times 10^4$ to $5 \times 10^5 M_\odot$.

In Figure 1 we also show by the dotted and double-dot-dashed lines the predicted emission produced by the truncated thin disk and jet, respectively. In this case, the mass loss rate in the jet is $M_{\text{jet}} = 1.5 \times 10^{-3} M_{\text{Edd}}$, which is $\sim 0.5\%$ of the accretion rate at $5r_s$. The power of this jet is $\sim 10^{41}$ ergs s$^{-1}$, which is comparable to the total X-ray luminosity emitted from the ADAF. Furthermore, the two parameters $\epsilon_e$ and $\epsilon_B$ were found to be 0.06 and 0.02, respectively. All these parameter values are surprisingly similar to the modeling results of the hard states of the two stellar mass black hole sources XTE J1118+480 and XTE J1550−564, where $M_{\text{jet}} = 0.5\% M(5r_s)$ and $0.6\% M(5r_s)$, respectively, and the values of $\epsilon_e$ and $\epsilon_B$ are the same (Yuan et al. 2005, 2007). Such a similarity provides some support to our assumption that M82 X-1 corresponds to the hard state of stellar mass black hole sources. For the truncated thin disk, which contributes from the ultraviolet to the infrared portion of the spectrum, $M = 0.55M_{\text{Edd}}$ and the viewing angle (as defined from the disk rotation axis) is assumed to be $\theta = 60^\circ$. The parameters for the predicted spectrum yield an infrared luminosity of $5 \times 10^{39}$ ergs s$^{-1}$. This value lies above the lower bound of the upper limit for the observed luminosity (see §3.1), as deduced for the lowest extinction, corresponding to $2.5 \times 10^{39}$ ergs s$^{-1}$. Thus, this computational model requires that the extinction not be very low or the viewing angle of the thin disk be larger than $\sim 70^\circ$.

In our procedure, the mass of the black hole based on the ADAF model is obtained simply from the observed luminosity and the spectral slope. This is a direct result of the fact that for a “pure” ADAF model, where the synchrotron photons are the only seed photons, a monotonic correlation is predicted between the spectral slope and the Eddington-scaled luminosity. Specifically, the ADAF models predict that for X-ray luminosities in the range of $\sim 10^{-4}L_{\text{Edd}}$ to $\sim 4\% L_{\text{Edd}}$, the spectrum hardens with increasing luminosity (Esin et al. 1997).

The predicted correlation is partially confirmed by observations, as shown in Figure 2. Here, a correlation is found to exist between the photon index $\Gamma$ and $L_X/L_{\text{Edd}}$ for the two stellar mass black hole X-ray sources that exhibit the widest range in hard state luminosity. The data in this figure has been taken from Tompkins et al. (2001) for the 2000 outburst of XTE J1550−564, and analyzed by ourselves for XTE J1118+480 from archival RXTE data. Note that we simply calculate $L_X$ by assuming that the power-law spectrum cuts off at the same energy as given by the thin solid line in Figure 1. We can see from the figure that the qualitative behavior of the correlation below $\sim 2\% L_{\text{Edd}}$ is consistent with the prediction of the spectra produced from ADAF models. However, the observational results reveal that the correlation is non-monotonic. That is, above $\sim 2\% L_{\text{Edd}}$, the spectrum softens with increasing luminosity. The physical mechanism underlying this change in correlation is not understood. Since the hard states approach a very high state where $L_X \approx 2\% L_{\text{Edd}}$, it is very likely that the non-monotonic behavior is related to an additional physical description of accretion and emission at the very high state. Although this regime is not understood, it is possible that the accretion flow responsible for the very high state and relatively luminous hard state consists of two phases, with cold clumps embedded within hot gas. In this model, the emission of the clumps supplies additional seed photons to those produced by the synchrotron process in the hot phases to harden the spectrum as a result of the Comptonization process in the accretion flow (see Yuan et al. 2007). This could result in a different correlation in comparison to the case of a “pure” one-phase ADAF model. Alternatively, this state may reflect the contribution of another component in the system (e.g., a consequence of the emission associated with a hot disk cooled by the cold disk photons). In this case, the variation of the spectral index with luminosity could be different from the pure ADAF solution. As the accretion rate increases, the transition radius decreases (e.g., Liu et al. 1999), the flux of seed photons and thus the the cooling of the ADAF are stronger, reducing the Compton $\gamma$-factor, thereby leading to softer spectra (e.g., Zdziarski et al. 1999). This would be in contrast to the pure ADAF model prediction, but in accordance with the variation observed in XTE J1550−564 at high luminosities.

