Multiwavelength Observations and State Transitions of an Ultra-luminous Supersoft X-ray Source: Evidence for an Intermediate-Mass Black Hole

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We report the results of *Chandra* and *XMM-Newton* observations of an ultra-luminous supersoft X-ray source in M101. M101 ULX-1 underwent 2 outbursts in 2004 during which the peak bolometric luminosities reached 10^{41} ergs s^{-1}. The outburst spectra were very soft and can generally be fitted with a blackbody model with temperatures of 50–160 eV. In two of the observations, absorption edges at 0.33 keV, 0.56 keV, 0.66 keV, and 0.88 keV were found. A cool accretion disk was also found in the 2004 December outburst. During the low luminosity state, a power-law tail was seen up to 7 keV. It is clear the source changed from a low/hard state to a high/soft state. In addition, it showed at least 5 outbursts between 1996 and 2004. This is the first ultra-luminous X-ray source for which recurrent outbursts with state transitions similar to Galactic X-ray binaries have been observed. From the *Hubble Space Telescope* data, we found an optical counterpart to the source. During the 2004 outbursts, we also performed radio and ground-based optical observations. All the results strongly suggest that the accreting object is a $> 2800 M_\odot$ black hole.

1. Introduction

Recent high angular resolution X-ray observations reveal that there are a large number of ultra-luminous X-ray sources (ULXs) in many nearby galaxies. ULXs are luminous ($L_X > 10^{39}$ ergs s^{-1}) non-nuclear X-ray point sources with apparent X-ray luminosities above the Eddington limit for a $\sim 10 M_\odot$ black hole (BH). While some ULXs have been associated with supernovae, many are thought to be accreting objects with X-ray flux variability observed on timescales of hours to years. A natural possibility is that the compact object is an intermediate-mass black hole (IMBH) with mass of $\sim 10^{2-4} M_\odot$ [1]. The origin of such objects remains uncertain. Some ULXs may have a stellar-mass black hole with beamed emission [2, 3]. While current observations are inconclusive about the nature of ULXs, recent X-ray observations show that some ULXs have a cool accretion disk ($kT \sim 0.1$ keV), suggesting the presence of IMBHs [4, 5].

While the majority of ULXs have X-ray emission from 0.1 to 10 keV, a few ULXs have very soft spectra with no X-ray emission above 1 keV [6, 7, 8], similar to supersoft X-ray sources (SSSs) in the Milky Way. The high luminosities of ultra-luminous SSSs are inconsistent with typical nuclear burning white dwarf models for Galactic SSSs. These ultra-luminous SSSs could, however, very well be IMBHs. Their luminosities and temperatures are consistent with what is predicted for accreting BHs with masses between roughly 100 and 1000 $M_\odot$. Alternatively, outflows from stellar-mass BHs could also achieve such a high luminosity and low temperature [9].

In this paper, we report a series of X-ray/optical/radio observations of the ultra-luminous SSS in M101 (CXOU J140332.3+542103; M101 ULX-1 hereafter) during the low states and outbursts.

2. X-ray Observations

M101 ULX-1 is one of the most luminous ULXs. It was discovered with *ROSAT* and was confirmed as a SSS with a blackbody temperature of about 100 eV, with *Chandra* [7, 10, 11]. During 2000 March, *Chandra* detected it at $L_X \sim 4 \times 10^{39}$ ergs s^{-1}, and then in 2000 October, its luminosity was around 10^{39} ergs s^{-1}. In 2004, *Chandra* conducted a monitoring program for M101. Figure 1 (Left) shows the long-term X-ray lightcurve of M101 ULX-1 from 2004 January to 2005 January. M101 ULX-1 was near the detection limit during January, March, and May; the X-ray spectra were harder with a power-law shape (see Figure 1 Right), and the X-ray luminosity was about 2×10^{37} ergs s^{-1}, a factor of about 10^2 fainter than that during the outbursts in 2000 [12]. The source was found to be in outburst during the July 5 observation, with an X-ray luminosity of about 7×10^{39} ergs s^{-1}. Data taken on July 6, 7, and 8 show that the source was in outburst with a peak bolometric luminosity (for assumed isotropic emission) of about 10^{41} ergs s^{-1} [12]. In general, the X-ray spectra are best described with an absorbed blackbody model with temperatures of $\sim 50-100$ eV (see Figure 1). In addition, we found absorption edges at 0.33, 0.57, 0.66, and 0.88 keV in two of the high state spectra. These features may signal

