AN ULTRALUMINOUS SUPERSOFT X-RAY SOURCE IN M81: AN INTERMEDIATE-MASS BLACK HOLE?

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ABSTRACT

Ultraluminous supersoft X-ray sources (ULSSSs) exhibit supersoft spectra with blackbody temperatures of 50–100 eV and bolometric luminosities above 10^{35} ergs s^{-1} and are possibly intermediate-mass black holes (IMBHs) of \( \geq 10^4 M_\odot \) or massive white dwarfs that are progenitors of Type Ia supernovae. In this Letter we report our optical studies of such a source in M81, M81-ULS1, with HST archive observations. M81-ULS1 is identified with a pointlike object, the spectral energy distribution of which reveals a blue component in addition to the companion of an asymptotic giant branch star. The blue component is consistent with the power law as expected from the geometricaly thin accretion disk around an IMBH accretor but inconsistent with the power law as expected from the X-ray–irradiated flared accretion disk around a white dwarf accretor. This result is strong evidence that M81-ULS1 is an IMBH instead of a white dwarf.

Subject headings: galaxies: individual (M81) — X-rays: binaries

Online material: color figures

1. INTRODUCTION

Luminous supersoft X-ray sources were discovered with the Einstein Observatory and were established as an important new class of X-ray binaries on the basis of ROSAT observations of 18 sources in the Milky Way and the Magellanic Clouds (Kahabka & van den Heuvel 1997, and references therein). These sources have extremely soft spectra with equivalent blackbody temperatures of 15–80 eV and are highly luminous with bolometric luminosities of \( 10^{35}–10^{38} \) ergs s^{-1}. They are thought to be white dwarfs that are steadily or cyclically burning hydrogen accreted onto the surface. Remarkably, the accretion rates must be in a narrow range of \((1–4) \times 10^{-7} M_\odot \text{ yr}^{-1}\), and the resultant luminosities are below \( 10^{39} \) ergs s^{-1} as observed. White dwarfs with steady nuclear burning are promising Type Ia supernova progenitors because, unlike explosive nova events, they can retain the accreted matter and their mass can increase until it approaches the Chandrasekhar limit.

More and more supersoft sources have been discovered in distant galaxies with the advent of the Chandra and XMM-Newton X-ray observatories. These distant supersoft sources, as compared to the canonical ones, are generally hotter, more luminous, and often associated with spiral arms, suggesting that some are young and massive systems (Di Stefano & Kong 2004). Some have bolometric luminosities, as derived from blackbody models, far above the Eddington luminosity \( L_{\text{Edd}} = 4\pi G M m_c c/\kappa \approx 1.3 \times 10^{38} (M/M_\odot) \text{ ergs s}^{-1} \) for white dwarfs, which we call ultraluminous supersoft sources (ULSSSs), or ULXs for a more compact name. One prototype ULX is M101-ULX1, which showed supersoft spectra of 50–100 eV, 0.3–7 keV luminosities of \( 3 \times 10^{39} \) ergs s^{-1}, and bolometric luminosities of \( \sim 10^{41} \) ergs s^{-1} during its 2004 outburst (Kong, Di Stefano, & Yuan 2004). While the supersoft spectrum can be explained by a white dwarf burning accreted materials on its surface, the white dwarf cannot explain the luminosities that are extremely super-Eddington for white dwarfs of \( \leq 1.4 M_\odot \). On the other hand, an intermediate-mass black hole (IMBH) of \( \gtrsim 10^4 M_\odot \), as Kong et al. suggested, can naturally explain both the high bolometric luminosities and the supersoft spectrum given the scaling relation \( T_{\text{bb}} \propto M^{-1/4} \) between the black hole mass and the accretion disk inner edge temperature.

