BLACK HOLE MASS LIMITS FOR OPTICALLY DARK X-RAY BRIGHT SOURCES IN ELLIPSOIDAL GALAXIES

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ABSTRACT

Estimation of the black hole mass in bright X-ray sources of nearby galaxies is crucial to the understanding of these systems and their formation. However, the present allowed black hole mass range spans five orders of magnitude ($10^3 M_\odot < M < 10^8 M_\odot$) with the upper limit obtained from dynamical friction arguments. We show that the absence of a detectable optical counterpart for some of these sources can provide a much more stringent upper limit. The argument is based only on the assumption that the outer regions of their accretion disks are a standard one. Moreover, such optically dark X-ray sources cannot be foreground stars or background active galactic nuclei, and hence must be accreting systems residing within their host galaxies. As a demonstration we search for candidates among the point-like X-ray sources detected with Chandra in 13 nearby elliptical galaxies. We use a novel technique to search for faint optical counterparts in the Hubble Space Telescope images whereby we subtract the bright galaxy light based on isophotal modeling of the surface brightness. We show that for six sources with no detectable optical emission at the 3σ level, their black hole masses $M_{BH} < 5000 M_\odot$. In particular, an ultra-luminous X-ray source in NGC 4486 has $M_{BH} < 1244 M_\odot$. We discuss the potential of this method to provide stringent constraints on the black hole masses, and the implications on the physical nature of these sources.

Key words: accretion, accretion disks – galaxies: photometry – X-rays: galaxies

Online-only material: color figure

1. INTRODUCTION

Compact, off-nuclear X-ray point sources in nearby galaxies with luminosities $10^{39}$–$10^{41}$ erg s$^{-1}$ are referred to as ultra-luminous X-ray sources (ULXs). Detected in the early 1980s, with the Einstein X-ray satellite (Fabbiano 1989), these objects were further studied with ROSAT (Colbert & Mushotzky 1999) and ASCA (Makishima et al. 2000). The XMM-Newton and Chandra X-ray observatories with their significantly higher angular resolution dramatically confirmed the presence of ULXs (Kaaret et al. 2001), and have enabled their spectral and temporal properties to be studied in detail (see Miller & Colbert 2004; Mushotzky 2004, 2006; Roberts 2007, for reviews).

The observed luminosities of ULXs exceed the Eddington limit for a $10^5 M_\odot$ black hole. Since ULXs are off-nuclear sources, their masses must be $<10^5 M_\odot$ from dynamical friction arguments (Kaaret et al. 2001). Thus, ULXs may represent a class of intermediate-mass black holes (IMBHs) whose mass range $(10^3 M_\odot < M < 10^5 M_\odot)$ lies between that of stellar mass black holes and supermassive black holes observed in galaxy centers (Makishima et al. 2000). Alternatively, ULXs may be stellar mass black hole systems exhibiting super-Eddington accretions with their radiation geometrically beamed (Shakura & Sunyaev 1973; King 2008).

X-ray spectroscopy has provided supporting evidence in favor of IMBHs of $\sim 1000 M_\odot$ in ULXs (Miller et al. 2003; Cropper et al. 2004; Dewangan et al. 2004; Roberts et al. 2005; Devi et al. 2008). Moreover, X-ray timing characteristics, i.e., the presence of low-frequency quasi-periodic oscillations and/or breaks in the power density spectra, also suggest that ULXs may harbor $\sim 100$–$1000 M_\odot$ black holes (Strohmayer & Mushotzky 2003; Dewangan et al. 2006; Mucciarelli et al. 2006; Strohmayer & Mushotzky 2009). While indicative, these results are not conclusive, since there are also several arguments against IMBHs in ULXs (see, e.g., Mushotzky 2004; Roberts 2007) and further investigations are required to reveal the true nature of these sources.

Study of the host galaxy properties of ULXs reveals that their number and total X-ray luminosity is related to recent star formation activity, suggesting that they originate in young short-lived systems (Swartz et al. 2004, 2009). While the number of ULXs per galaxy is roughly the same for both spirals and ellipticals, the ones in the spirals have significantly higher luminosities (Swartz et al. 2004). Optical counterparts have been reported for some ULXs (Liu et al. 2004; Kuntz et al. 2005; Ramsey et al. 2006; Terashima et al. 2006). While some of the counterparts have been identified as O stars (Liu et al. 2002, 2007), for most ULXs, the optical counterparts are stellar clusters (Goad et al. 2002; Ptak et al. 2006). However, for many ULXs, the optical counterparts reveal that they are either background active galactic nuclei (AGNs; Gutierrez 2006; Bonfini et al. 2009) or foreground stars. ULXs found in elliptical galaxies may have contamination from background sources at $\sim 44\%$ level (Swartz et al. 2004). Detailed studies of X-ray sources in general and their connection with globular clusters have been undertaken by Kim et al. (2006, 2009) who note that the X-ray properties of the sources in the field (i.e., without optical counterparts) are not different from those in globular clusters.