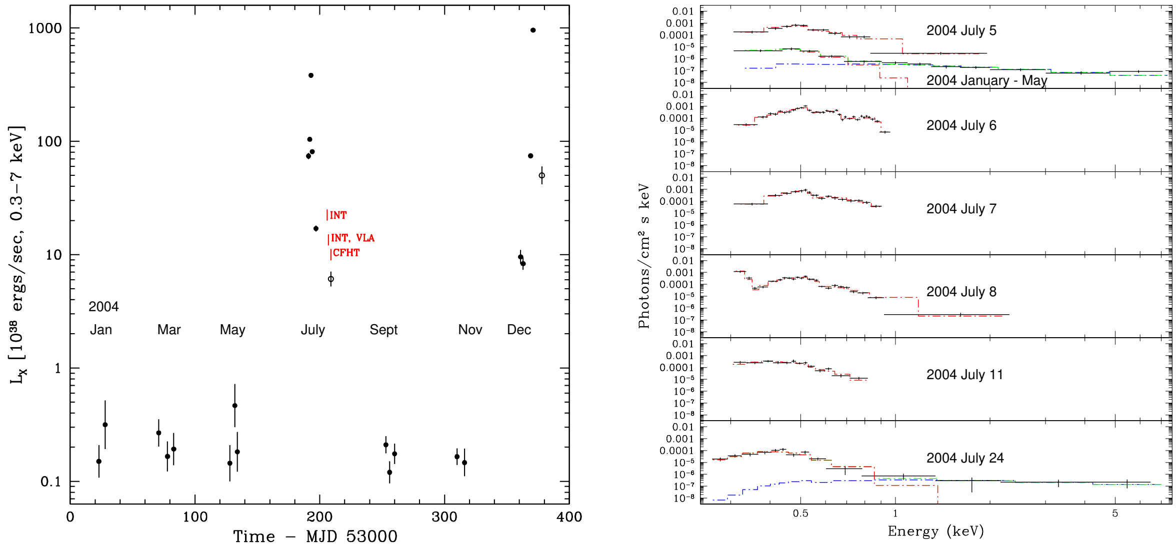

Figure 1: Left: The light curve of M101 ULX-1 in 2004 as observed by *Chandra* (solid circles) and *XMM-Newton* (open circles). It is very clear that the source stays at $\sim 10^{37}$ ergs s^{-1} during the low luminosity state. When it went into an outburst in 2004 July and December, the peak 0.3-7 keV luminosity was near 10^{41} ergs s^{-1}, a factor of ~ 1000 comparing to the low state. We also show the optical (INT and CFHT) and radio (VLA) coverage in the figure. It is worth noting that the CFHT observation was taken simultaneously with *XMM-Newton*. Right: Unfolded spectra of M101 ULX-1. The total spectrum, blackbody component, and power-law component are shown in green, red, and blue, respectively. During the 2004 July outburst, the spectra can be fitted with blackbody/disk blackbody model with temperatures of 50-100 eV. In two of the observations, absorption edges at 0.33, 0.57 (July 8), 0.66, and 0.88 keV (July 6) were found. On July 7, the peak bolometric luminosity reached 10^{41} ergs s^{-1} (which is one of the most luminous ULXs). The *XMM-Newton* spectrum taken on July 23 can be fitted with a blackbody ($kT = 53$ eV) and a power-law ($\alpha = 0.72$) model. The combined Jan-May spectrum is similar to the *XMM-Newton* spectrum, but with much lower luminosities ($\sim 10^{37}$ ergs s^{-1}).