The correlation displayed in Figure 2 must be confirmed over a much larger sample of black hole binary X-ray sources to determine its generality. Existing work appears to partially confirm the existence of such a correlation (e.g., Shemmer et al. 2006; Remillard & McClintock 2006), suggesting that the correlation is, indeed, multivalued. That is, a given spectral index $\Gamma$ may correspond to two different luminosity levels, with the luminosity difference greater for sources characterized by softer spectra. Thus, it is possible that M82 X-1 may correspond to the very luminous hard state of stellar mass black hole sources. In the model studied here, the “pure” ADAF model can only describe the relatively dim hard state. Unfortunately, the physical description of the high-luminosity hard state has not been developed sufficiently to present a detailed numerical model. Instead, we roughly estimate the properties of a black hole X-ray binary source in this regime. From Figure 2, and given the possible scattering in the relation due to, for example, hysteresis effects (see Zdziarski & Gierlinski 2004), a spectrum with $\Gamma \approx 1.67$ can be reached at luminosities as high as $L \lesssim 4\% - 10\% L_{\text{Edd}}$. In this case, the cutoff energy of the X-ray luminosity should be slightly lower than in the ADAF model, and thus the bolometric luminosity of M82 X-1 should be slightly lower, $\sim 10^{41}$ ergs s$^{-1}$. The mass of the black hole in M82 X-1 would then be in the range of $\sim (1-2) \times 10^4 M_\odot$, and the required mass accretion rate may be as high as $M_{\text{Edd}}$, according to our modeling experience in XTE J1550−564 (Yuan et al. 2007). We note that for the high-luminosity model, our calculation shows that the predicted luminosity at
\( \sim 10^{14} \) Hz is about an order of magnitude lower than the model illustrated in Figure 1, thus satisfying the observed infrared upper limit by a larger margin.

4. IMPLICATIONS

In this paper, we have presented a detailed theoretical emission spectrum for M82 X-1, within the advection dominated accretion flow framework, which is widely used to model the relatively low luminosity hard state of Galactic black hole X-ray binaries. The results of our detailed numerical calculations reveal that an X-ray photon power-law spectrum of index \( \Gamma = 1.67 \) can be reproduced by the synchrotron self-Comptonization process of the thermal electrons in the ADAF. The X-ray luminosity in this solution is \( L_X \approx 0.9\% L_{\text{Edd}} \) (note that it is \( L_X \), not \( L_{2-10 \text{ keV}} \)). A comparison of the model results with the constraints imposed by the X-ray spectral index and luminosity yields a mass for the black hole in the range \( 9 \times 10^4 - 5 \times 10^5 M_\odot \). The model parameters required are similar to those obtained by detailed fitting of stellar mass black holes, with the exception of the high value of the black hole mass.

The accretion disk modeling of the system, however, is not unique, since observations of stellar mass black hole sources, such as XTE J1550—564, reveal the existence of a luminous hard state. These states can have the same spectral slope of \( \Gamma = 1.67 \), but at luminosities that are significantly higher, \( L_X \approx 4\% -10\% L_{\text{Edd}} \). For this regime, the accretion efficiency is likely higher and can be comparable to the efficiencies characteristic of a standard optically thick disk (see Yuan et al. 2007). The detailed accretion flow model for these luminous hard states is, however, still lacking, but the cause for the multivalued nature of the accretion flow spectral solutions is likely associated with the presence of additional seed photons for the Comptonization in the hot accretion flow. This may arise from the outer cool disk or from the cool clumps within a highly inhomogeneous accretion flow structure, perhaps analogous to the two-phase disks discussed by Yuan et al. (2007) and Merloni et al. (2006). If M82 X-1 is in such a luminous hard state, the mass of the black hole could be reduced by an order of magnitude to \( \sim 10^4 M_\odot \).

