X-ray Verification of a Low-Mass AGN Powered by a Black Hole in the Thousand Solar Mass Range

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I. Introduction

1. Background on IMBHs

As a black hole (BH) grows via accretion and/or mergers, it must pass through an "intermediate" mass stage in order to reach the supermassive regime [5]. These intermediate-mass black holes (IMBHs) are defined by masses $10^2 - 10^6$ $M_\odot$. Though several hundred $10^4 - 10^6$ $M_\odot$ have been identified, a gap exists in the $< 10^3 - 10^4$ $M_\odot$ range.

Identification of additional lower-mass IMBHs will further inform BH growth mechanisms and provide new insight toward early Universe cosmology, and galaxy formation and evolution studies [3].

2. Black hole accretion and mass regime relation

Accretion disks feeding supermassive black holes (SMBHs) emit spectra that peak in the UV regime, whereas accreting IMBH spectra peak in the soft (lower energy) X-ray regime when systems are accreting at >~1% of their Eddington luminosity (maximum luminosity/accretion rate) [2]. Here, we present an X-ray spectrum of a luminous active galactic nucleus (AGN) that peaks in the soft X-ray, making it an excellent candidate for a ~10^3 $M_\odot$ IMBH.

II. Target

1. XMM-Newton X-ray Observations

From the Sloan Digital Sky Survey we identified a low-mass star forming galaxy ~180 Mpc away.

A low-count archival Chandra X-ray observation (110 counts) suggests a luminous (~10^{40} erg s^{-1}) nuclear X-ray source with a spectrum that peaks in the soft X-ray (~0.3 keV), suggestive of an IMBH. The Chandra spectrum contained high uncertainties and was too low count to confirm the central BH's mass regime as an IMBH. We therefore obtained a new observation with the XMM-Newton X-ray Observatory.

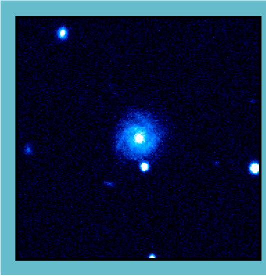


Figure 1: Optical image in the g'-band (400–550 nm with a peak sensitivity around 475 nm) of our target.

Image Credit: Sloan Digital Sky Survey

III. Observations

1. Observation data parameters

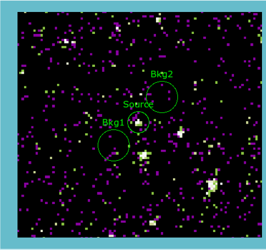


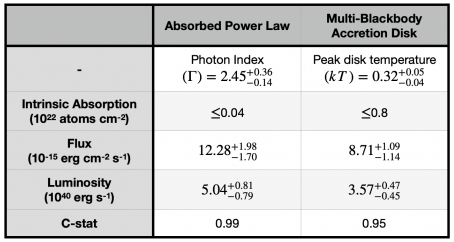
Figure 2: Source and background radii of 15" and 36", respectively, of the MOS1 exposure.

Our target was observed with XMM-Newton for 76 ks using the MOS and PN detectors on the European Photon Imaging Camera (EPIC). Data were processed using standard procedures in the Science Analysis Software (SAS) and a small amount of time was filtered due to background flaring, allowing for a total of 360 counts obtained across all three cameras (MOS1, MOS2, PN).

2. XSPEC Modeling

Combined spectral fitting was performed in XSPEC for the three extracted spectra. W-statistics were used due to the low number of counts. Two simple XSPEC models were applied, both accounting for Galactic and internal absorption:

(a) Absorbed Power Law: to represent non-thermal X-ray emission (tbabs*ztbabs*cflux* pow).
(b) Multi-Blackbody Accretion Disk: to represent thermal emission from a geometrically thin accretion disk (tbabs*ztbabs*cflux*diskbb).



