SPECTROSCOPIC STUDIES OF AN ULTRALUMINOUS SUPERSOFT X-RAY SOURCE IN M81

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Received 2015 January 18; accepted 2015 March 17; published 2015 April 2

ABSTRACT

Ultrapluminous supersoft X-ray sources (ULSs) exhibit supersoft X-ray spectra with blackbody temperatures below 0.1 keV and bolometric luminosities above $10^{39}$ erg s$^{-1}$. In this Letter, we report the first optical spectroscopic observations of a ULS in M81 using the LRIS spectrograph on the Keck I telescope. The detected Balmer emission lines show a mean intrinsic velocity dispersion of 400 ± 80 km s$^{-1}$, which is consistent with that from an accretion disk. The spectral index of the continuum on the blue side is also consistent with the multi-color disk model. The H$_\alpha$ emission line exhibits a velocity of ~180 km s$^{-1}$ relative to the local stellar environment, suggesting that this ULS may be a halo system in M81 belonging to an old population. No significant shift is found for the H$_\alpha$ emission line between two observations separated by four nights.

Key words: galaxies: individual (M81) – X-rays: binaries

1. INTRODUCTION

Ultrapluminous supersoft X-ray sources (ULSs) are pointlike, non-nuclear X-ray sources that have extremely soft spectra with equivalent blackbody temperatures below 0.1 keV and bolometric luminosities above $10^{39}$ erg s$^{-1}$. They are thought to be massive white dwarfs (WDs) burning accreted material on their surface or intermediate-mass black holes (IMBHs; $10^2$–$10^4 M_\odot$) with sub-Eddington accretion (Liu & di Stefano 2008).

Swartz et al. (2002) observed the nearby spiral galaxy M81 with Chandra ACIS, and discovered an intriguing ULS in the bulge, R.A. = 09$^h$55$^m$42$^s$.2, decl. = +69$^\circ$03$'$36$''$.5 (J2000.0) (hereafter M81 ULS1). Its spectrum can be fitted by a blackbody model with a temperature of ~70 eV. The bolometric luminosity calculated with the distance of M81 is ~$10^{39}$ erg s$^{-1}$. The follow-up X-ray study reveals that its spectrum can be described by either a blackbody for a WD or a multi-color accretion disk for an IMBH (Liu 2008).

Its optical counterpart was detected by the Hubble Space Telescope (HST; Liu & di Stefano 2008). The spectral energy distribution (SED) from broadband photometry exhibits a blue component and a red component. The spectral index of the blue component is consistent with a geometrically thin accretion disk and the red component could be described by an AGB star. The SED also shows excessive H$_\alpha$ emission which probably originated from the accretion disk or surrounding material that has been photo-ionized by the soft X-ray emission of M81 ULS1, but the band photometry results cannot provide the width of the emission line that is known to be an indicator of physical process.

The SED measurements, however, suffer from the intrinsic variabilities of ULS1, since a flux decrease by a factor of ~2.4, as Tao et al. (2011) presented, occurred in less than a week in optical wavelength. Spectral observations, on the other hand, are independent of variabilities. The expected Balmer emission lines in the spectrum will enable us not only to characterize its physical conditions but also to probe its local environments (Moon et al. 2011). This information is essential for us to understand the nature of M81 ULS1.

In this Letter, we report Keck spectroscopic observations of M81 ULS1 and present evidence for the existence of an accretion disk. Section 2 describes the Keck/Low Resolution Imaging Spectrograph (LRIS) observations and the result. A discussion is presented in Section 3.

2. DATA ANALYSIS AND RESULTS

Observation of M81 ULS1 occurred on 2010 April 13 and 17 during its expected X-ray low state (S. Wang et al. 2015, in preparation) using the LRIS on the Keck I 10 m telescope. Three exposures of 1000 s were taken in the first night and two of 1200 s in the second night. The mean seeings in the B band were 0′′8 and 0′′8, respectively. The light of the counterpart was masked with a 0′′7 wide slit and split with a beam dichroic to the blue and red sides followed by a 300 lines mm$^{-1}$ and a 400 lines mm$^{-1}$ grating.

The spectra were reduced in a standard way with IRAF. First, raw FITS files were bias-subtracted, flat-corrected, and combined. On the blue side of the spectra, the position of the optical counterpart along the slit was verified by comparing its position in the target acquisition image (Figure 1(b)) with an HST Advanced Camera for Surveys (ACS) F606W image (Liu & di Stefano 2008). On the red side, since the counterpart was not obvious along the slit, an offset between the counterpart and the WD (PG1708 + 602) was used to verify the position of the counterpart.