the presence of highly ionized gas in the vicinity of the accretor (e.g., warm absorber). A DDT *XMM-Newton* observation was made on July 23 and the luminosity was about 6×10^{38} ergs s^{-1}. A harder X-ray spectrum with a power-law tail ($kT = 53$ eV and $\alpha = 0.72$) was seen up to 7 keV. More recently, *Chandra* observations made in September and November indicated that the source returned to the low state with a power-law spectrum and a luminosity of $\sim 2 \times 10^{37}$ ergs s^{-1}. In 2004 December, the source was in outburst again with very soft spectra ($kT = 50 - 160$ eV) and a peak luminosity of about 10^{41} ergs s^{-1}. During the rise of the outburst, the spectra were supersoft with blackbody temperatures of 40–70 eV. The source showed a cool accretion disk near the peak of the outburst on 2005 January 1. The X-ray spectrum can be fitted with a disk blackbody model with $kT_{DBB} = 0.16$ keV which is significantly harder than previous supersoft X-ray spectra. The peak luminosity of the 2004 December outburst is about 9×10^{40} ergs s^{-1} which is very similar to the 2004 July outburst. A DDT *XMM-Newton* observation made on 2005 January 8 indicated that the source was in the decline stage ($L_X = 6 \times 10^{39}$ ergs s^{-1}) and the X-ray spectrum returned to a supersoft state ($kT = 56$ eV) [13].

3. Optical Observations

M101 ULX-1 is located near star forming regions in a spiral arm. Figure 2 shows a far UV (1350–1750 Angstroms) image of M101 taken with GALEX. While GALEX cannot detect M101 ULX-1 because of the sensitivity and confusion, the ultra-luminous SSS is about $10''$ away from a bright UV source. Based on the position provided by *Chandra*, we searched for optical counterpart of M101 ULX-1 in archival *Hubble Space Telescope (HST)* data. The region of M101 ULX-1 was observed with *HST* using Wide Field Planetary Camera 2 (WFPC2) and Advanced Camera for Surveys (ACS) in 1994, 1995, and 2002. After reducing the data with standard procedures and correcting the astrometry of the *HST* and *Chandra* images, we found a blue object ($V = 23.8$, $B - V = -0.2$) within the $0.6''$ *Chandra* error circle (Figure 3). At the distance of M101 (d=6.7 Mpc), the absolute magnitude corresponds to $M_V = -5.3$. The magnitudes and colors of the blue star are consistent with an OB star. During the 2004 July outburst, we performed a series of target-of-opportunity observations at ground-based optical telescopes (see Figure 1 and 3). These observations included WIYN 3.5m, the 4.2m William

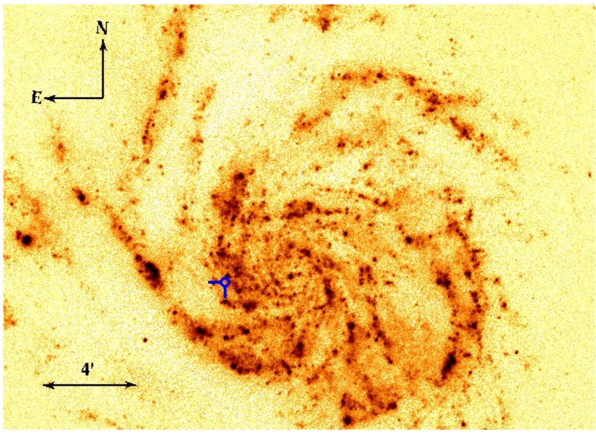

Figure 2: GALEX far UV (1350–1750 Angstroms) image of M101. The blue circle is the location of M101 ULX-1.

Herschel Telescope (WHT), the 2.5m Isaac Newton Telescope (INT), and the 3.6m Canada-France-Hawaii Telescope (CFHT). Unfortunately, WIYN and WHT observations were affected by bad weather and bright moon. M101 ULX-1 was barely detected in the INT images but was clear seen in the CFHT images even under very bad seeing (Figure 3). It is worth noting that the CFHT observations were performed *simultaneously* with *XMM-Newton*. These are the *first* simultaneous X-ray/optical observations for an ULX. During the 2004 December outburst, we also performed an optical follow-up observation with the WIYN 3.5m on 2005 January 17 and M101 ULX-1 was clearly detected.