Intermediate-mass black holes (10^2–10^5 M_\odot) have played an important role in the hierarchical merging scenario of galaxy formation (Madau & Rees 2001). They have long been searched for in the cores of globular clusters, but iron-clad evidence is lacking (for a review, see Miller & Colbert 2004). Recently, much interest has been directed toward ultraluminous X-ray sources (ULXs), which have been found to exist outside the nuclear regions with \( L_x \sim 10^{39}–10^{41} \) ergs s^{-1} in many nearby galaxies (Miller & Colbert 2004). Such luminosities require IMBHs of \( \geq 10^4 M_\odot \) if ULXs radiate at \( 10^{-2} \) Eddington level, as do many active galactic nuclei and Galactic X-ray binaries. One type of evidence for IMBHs comes from X-ray spectroscopy that reveals a cool accretion disk component with the inner edge temperature of a few \( \times 10 \) eV, which corresponds to an IMBH of a few \( \times 10^3 M_\odot \) if the inner edge of the accretion disk corresponds to the last stable orbit (Miller, Fabian, & Miller 2004). However, in many cases the cool component is dominated by a hard power-law component. This hard component resembles those from the hot corona in stellar black hole X-ray binaries that will erode and envelope the inner part of the accretion disk, raising doubts against the IMBH interpretation and suggestions that ULXs may be black holes of 20–100 M_\odot in a very high state (Done & Kubota 2006; Soria 2007). Indeed, ULXs can, from a theoretical perspective, be stellar-mass black holes with beaming effects or radiating at super-Eddington levels with the photon-bubble instability operating in a radiation pressure dominated magnetized accretion disk (Begelman 2002).

Ultraluminous supersoft sources, with bolometric luminosities \( \geq 10^{39} \) ergs s^{-1} and supersoft spectra of 50–100 eV, are more promising IMBH candidates (Kong et al. 2004; Kong, & Di Stefano 2005). As compared to ULXs, ULSSs exhibit spectra that do not show a hard power-law component, making it (more) reasonable to link the temperature to the inner edge of the accretion disk, thereby strongly suggesting an IMBH as the accretor. ULSSs can be the ultraluminous version of the canonical supersoft sources as ULXs can be stellar black holes. However, given the nature and dimension of the surface nuclear burning for white dwarfs, it is unlikely to make apparent super-
Eddington emitters with beaming effects or the photon-bubble instability in magnetized accretion disks as proposed for stellar black holes in ULXs. Of course, applying white dwarf atmosphere models to supersoft source spectra may reduce their bolometric luminosities by a factor of 10 (van Teeseling, Heise, & Kahabka 1996), hence alleviating the super-Eddington problem for some ULSs, but it is unlikely to push the most luminous ones below the Eddington limit.

Swartz et al. (2002) observed the nearby spiral galaxy M81 with Chandra ACIS and discovered an intriguing ULS in the bulge at R.A. = 09h55m42.2s, decl. = 69°03'36.5", which we designate as M81-ULS1 in this Letter. Liu (2007) studied the spectral properties of this ULS with 17 Chandra ACIS observations and found its spectra persistently supersoft in 6 yr despite dramatic flux changes. The spectrum from the longest observation can be well fitted in 0.3–2 keV by an absorbed blackbody model for a nuclear-burning white dwarf, with \( \chi^2/\text{dof} = 1.196/38 \), \( n_{\text{H}} = 8.6 \pm 0.9 \times 10^{20} \text{ cm}^{-2} \), \( kT = 73 \pm 1.5 \text{ eV} \), \( L_\lambda(0.3–2 \text{ keV}) = 3.2 \times 10^{38} \text{ ergs s}^{-1} \), and \( L_{\text{bol}} = 2.5 \times 10^{39} \text{ ergs s}^{-1} \). The spectrum can be equally well fitted by a multicolor disk model, with \( \chi^2/\text{dof} = 1.073/38 \), \( n_{\text{H}} = 10.5 \pm 0.9 \times 10^{20} \text{ cm}^{-2} \), \( kT_{\text{in}} = 83 \pm 1.4 \text{ eV} \), and \( L_\lambda(0.3–2 \text{ keV}) = 3.2 \times 10^{38} \text{ ergs s}^{-1} \). The inner disk radius derived from the model normalization is \( R_{\text{in}} \approx 24,500/\cos(i) \text{ M}_\odot \), which corresponds to an IMBH of \( \sim 2700/\cos(i) M_\odot \), assuming \( R_{\text{in}} \) corresponds to the last stable orbit. Thus, the X-ray spectra are suggestive of M81-ULS1 being either a white dwarf or an IMBH.