Subsequently, raw spectra of the counterpart were extracted with an aperture size of 1′′. The wavelength calibration was then carried out based on the line lists given in the manual of Keck. The precision of the calibration is 0.2 Å, which is obtained from the rms of arc-lamp fitting.

Finally, PG1708 + 602 was used as the standard star to calibrate the flux by applying the standard flux given by Massey & Strobel (1988). Since the standard flux of PG1708 + 602 covered the wavelength from 3126 to 8004 Å, we had to extend the tabulated values to 10,000 Å for calibration on the red side (the upper panel in Figure 2).

2.1. Balmer Emission Lines

As shown in Figure 2, the Balmer emission lines are notable features in the spectra. Here, we used $\chi^2$ minimization to fit the...
centers and FWHMs of Hβ, Hα, and another notable emission line around 5530 Å. The results with 1σ errors are listed in Table 1. The mean FWHM of the Hβ and Hα emission lines derived from the fitting is 490 ± 80 km s⁻¹, which is significantly larger than the spectral resolution, 280 ± 10 km s⁻¹, measured from Hg Ⅰ λ5461 in the arc-lamp spectrum. The intrinsic dispersion is 400 ± 80 km s⁻¹ for the Balmer emission lines. The radial velocity of ULS1 is consistent with zero (an average of 2 ± 23 km s⁻¹) within the precision of the wavelength calibration, which implies that M81 ULS1 is unlikely to be a distant AGN with a large receding velocity.

The Balmer emission lines are mainly seen in the spectra of H II regions, planetary nebulae, and accretion disks around compact objects. The line dispersions for H II regions and planetary nebulae should be comparable to instrumental dispersions (Fang et al. 2013; Nicholls et al. 2014), while for accretion disks the line dispersions range from a few hundreds to thousands of kilometers per second. The detected Balmer emission lines of M81 ULS1 are significantly broader than the instrumental dispersion, and are consistent with originating from an accretion disk around a compact object.

The observations in two nights enable us to measure the shift of Hα related to the binary motion. We used the technology of the cross-correlation phasor to estimate the relative velocity. The technology is based on the correlation in wave-number space and can provide more information than the normal cross-correlation, such as the significance level (see Misra et al. 2010 for detail). The shifts of Hα and sky emission lines are measured in the pixel space to avoid the uncertainty of the wavelength calibration. The relative shift of Hα to the sky line is 0.43 ± 0.19 pixel, corresponding to 0.61 ± 0.38 Å toward short wavelengths. Then, we used $\chi^2$ minimization to check the relative shift and the result is 0.42 ± 0.36 pixel. No shift is found for the Hα emission line at a high significance level in the two nights of observations with a span of four nights.

### 2.2 Balmer Absorption Lines

Hβ absorption features are detected in a specific region along the slit as illustrated in Figure 1(c). The regions with absorption features are located in the same area of the sky but different parts of the CCD in two nights of observations, so these absorption features are unlikely artifacts of the CCD. The same features were also found near Hβ, but the signal is too low to derive a reliable velocity.

In order to investigate the association between the Balmer absorption lines and the environment of M81 ULS1, false-color maps were constructed in the optical (HST), UV (GALEX), and IR (Spitzer) wavelengths. Only the map of Spitzer exhibits obvious structures along the slit (Figure 1(a)). The region with the absorption features is correlated with the dark area in the map of 8 μm, and the absorption features disappear when the 8 μm emission is strong. Note that there is a positive correlation
between the 8 μm surface brightness and the H₂ emission powered by star-forming activity (Young et al. 2014). The observed absorption features appear in the non-star-forming regions, and likely come from the local stellar environments in the M81 bulge.

The absorption features in the background exhibit high velocities, \(-180 \pm 25 \text{ km s}^{-1}\) at 52″ from the nucleus. The stellar kinematics studies (Vega Beltrán et al. 2001) show that the bulge of M81 is rotating and the south–east side is approaching with velocities around \(-180 \text{ km s}^{-1}\) at 45″ from the nucleus. The similar velocity \((-180 \text{ km s}^{-1})\) suggests that the observed H₂ absorption lines come from stars in the bulge of M81. In comparison, the systemic velocity of M81 is \(-34 \text{ km s}^{-1}\) (obtained from NED).