The allowed black hole mass range for X-ray sources in nearby galaxies spans five orders of magnitude $(10^3 M_\odot < M < 10^8 M_\odot)$ and it is important to obtain tighter constraints. Here we show that the absence of a detectable optical emission allows us to impose an upper limit on the black hole mass for these accreting systems based on some standard assumptions. Moreover, we argue that these optically dark X-ray sources cannot be foreground stars or background AGN and hence are a true sample of sources located within the host galaxy. To demonstrate the technique, we search for candidates among X-ray bright sources detected by Chandra in archival Hubble.
The Astrophysical Journal observations are available. Devi et al. (2007) analyzed a subset of these we select 13 elliptical galaxies for which the X-ray sources with both a power-law and a disk blackbody model, hence obtaining a more conservative and robust estimation of their X-ray luminosity. Nine out of the four for these galaxies we use the X-ray luminosity and coordinates given by them for the present analysis. For the remaining four galaxies were analyzed when available, so as to maximize the level of 3

3. OPTICALLY DARK X-RAY SOURCES

These optically dark sources are X-ray bright compared to their optical emission and hence are not foreground stars. This can be further quantified by estimating the X-ray-to-optical flux ratio \( f_X/f_O \), where \( f_X \) is the unabsorbed flux in the 0.3–8 keV band and \( f_O \) is the flux in an optical band. This ratio ranges from 0.1 to 50 for AGNs including BL Lac objects when \( f_X \) is in the 0.3–3.5 keV band and the V-band magnitude is used (Stocke et al. 1991). In contrast, the estimated lower limit for the optically dark sources in the sample is significantly larger. This is illustrated in Table 2 where the ratio is given for 10 sources. We, therefore, conclude that these sources are not background AGNs.

Thus, these sources are most likely to be bright X-ray binaries (or at least accreting systems) within the galaxy. An accretion disk around a compact object should also produce optical emission whose flux can be estimated as follows. In the standard accretion disk theory ( Shakura & Sunyaev 1973 ), the effective temperature profile as a function of radius \( R \), of an accretion disk around a black hole with mass \( M \) and accretion rate \( \dot{M} \), is given by \( T(R) = \frac{3 \dot{M} M}{4 \pi R^3} \delta(R) \), where \( \delta(R) = 1 - (6G M / R c^2)^{1/2} \). The observed flux from the disk at a frequency \( \nu \) is then given by the integrated sum of the blackbody emission over all radii,

\[
F_{\nu} = \frac{\cos i}{D^2} \int_{R_{\text{out}}}^{R_{\text{in}}} B_{\nu}(v, T(R)) 2\pi RdR, \tag{1}
\]

where \( B_{\nu}(v, T(R)) \) is the blackbody intensity, \( R_{\text{out}} \) and \( R_{\text{in}} = 6G M/c^2 \) are outer and inner radii of the disk, \( i \) is the inclination angle of the disk, and \( D \) is the distance to the source. Assuming that most of the contribution to \( F_{\nu} \) arises from regions in the disk that are far away from the inner and outer radii, the expected observed flux can be written as

\[
F_{\nu} \sim 7 \times 10^{-31} \text{ erg s}^{-1} \text{ cm}^{-2} \text{ Hz}^{-1} \left( \frac{\lambda}{5000 \text{ Å}} \right)^{-1/3} \left( \frac{\eta}{0.1} \right)^{-2/3} \times \left( \frac{L_x}{10^{39} \text{ erg s}^{-1}} \right)^{2/3} \left( \frac{D}{10 \text{ Mpc}} \right)^{-2} \left( \frac{M}{1000 M_\odot} \right)^{2/3}, \tag{2}
\]

where \( \lambda \) is the wavelength, \( \eta = L_x/\dot{M} c^2 \) is the radiative efficiency of the accreting system, and \( \cos i \) is taken to be 0.5. For an optically dark ULX, the predicted accretion flux should be less than the measured upper limit \( F_{\nu,\text{max}} \). Thus, one can