4. Radio Observations

After the discovery of the outburst of M101 ULX-1 in 2004 July with *Chandra*, we observed M101 ULX-1 under target-of-opportunity time with Very Large Array (VLA) D-array at 4.86 (14 arcsec resolution) and 8.46 GHz (8.4 arcsec resolution; Fig. 4) for about 1.5 hours on 2004 July 21. There is no radio counterpart with a 3σ detection limit of 0.075 mJy/beam at 8.46 GHz. We also searched for the radio emission from archival VLA data. In the 2002 May 7 A-array 1.4 GHz (1.5 arcsec resolution) data, the source was not detected in the 6-hour observation but there is a 2σ hint of a source about $1''$ away from M101 ULX-1; the 3σ detection limit of the observation is 0.075 mJy/beam.

5. Discussion

M101 ULX-1 is a very unique ULX. It has a very soft blackbody spectrum during outburst while it has a hard power-law tail in the low state. It also has recurrent outbursts which provide an excellent opportunity to explore a totally new variability timescale for an ULX. Only a handful of transient ULXs have been detected. This may be due to the lack of repeated observations of nearby galaxies. M101 ULX-1 is the only ULX that has been observed regularly with X-ray telescopes. Hence, rapid multiwavelength follow-up observations become possible and meaningful. The X-ray/optical/radio observaitons of M101 ULX-1 reported here is the first and only rapid follow-up observations for an ULX.

Although over 100 ULXs have been discovered [1], only a handful of sources have $L_X \gtrsim 10^{41}$ ergs s^{-1}, assuming isotropic radiation [14, 15, 16, 17]. A luminosity this high is difficult to achieve in an X-ray binary unless the accretor has a mass greater than roughly 10 $M_\odot$. We do have evidence that M101 ULX-1 is likely to be an X-ray binary, since its luminosity has been observed to change by a factor of $\gtrsim 10$ on a time scale of hours [7, 11]. While it is possible that our luminosity estimates are higher than the true luminosity, the effects that lead to overestimates, such as beaming, or various anisotropies, tend to change estimated luminosities downward by a factor of roughly 10. Its unusually high bolometric luminosity (10^{41} ergs s^{-1}), coupled with its short-time-scale time variability, therefore make M101 ULX-1 a good candidate for an accreting IMBH. For instance, anisotropic X-ray emission can result super-Eddington luminosity for a stellar-mass BH [2]. However, in order to achieve such a high luminosity for a stellar-mass BH, extreme beaming is required and the disk is expected to be much hotter. Similarly, the temperature of radiation pressure-dominated accretion disk model proposed is too high [18]. The pure blackbody spectrum also makes relativistically beaming unlikely [3].

Its soft spectrum in the high state is another important piece of evidence. An accretion disk around a very massive BH is expected to produce supersoft X-ray emission [19]. If we used the 90% lower limits of the inner disk temperature derived from the disk blackbody fits, the BH mass is estimated to be $> 2800 M_\odot$ [20]. This is consistent with prior work on IMBH models for ULXs [1]. It also complements other work on evidence for cool disks in ULXs that has also been considered as evidence for IMBH models [4, 5] although a power-law component usually contributes a significant fraction of X-ray emission. Indeed, M101 ULX-1 showed a cool accretion disk spectrum ($kT_{DBB} = 0.16$ keV) during the December outburst. Furthermore, the high state luminosity is approximately 16% of the Eddington luminosity for a 6000 $M_\odot$ BH; we therefore expect the inner disk to be optically thick, which is consistent with the IMBH interpretation.