	Absorbed Power Law	Multi-Blackbody Accretion Disk
-	Photon Index $(\Gamma) = 2.45^{+0.36}_{-0.14}$	Peak disk temperature $(kT) = 0.32^{+0.05}_{-0.04}$
Intrinsic Absorption (10^{22} atoms cm^{-2})	≤0.04	≤0.8
Flux (10^{-15} erg cm^{-2} s^{-1})	$12.28^{+1.98}_{-1.70}$	$8.71^{+1.09}_{-1.14}$
Luminosity (10^{40} erg s^{-1})	$5.04^{+0.81}_{-0.79}$	$3.57^{+0.47}_{-0.45}$
C-stat	0.99	0.95

Figure 3: Best-fit parameters for both XSPEC models. Flux and luminosity energy ranges are 2-10 keV for the Absorbed Power Law model and 0.001-50 keV for the Multi-Blackbody Accretion Disk model.

IV. Results

1. MBH, LX, and Tin relation

To estimate a BH mass from the thermal accretion disk model, we adopted Equation 6 from Soria (2007) [4].

$$M \approx 10.0 \left(\frac{\eta}{0.1}\right)\left(\frac{\xi\kappa^2}{1.19}\right)\left(\frac{L_{disk}}{5\times10^{38}\ erg\ s^{-1}}\right)^{1/2} \times \left(\frac{kT_{in}}{1\ keV}\right)^{-2}\ M_\odot$$

Where η is the radiative efficiency, ξ is the bolometric normalization factor, κ is the hardening factor, L_{disk} is the bolometric disk luminosity, and kT_{in} is the peak disk temperature. Following Soria (2007), we adopt $\eta = 0.2$, $\xi = 1$, $\kappa = 1.7$.

Our mass estimate for the thermal disk emission model with a bolometric luminosity integrated over the full disk in XSPEC (listed in Fig. 3) and a peak disk temperature ≈ 0.32 keV is $M_{BH} \approx 1697^{+412}_{-336}\ M_\odot$.

2. Γ-L/L$_{Edd}$ relation

From the powerlaw model, we obtain a crude estimate of the BH mass by examining a known relation between photon index (Γ) and Eddington ratio (L/L$_{Edd}$), where one expects larger photon indices for AGN at both high- and low-Eddington ratios [1].

We compare our best-fit photon index to Figure 8 of Constantin et al. (2009) (which we replicate below). We find that such a steep photon index could be consistent with either a low bolometric Eddington ratio $\left(L_{bol}/L_{Edd} < 1.7\times10^{-6}\right)$ or a high Eddington ratio $\left(L_{bol}/L_{Edd} > 4\right)$.

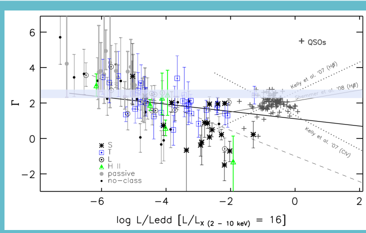


Figure 4: Constantin et al. (2009)'s photon index (Γ) vs. Eddington ratio (log L/L$_{Edd}$) using L$_{bol}$=16L$_X$. Log L/L$_{Edd}$ values were obtained using our best-fit Γ at low-Eddington ratios and Shemmer et al. (2008)'s trendline at high-Eddington ratios.

Our best-fit photon index is consistent with a 2×10^{10} $M_\odot$ SMBH or a super-Eddington IMBH (595^{+754}_{-540} $M_\odot$; see next section).

V. Discussion

For the thermal emission-dominated model, our result of ~1700 $M_\odot$ provides reasonable validation of an IMBH interpretation of the central BH in our target. This result is in agreement with our powerlaw model's high-Eddington limit mass estimate of $M_{BH,high} = 595^{+754}_{-540}\ M_\odot$, as the top error bound provides a result of 1349 $M_\odot$, aligning with an interpretation of an IMBH accreting at near-Eddington to super-Eddington rates. Conversely, our low-Eddington limit mass estimate of $M_{BH,low} \gtrsim 10^{10}\ M_\odot$ is unrealistic, as the existence of such a large BH is unlikely for our low-mass target galaxy.

Due to low XMM-Newton observation count rates, future missions (i.e. NewAthena) launching in the late 2030s hold promise for obtaining the necessary quality of spectra needed to fully resolve the source.

VI. References

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