Observations in other wavelengths can shed light on the nature of this class of X-ray sources. We have embarked on an effort to study such sources in nearby galaxies with HST observations. In this Letter we report the optical studies of M81-ULS1 with HST archive data. Section 2 describes the HST archive data sets utilized, the optical identification, and photometric measurements of ULS1. The photometric measurements of ULS1 are interpreted in light of the white dwarf model and the IMBH model in § 3. We discuss our results and their implications in § 4. The distance of M81 is taken to be 3.63 Mpc (\( \mu = 27.8 \text{ mag} \); Freedman et al. 1994) in this work.

### 2. ANALYSIS OF HST DATA

**HST** has observed the sky region around ULS1 several times (Table 1). These include an observation on 1996 January 1 in filters WFPC2/F547M (3 × 30 s) and WFPC2/F656N (3 × 600 s), an observation on 2003 September 18 in filters ACS/WFC F658N (700 s) and ACS/WFC F814W (120 s), an observation on 2004 September 14 in ACS/WFC F814W (1650 s), and an observation on 2006 March 27 in filters ACS/WFC F435W (465 s) and ACS/WFC F606W (470 s). All data sets were downloaded from MAST and calibrated on the fly with the best calibration files as of 2007 November.

To identify the X-ray sources on the **HST** images, we register both the **HST** images and the *Chandra* images onto the 2MASS reference frame. This was achieved by identifying 11 2MASS sources on the ACS/WFC F814W image taken in 2004 and two 2MASS sources on the combined *Chandra* image. After both were registered onto the 2MASS reference frame, the X-ray image was overlaid onto the ACS/WFC F814W image. Six X-ray sources were coincident with optical objects within error circles of 0.5", including ULS1, which is identified with a pointlike object. This object appeared in all **HST** observations (Fig. 1) and is located in the smooth bulge of M81 with the closest object of equal brightness in F814W 10" away.

The photometry for this pointlike object was calculated with an aperture of 0.5" on WFPC2/PC1 and ACS/WFC images. The count rates and the corresponding magnitudes in the VEGAMAG photometric system are listed in Table 1 for the

### Table 1: HST Observations for M81-ULS1

| ID          | Filter (1) | Exposure (2) | Date (3)   | Count Rate (4) | VEGAMAG (5) |
|-------------|------------|--------------|------------|----------------|--------------|
| U32L0102/5/8| WFPC2/F547M| 3 × 30       | 1996 Jan 01| 0.67 ± 0.17    | 22.1 ± 0.2   |
| U32L0101/4/7| WFPC2/F656N| 3 × 600      | 1996 Jan 01| 0.09 ± 0.01    | 20.2 ± 0.1   |
| J8MX18010   | WFC/F658N  | 700          | 2003 Sep 18| 8.7 ± 0.5      | 20.0 ± 0.05  |
| J8MX18AQ    | WFC/F814W  | 120          | 2003 Sep 18| 82.4 ± 5      | 20.7 ± 0.06  |
| J90L5AQ010  | WFC/F814W  | 1650         | 2004 Sep 14| 73.3 ± 3      | 20.8 ± 0.04  |
| J9EL28AQ0Q  | WFC/F435W  | 465          | 2006 Mar 27| 29.9 ± 0.5    | 22.09 ± 0.02 |
| J9EL28AQ    | WFC/F606W  | 470          | 2006 Mar 27| 57.8 ± 1.7    | 21.98 ± 0.03 |

Note—Col. (1): Exposure ID. Col. (2): Filter. Col. (3): Total exposure in seconds. Col. (4): Observation date. Col. (5): Count rate in \( \text{e}^{-} \text{s}^{-1} \) for the counterpart. Col. (6): Magnitudes in the VEGAMAG photometric system.