The state changes of M101 ULX-1 span a luminosity range larger than a factor of 1000. M101 ULX-1 was first detected by *ROSAT* in 1996 November

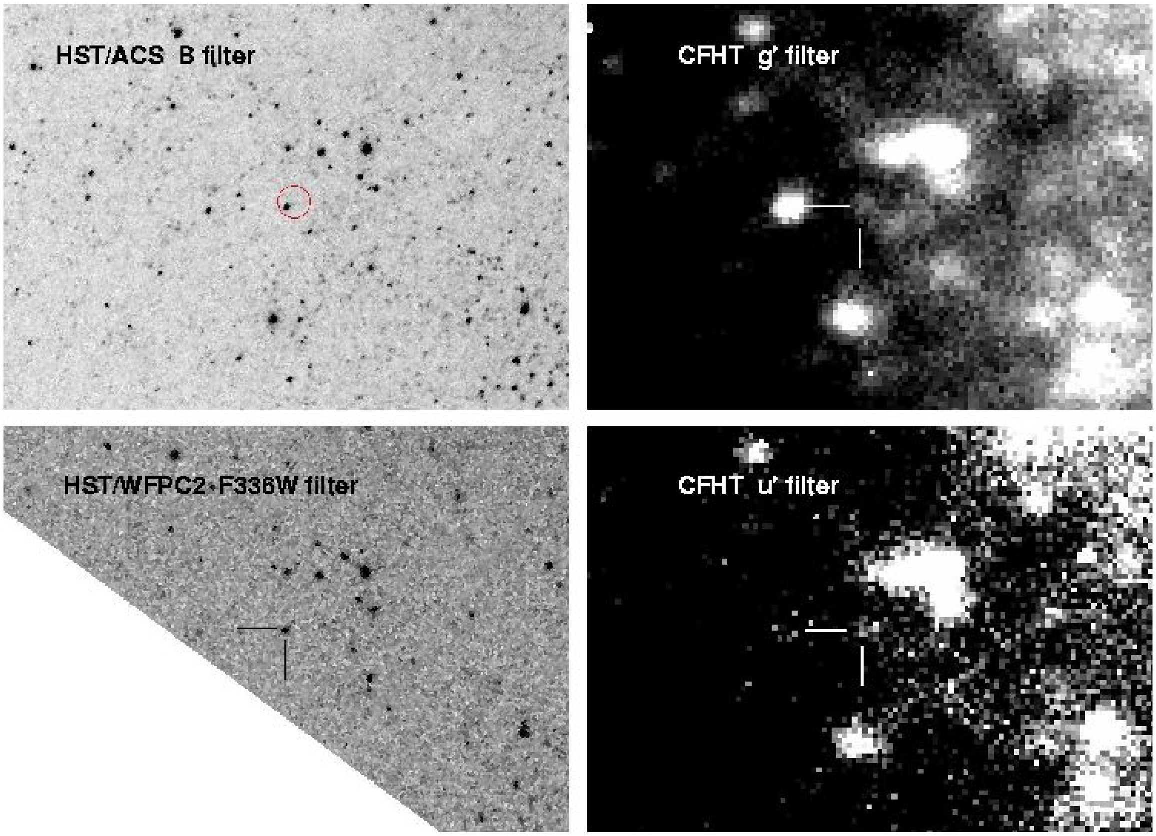

Figure 3: Upper Left: *HST*/ACS B band image (900s) of the field near the SSS. The image has been corrected for astrometry using 2MASS catalog. The 0.6″ *Chandra* error circle is indicated. The B magnitude is about 23.6. Lower Left: HST/WFPC2 U band (F336W) image (1200s) of the same field. The U magnitude of the source is about 22.3. Upper Right: CFHT g' band image (600s) of the same field. The image was taken simultaneously with *XMM-Newton* on 2004 July 23. Lower Right: CFHT u' band image (600s) of the same field.