### Table 1

| Galaxy      | Distance (Mpc) | \( N_x \) | \( N_O \) |
|-------------|----------------|----------|----------|
| NGC 1399    | 18.3           | 26       | 4        |
| NGC 4649    | 16.6           | 12       | 5        |
| NGC 4697    | 11.8           | 11       | 3        |
| NGC 1291    | 8.9            | 5        | 1        |
| NGC 4365    | 20.9           | 4        | 3        |
| NGC 1316    | 17.0           | 7        | 3        |
| NGC 4125    | 24.2           | 3        | 3        |
| NGC 3379    | 11.1           | 3        | 1        |
| NGC 4374    | 17.4           | 2        | 1        |
| NGC 4486    | 15.8           | 5        | 2        |
| NGC 4472    | 15.9           | 1        | 0        |
| NGC 1407    | 17.6           | 2        | 2        |
| NGC 4552    | 15.9           | 3        | 0        |

**Notes.** Columns: (1) host galaxy name; (2) distance to the galaxy; (3) number of X-ray sources within HST field of view; (4) number of X-ray sources without optical counterparts.
estimate an upper limit on the black hole mass as

\[ M_U < 1000 \, M_\odot \left( \frac{F_{i,\text{max}}}{7 \times 10^{-31} \, \text{erg s}^{-1} \text{cm}^{-2} \text{Hz}^{-1}} \right)^{3/2} \times \left( \frac{\lambda}{5000} \right)^{1/2} \left( \frac{\eta}{0.1} \right) \left( \frac{L_x}{10^{39} \, \text{erg s}^{-1}} \right)^{-1} \left( \frac{D}{10 \, \text{Mpc}} \right)^{3/2} \cdot \]

(3)

For each dark X-ray source in our sample, and for all available filters, we estimate this upper limit on the black hole mass. We use the integration (Equation (1)) to evaluate the upper limit, rather than the approximation Equation (3), i.e., we take into account the effect of the inner boundary condition \((\delta(R) = 1 - (6GM/Rc^2)^{1/2})\) on the temperature profile. The difference in the upper limit obtained is marginal (< 20%). We assume a standard radiative efficiency of \(\eta = 0.1\) and \(\cos i = 0.5\). To obtain a more conservative upper limit, the lower value of the X-ray luminosity is used \(L_x - \Delta L_x\). In Table 2, we list the 10 best cases in ascending order of black hole mass limit \(M_U\). For the other sources, \(M_U > 10,000 \, M_\odot\) and hence is not a significant constraint. The best case is for the ULX in NGC 4486, for which \(M_U = 1244 \, M_\odot\).

X-ray irradiation of the outer disk may increase the local temperature there and the disk may emit a larger optical emission. We have estimated this effect using the formalism given in the Appendix of Vrtilek et al. (1990) and find that X-ray irradiation is not important for the constraint obtained here.

4. DISCUSSION

Optically dark X-ray sources cannot be foreground stars or background AGNs, otherwise their optical emission would be

Table 2

Upper Limit of Black Hole Mass of Some of the Optically Dark X-ray Sources

| Galaxy     | R.A.(J2000) | Dec.(J2000) | log \(L_x\) | \(HST\) Filter | \(F_x/F_O\) | \(M_U\) (\(M_\odot\)) |
|------------|-------------|-------------|-------------|----------------|-------------|-----------------------|
| NGC 4486   | 12 30 50.82 | +12 25 02.66 | 39.17\(^{+0.05}_{-0.04}\) | F475W | 0.409 | 533 | 1244 |
| NGC 4697   | 12 48 33.20 | -05 47 41.17 | 38.84\(^{+0.06}_{-0.05}\) | F475W | 0.752 | 243 | 2890 |
| NGC 4649   | 12 43 41.90 | +11 34 33.83 | 38.91\(^{+0.67}_{-0.11}\) | F475W | 0.402 | 164 | 3073 |
| NGC 4374   | 12 25 01.54 | +12 52 35.59 | 39.10\(^{+0.07}_{-0.22}\) | F475W | 0.441 | 347 | 3378 |
| NGC 1399   | 3 38 35.92  | -35 27 42.37 | 38.62\(^{+0.12}_{-0.09}\) | F606W | 0.370 | 228 | 3927 |
| NGC 1316   | 3 38 35.58  | -37 13 14.10 | 38.78\(^{+0.40}_{-0.07}\) | F555W | 0.520 | 287 | 6366 |
| NGC 1399   | 3 38 33.23  | -35 29 45.73 | 38.54\(^{+1.13}_{-0.41}\) | F606W | 0.377 | 186 | 7829 |
| NGC 1316   | 3 38 27.62  | -35 26 48.76 | 39.42\(^{+0.16}_{-0.14}\) | F606W | 0.766 | 702 | 7829 |
| NGC 4649   | 12 43 34.17 | +11 33 41.93 | 39.04\(^{+0.10}_{-0.11}\) | F475W | 0.912 | 97  | 8073 |