To discriminate between the possible solution at high luminosity and the “pure” ADAF one at low luminosity, future simultaneous observations will be necessary. A particularly important wavelength region for study is the infrared where the infrared emission associated with the high-luminosity solution is significantly lower than at low luminosities. A better observational estimate for the infrared luminosity would entail a more precise determination of the extinction and removal of the infrared contribution from the stellar cluster MGG 11. If the obtained infrared luminosity were to lie below the prediction of the thick solid line in Figure 1, the model with \( M = 1.8 \times 10^5 M_\odot \) could be ruled out. We note that such a solution would alleviate the severe constraints on the required viewing angle of the system if the observed infrared luminosity were significantly less than our adopted upper limit. An additional discriminant between the two models can be explored in the hard X-ray band, where the model shown in Figure 1 predicts a cut-off energy of \( \sim 100 \) keV. The cut-off energy for the high-luminosity, low black hole mass model should be lower, perhaps \( \sim 30-50 \) keV. Hence, X-ray observations in the hard X-ray band can also be used to discriminate between these models.

Our modeling results suggest that an ADAF interpretation for ULXs is viable and supports the idea that M82 X-1 can harbor an IMBH with a mass close to the AGN limit of \( 10^5 - 10^6 M_\odot \) (Greene & Ho 2004; Barth et al. 2005). Our results on the low-luminosity state of black hole X-ray binaries as applied to M82 X-1, however, are in conflict with the results based on the hypothesis that it is a binary system with an orbital period of 62 days. Such a period was inferred from an RXTE X-ray monitoring campaign of M82 by Kaaret et al. (2006). If this variability is attributed to M82 X-1 orbiting about its common center of mass in a binary system, evolutionary calculations for the system place constraints on the masses of the binary system components. In particular, Patruno et al. (2006) find a solution in which a donor in the mass range of \( 22 - 25 M_\odot \) transfers mass to an IMBH of mass \( 200 - 5000 M_\odot \) under the assumption that the system is associated with the star cluster MGG 11. This latter assumption constrains the age of the system to be in the range of 7–12 Myr. Although a solution was also found for a stellar mass black hole accreting at super-Eddington rates, this solution was considered unlikely due to its very restrictive parameter space. Very recently, Okajima et al. (2006) have proposed a stellar mass black hole interpretation for M82 X-1 based on XMM-Newton observational data. In their model, a slim disk description has been adopted. However, the existence of multiple sources in the XMM-Newton field of view of M82 X-1 makes their interpretation premature for the brightest source, X41.4+60.

We point out that the inferred black hole masses are dependent on the radiative efficiency of the accretion process. For example, the estimates based on binary evolution theory implicitly assume an efficiency of \( \sim 0.1 \), whereas the efficiencies can range from 0.01 to \( \sim 0.1 \) in the hot accretion disk solutions for the low-luminosity and high-luminosity regimes respectively. If one adopts the estimated mass in the high-luminosity solution of \( 10^4 M_\odot \), then it is only a factor of 2 higher than the estimated upper limit of \( 5000 M_\odot \) from the binary evolutionary calculations.

Thus, taking into account accretion disk theory, as well as binary evolutionary theory, and given the uncertainties, a mass for the black hole in M82 X-1 may well lie in the range of \( 5000 - 10^5 M_\odot \).

Future X-ray observations of M82 X-1 will be essential to determine the viability of hot accretion flows to this ULX and its nature. In particular, it would be important to determine whether the correlation between the X-ray luminosity and the photon spectral index is confirmed as M82 X-1 varies. Such a test would necessarily involve future Chandra off-axis observations, since XMM-Newton studies of this region are affected by source confusion and previous Chandra on-axis observations suffer from pile-up effects. Thus, the results of this study highlight the need for additional future off-axis Chandra observations of this source.

Studies of M82 X-1 at energies greater than 10 keV are also important, since curvature in the X-ray spectrum is expected from the thermal Comptonization of electrons in the coronae of standard optically thick disks or slim disk models, whereas a power-law spectrum is expected for hot disk models. Thus, such observations have the potential to discriminate between the optically thick slim disk models and the optically thin hot accretion disk models.

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