[21], with an extrapolated unabsorbed 0.3–7 keV luminosity of 8×10^{38} ergs s^{-1} (blackbody model with $N_H = 10^{21}$ cm^{-2}, $kT = 75$ eV). Higher absorption (3×10^{21} cm^{-2}) would imply a luminosity up of 4×10^{39} ergs s^{-1}. The source was not detected in other *ROSAT* observations [21]. In a 108 ks *ROSAT* HRI observation taken in 1996 May/June, we can set a 3σ detection limit at 6.8×10^{37} ergs s^{-1} (power-law model with $N_H = 1.2 \times 10^{20}$ cm^{-2} and $\alpha = 2$). Setting the N_H at 1.5×10^{21} cm^{-2}, the luminosity limit becomes 1.5×10^{38} ergs s^{-1}. In 2000 March and October, *Chandra* detected the SSS in the very soft state with luminosities of $\sim 10^{39}$ ergs s^{-1} [7, 11]. In 2002 June, *XMM-Newton* observed M101 and did not detect the SSS [22]. We re-analysed the image and found that the SSS may be barely detected with possible contamination from nearby sources. We derived the 0.3–7 keV luminosity of the SSS as $\sim 10^{37}$ ergs s^{-1}, by assuming a power-law model. The source was also in the low state between 2004 January and May with luminosity of $\sim 10^{37}$ ergs s^{-1}. It is clear that the SSS has had at least 5 major outbursts ($L_X > 10^{39}$ ergs s^{-1}). On the other hand, the very low luminosities ($\sim 10^{37}$ ergs s^{-1}) during 2002 and 2004 indicate that the source was in the low state. The source varies by as much as a factor of 1000 between the low state and the high state. This amplitude is even greater than many Galactic BHs. Remarkably, the source also shows spectral changes. It is very clear that there is a power-law component ($\alpha = 1.4$) in the composite low state spectrum, while the high state spectra are supersoft. The *XMM-Newton* observation taken during the decay of the July outburst revealed that the blackbody component was still strong and there was a very hard power-law tail, similar to the low state. In addition, the source showed spectral change during the 2004 December outburst. During the peak of the outburst, the X-ray spectrum changed from a supersoft spectrum to a quasisoft spectrum [23]. It is clear that the spectrum was significantly harder than typical outburst supersoft spectra. This is the first and only ULX for which recurrent outbursts with state transitions similar to Galactic X-ray binaries have been observed.

With a peak bolometric luminosity $\approx 10^{41}$ ergs s^{-1}, it is likely that IMBH is the central engine of the system. Interestingly, the blackbody component is al-