Notes. Columns: (1) host galaxy name; (2) right ascension of shifted position in hours, minutes, and seconds; (3) declination of shifted position in degrees, arcminutes, and arcseconds; (4) log of X-ray luminosity in erg s\(^{-1}\); (5) \(HST\) filter for which the upper limit on flux and the black hole mass limit are calculated; (6) upper limit on optical flux in erg s\(^{-1}\) cm\(^{-2}\) Hz\(^{-1}\); (7) lower limit on the ratio of X-ray to optical flux; (8) \(M_U\), upper limit on black hole mass.
significantly higher than what is detected. Hence, these are a clean sample of sources within the host galaxies, which are probably accreting black hole systems. The optical emission from a standard accretion disk scales as mass of the black hole $M^{2/3}$ and hence the non-detection of optical emission imposes an upper limit on the black hole mass $M_U$. For 10 of the sources $M_U < 10,000 M_\odot$. For a source in NGC 4486 with an X-ray luminosity clearly exceeding $10^{39}$ erg s$^{-1}$ (and therefore a bona fide ULX by definition), the estimated black hole mass is smaller than 1244 $M_\odot$. This is two orders of magnitude smaller than the constraint obtained from dynamical friction, which is $10^5 M_\odot$.

These sources with black hole mass $M_U < 5000 M_\odot$ cannot be accreting systems with massive black holes residing in star clusters, or in the nuclei of merged satellite galaxies. For typical low-luminosity dwarf galaxies ($M_B \sim -8.0$; Mateo 1998), such an optical counterpart would be easily detected, given that our $3\sigma$ limits on the HST images are much fainter. Even a compact nucleus of a merged dwarf galaxy ($M_B \sim -7.0$; Lotz et al. 2004) would have been easily identified. If they are binary systems, their companion cannot be a massive O star as such a star would have been detected in the optical image. Assuming an O star, with $M_B \sim -5.5$, we find that the possibility of such a companion can be ruled out in all cases for which $M_U < 5000 M_\odot$ (Table 2).

In all of the above arguments, we have ignored the effect of dust obscuration in the host galaxies, because we are only considering elliptical galaxies in the present work. Although some ellipticals are known to have dust lanes, and nuclear rings in their centers, the X-ray sources we are considering here are in their centers, the X-ray sources we are considering here are distributed at fairly large radial distance from the center to be significantly affected by dust.

Even for the best cases of optically dark X-ray sources presented in Table 2, the range of black hole mass allowed is still large as the source could be a $\lesssim 1000 M_\odot$ IMBH, or a few solar mass object emitting at super-Eddington luminosities. The brightest X-ray sources in the sample have a luminosity of a few times $10^{39}$ erg s$^{-1}$. This is unfortunate, since a dark source with luminosity $>10^{40}$ would have provided an order of magnitude better constraint on the black hole mass. Since the black hole mass upper limit $M_U \propto D^3$ a bright X-ray source in a more nearby galaxy ($D \sim 2$ Mpc) would have also provided significantly better constraints. A systematic search for such sources in very nearby galaxies may indeed prove fruitful. Another point to note is that bright X-ray sources in these galaxies are known to be variable in X-rays. Our analysis in this work implicitly assumes that the X-ray luminosity observed through a single Chandra observation represents an average luminosity which is used to derive an average accretion rate $M = L_X/(\eta c^2)$ which in turn is used to estimate the upper limit on the black hole mass (Equation (3)). This assumption is required because the expected optical emission arises from the outer part of the disk and the local accretion rate there may be different than the one in the inner region which produces the X-rays. Any accretion rate fluctuation in the outer disk will be transferred along the disk on the viscous timescale which could be significantly longer than a day. Thus, in principle one needs to ascertain the average X-ray luminosity of a source, and using a single very bright, but rare, X-ray observation of the source will not represent the average accretion rate.

A systematic and comprehensive multi-wavelength study (using also other bands like infrared and radio), along with X-ray variability studies, can shed further light on the nature of these sources.

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