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**Fig. 1**.—The optical counterpart for M81-ULS1 on **HST** images in F547M (1996), F656N (1996), F658N (2003), F814W (2004), F435W (2006), and F606W (2006). The WFPC2 F547M/F656N and ACS/WFC F435W images are plagued with cosmic rays. All images are aligned with the counterpart at the image centers. The error circles have a radius of 0.5". North is up in all images. The counterpart also appeared on the ACS/WFC F814W (2003) image, which was very noisy due to the short exposure and not shown here. [See the electronic edition of the Journal for a color version of this figure.]
counterpart in the seven observations. We calculate the magnitudes for two Hα filters with SYNPHOT assuming an Hα emission line atop the continuum of the Bruzual stellar spectrum $f_{547M} = 1.3$ as similar to observed, is normalized to give the observed $F547M$ magnitude. The observations require an Hα emission-line luminosity of $(1.9-3.2) \times 10^{36}$ erg s$^{-1}$ during the 1996 WFPC2/F656N observation and $(0.8-1.1) \times 10^{36}$ ergs s$^{-1}$ during the 2003 WFC/F658N observation.

3. INTERPRETATION OF HST OBSERVATIONS

The optical counterpart of ULS1, placed at the distance of M81, has an absolute magnitude of $M_{F814W} \approx -7$ mag, a color of $F547M - F814W \approx 1.3$ as for K–M stars, and $F435W - F547M \approx -0.1$ as for late B stars. The red color and absolute magnitudes in $F547M$ and $F814W$ might be obtained from a massive old globular cluster of $\sim 10^{6}$ K–M dwarfs. However, the same globular cluster cannot explain the late B–like blue color in $F435W$. The blackbody spectral fit to the optical counterpart of ULS1, placed at the distance of M81, is normalized to give the $F814W$ magnitude, which is less than a few percent of the Eddington luminosity, the Roche lobe size of the black hole. With similar procedures as in the white dwarf model, the four observed magnitudes determine a best combination, at $\Delta m^2 = 0.16$, of the $\nu^{1/3}$ power-law component and an AGB star, which has $M_e = 1.30 M_\odot$, $R = 1301 R_\odot$, and $T = 2277 K$. The model, plotted in Figure 3 with the MCD model fit (Liu 2007) overplotted for comparison, can explain all observed magnitudes. Remarkably, the required $\nu^{1/3}$ power-law component in the optical is consistent to within 30% with the MCD fit to the X-ray spectrum.

The properties of the companion AGB star may differ considering the uncertainties in the theory and the observations. In particular, the analytical form for the core-mass radius relation for AGB stars, adopted for the convenience of calculations, tends to overestimate the radius (Rappaport et al. 1995). To test how this affects our results, we recalculate the models by setting $R_\odot = 3300$, i.e., reducing the radius by 33%. Under this simplistic modification, we find an AGB star with $M_e = 0.60 M_\odot$, $R = 219 R_\odot$, and $T = 3119 K$ for the white dwarf model and an AGB star with $M_e = 0.93 M_\odot$, $R = 595 R_\odot$, and $T = 2859 K$ for the IMBH model. The white dwarf model has a $\Delta m^2 = 0.42$ and cannot explain all the observations because it does not give enough blue light. The IMBH model can fit all the observations simultaneously, but to a less satisfactory level ($\Delta m^2 = 0.26$) as compared to the model with $R_\odot = 4950$ ($\Delta m^2 = 0.16$). The white dwarf model is hotter and more compact. It has a less massive core ($0.93 M_\odot$), which is consistent with the final core masses of AGB stars with heavy stellar wind (Weidemann 2000). If the AGB star is at its final stage, its core mass indicates an initial mass $\sim 10^{5} M_\odot$ and a lifetime shorter than 0.1 Gyr (Vassiliadis & Wood 1993).
consistent with a power law as expected from the 1/3 to the companion of an AGB star. The blue component is M81-ULS1 in the optical reveals a blue component in addition with up the differences. In this Letter, we report the optical studies observations in the optical and infrared are capable of picking a white dwarf accretor for the same X-ray luminosities, and behaves quite differently in presence of an IMBH accretor or black holes (IMBHs) or massive white dwarfs that are pro-
copy suggests, are possibly the long-sought intermediate-mass has a form of . The multicolor disk has an inner edge temperature of 1/3