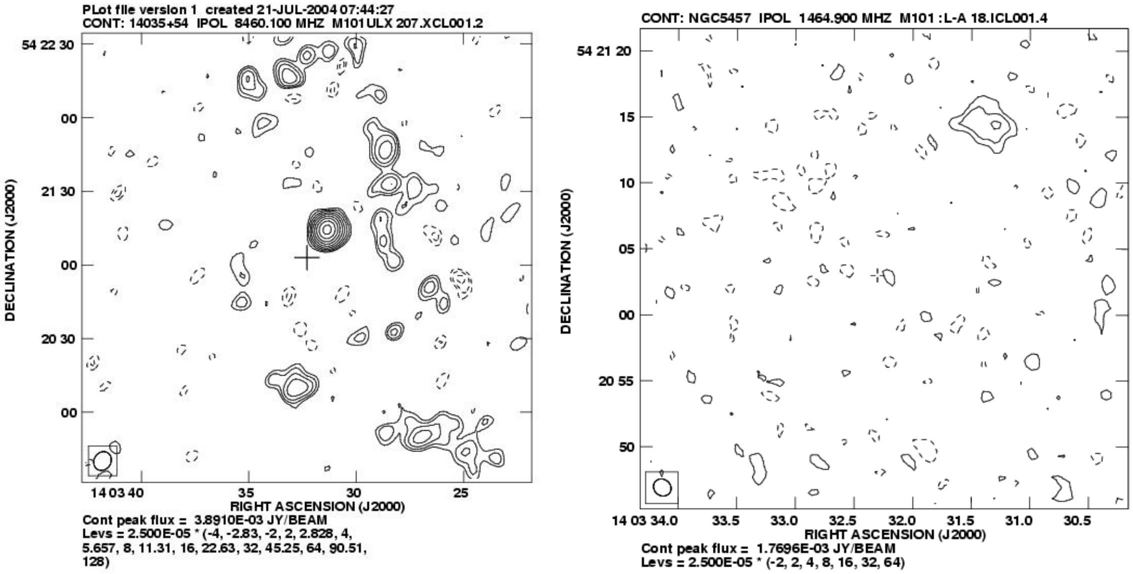

Figure 4: VLA observations of M101 ULX-1 with 4.86 GHz (14 arcsec resolution; Left) and 1.4 GHz (1.5 arcsec resolution; Right). The cross is the *Chandra* position of M101 ULX-1.

ways seen while the power-law component becomes stronger when the source is at lower luminosities. It may indicate that the power-law component is due to Comptonization of soft photons [24]. The photon index is, however, harder than that of Galactic BHs in the low state ($\alpha \sim 1.7$). None of the Galactic BHs has similar spectrum [25]. The closest example is Galactic microquasar V4641 Sgr for which the photon index was measured to be between 0.6 and 1.3 [25, 26].

Another important feature of our X-ray spectral fits is the presence of absorption edges, which we found at 0.33, 0.57, 0.66, and 0.88 keV in two of the high state spectra. These are consistent with C V, N VI, N VII, and O VIII edges. We note, however, that the 0.33 keV edge may be due to calibration of the ACIS-S near the carbon edge around 0.28 keV. These features may signal the presence of highly ionized gas in the vicinity of the accretor (e.g., warm absorber), and may be consistentwith an outflow from the source. In fact, outflow models have been suggested for ULXs in which the soft component of some ULXs is due to outflow of a stellar-mass BH [9]. Similar argument to explain the super-Eddington luminosity of M101 ULX-1 [11]. However, the new data which reveal the changes of temperature and bolometric luminosity, the extremely high luminosity, and the state transition of the source will be difficult to explain by such a model. It remains a puzzle that we saw different edges in the two observations, possibly related to the geometry of the system. Nevertheless, outflows from IMBHs may be expected.

It is also interesting to note that similar absorption edges are expected and have been observed in white dwarf (WDs) systems such as the recurrent nova U Sco [27], CAL 87 and RX J0925.7–4758 [28]. SSS radiation with luminosities in the range from 10^{37} ergs s^{-1} to roughly the Eddington limit for a 1.4 $M_{\odot}$ WD are expected for nuclear burning WDs [29]. Indeed, such models have been proposed to explain SSSs in the Galaxy and Magellanic Clouds. Note, however, that neutron star and BH models have also been proposed. The high state luminosity of this source is almost two orders of magnitude larger than that of any other known SSS, and it rules out steady nuclear burning on hot WD models as an explanation for M101 ULX-1. A similar argument can be made for neutron star models. A nova explosion could explain some features of the data. It is not favored, however, because the photospheric radius and lack of hard radiation at the peak of the outburst have no obvious explanation.

We expect that at least some of the ULXs involving IMBH accretors are transients [2, 30]. The required condition is that the donor must be a massive star ($\gtrsim 5\ M_{\odot}$) in regions of young populations. M101 ULX-1 satisfies these conditions. The colors of the optical counterpart are consistent with an OB star. More recent optical observations suggest that the optical counterpart is a B supergiant with a mass of $9-12 M_{\odot}$ and the optical spectrum indicates that M101 ULX-1 is consistent with a high-mass X-ray binary [31]. The source is also very close to star forming regions in a spiral arm as indicated in Figure 2.

It may be impossible to conclusively establish, using current technology, that any X-ray source in an external galaxy is an IMBH. A system like M101 ULX-1 is therefore particularly valuable, because it provides 5 different pieces of evidence that together make a consistent argument in favor of an IMBH interpretation.

Its high-state luminosity, its short-time-scale variability, its soft high-state spectrum, its pronounced spectral changes, and the high-mass companion all suggest that M101 ULX-1 is a strong IMBH candidate.

Acknowledgments

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