\[ F \propto n^{-1/3} \]

disk around an IMBH accretor but

\[ F \propto n^{-1} \]

power law instead of a power law. This is because the distinguishing power of the optical data mainly comes from the blue color between F435W and F606W (or F547M), as illustrated in Figures 2 and 3, yet F435W and F606W were already observed simultaneously.

The conclusion would be invalidated if the optical counterpart were an interloper close to M81-ULS1 by projection. Such projection, however, is unlikely because the probability of finding such an AGB star in a 0.5° error circle by chance is quite small (<0.003), as calculated from the error circle size and the fact that no stars of equal brightness were found within 10°. Also, the prominent Hα emission is suggestive of the photo-ionization of surrounding materials by the soft X-ray emission from ULS1, and the Hα variation between two observations is somehow expected due to the long-term X-ray variability of ULS1 (Liu 2007). Furthermore, a companion of an AGB star with a supergiant size, if overflowing or underfilling its Roche lobe, implies a period of 30 yr or longer, which is consistent with the failure to detect any period from the 6 yr Chandra observations (Liu 2007).

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Fig. 3.—Fit for the optical observations with an AGB plus the power-law component of a multicolor disk around an IMBH. The power-law component has a form of \( F \propto n^{-1/3} \). The multicolor disk has an inner edge temperature of 83 eV as from X-ray analysis, and its unabsorbed and absorbed spectra are plotted for comparison. [See the electronic edition of the Journal for a color version of this figure.]

4. DISCUSSION

Ultraluminous supersoft sources (ULSs), as X-ray spectroscopy suggests, are possibly the long-sought intermediate-mass black holes (IMBHs) or massive white dwarfs that are progenitors of Type Ia supernovae. We note that the accretion disk behaves quite differently in presence of an IMBH accretor or a white dwarf accretor for the same X-ray luminosities, and observations in the optical and infrared are capable of picking up the differences. In this Letter, we report the optical studies with HST archive observations of M81-ULS1, a ULS in the M81 bulge. To summarize, the spectral energy distribution of M81-ULS1 in the optical reveals a blue component in addition to the companion of an AGB star. The blue component is consistent with a \( F_n \propto n^{-1/3} \) power law as expected from the geometrically thin accretion disk around an IMBH accretor but inconsistent with a \( F_n \propto n^{-1} \) power law as expected from the X-ray-irradiated flared accretion disk around a white dwarf accretor. This is strong observational evidence that M81-ULS1 is an IMBH instead of a white dwarf.

The HST archive observations, however, were taken at different times spanning 6 yr. This may affect our conclusion because the differences between different bands could result (partly) from the intrinsic variabilities of the accretion disk and the AGB companion. The accretion disk may have changed as suggested by the X-ray variability over the years, while AGB stars are known to be long-period variables with amplitudes of up to \( \Delta V \sim 2.5 \). The marginally significant change in the F814W magnitudes from two observations separated by 1 yr may have reflected such variabilities. Simultaneous observations in multiple bands are thus required to make clear whether and how much the spectral energy distribution in this work was contaminated by the variabilities. While such simultaneous observations may change the details of the AGB companion and the accretion disk, they probably will not change the main conclusion that the blue component comes from a \( F_n \propto n^{-1/3} \) power law instead of a \( F_n \propto n^{-1} \) power law. This is because the distinguishing power of the optical data mainly comes from the blue color between F435W and F606W (or F547M), as illustrated in Figures 2 and 3, yet F435W and F606W were already observed simultaneously.