The H₂ emission line \((2 \pm 23 \text{ km s}^{-1})\) exhibiting a receding velocity of \(182 \pm 35 \text{ km s}^{-1}\) relative to the H₂ absorption line from the stellar environment. This suggests that UL81 is not a system comoving with stars in the bulge of M81. Such a relative velocity can come from an object in the halo of M81 projected onto its bulge, which is receding along the line of sight. Here, we rule out the possibility that the system is located in the Milky Way, since the column density of neutral hydrogen atoms at the location of UL81 is \(5.4 \pm 0.5 \times 10^{20} \text{ cm}^{-2}\) in the Milky Way (Güver and Özel 2009), which is smaller than that derived from the X-ray spectrum fitting by a factor of two (Liu 2008).

2.3. SED Construction

Spectral observations of M81 ULS1 enable us to obtain the SED uncontaminated by its intrinsic variabilities. Here, we removed all of the emission lines and used a power-law function, \(f_\nu \propto \nu^\beta\), to fit the continuum of \(-4500–6000 \text{ Å}\), the high response wavelength range, in order to estimate the spectral index on the blue side. The \(\beta\) derived from the best fitting is \(-2.36 \pm 0.02\), which corresponds to \(\alpha \sim 0.36 \pm 0.02\) for \(f_\nu \propto \nu^\alpha\). The continuum on the blue side is consistent with the \(f_\nu \propto \nu^{1/3}\) relation expected for the multi-color disk (MCD) model. On the red side, the spectrum of an AGB star modeled with a temperature of 2277 K and a radius of 1301 \(R_\odot\), as suggested by Liu & di Stefano (2008), is presented in Figure 3. The combined SED is not consistent with the red-side spectrum, which suggests that the AGB model may not be a good explanation of the red component.

As a connection between the X-ray and optical wavebands, the UV emission is important for understanding the SED of M81 ULS1. In order to probe the UV emission of M81 ULS1, we used the archive data of GALEX (Martin et al. 2005). M81

### Table 1

| Center (Å) | FWHM (Å) |
|------------|-----------|
|            |           |
| 4.13       | 1.1       |
| 4.17       | 0.3       |
| Combined   | 0.6       |
| 8.8        | 2.7       |
| 8.2        | 0.7       |
| 8.6        | 1.3       |

### Notes

Col. (1): tile name. Col. (2): band name. Col. (3): effective wavelength in angstrom. Col. (4): total exposure time in seconds. Col. (5): earliest observation UT date for visits which make up the coadd. Col. (6): latest observation UT date. Col. (7): inner radius in arcseconds for signal integration. Col. (8): outer radius in arcseconds for background subtraction. Col. (9): magnitudes in AB system without correction for Galactic extinction.

### Table 2

| Tile           | Band | Effective Wavelength | ExpTime | Min ObsDate | Max ObsDate | Inner Radius | Outer Radius | AB Mag. |
|----------------|------|----------------------|---------|-------------|-------------|--------------|--------------|----------|
| GH_071001_M81  | FUV  | 1538.6               | 14706.7 | 2006 Jan 05 | 2007 Mar 31 | 6.3          | 10.5         | 22.27    |
| NUV            |      | 2315.7               | 29421.5 | 2005 Jan 12 | 2007 Mar 31 | 7.9          | 13.2         | 21.36    |

### Figures

**Figure 3.** SED of M81 ULS1. The blue and red components suggested by Liu & di Stefano (2008) are plotted in red lines. Red points are the photometric results of GALEX and squares are those of HST obtained from Liu & di Stefano (2008). For correction of Galactic extinction, we have adopted the Galactic color excesses, \(E(B-V) = 0.08\), given by Schlegel et al. (1998), and the parameterization of the Galactic extinction law given by Cardelli et al. (1989) with an extinction ratio of \(R_V = 3.1\), and the conversion factors for the FUV and NUV are \(A_{FUV} = 7.9E(B-V)\) and \(A_{NUV} = 8.0E(B-V)\), respectively.
has been observed with three different tiles, and here we used the tile with an exposure time over $10^5$ s to perform accurate photometry. All of the sub-exposures of the tile were taken during the expected low state of M81 ULS1 (Liu 2008, S. Wang et al. 2015, in preparation). The photometric results are listed in Table 2 and are also shown in Figure 3. Although with dispersions, the UV fluxes lie along the MCD power law.

3. DISCUSSION

In this Letter, we report the first optical spectroscopic confirmation of an accretion disk around a ULS. The broad Balmer emission lines of M81 ULS1 revealed by the Keck/LRIS observations are consistent with those of an accretion disk around a compact object. The spectral index of the continuum on the blue side is also consistent with the disk around a compact object. The latter can come from a long orbital period or a very massive compact object such as an IMBH. However, the exact nature of the compact object is still unknown without monitoring the long-term motion of the system.

Besides the emission lines of Balmer series, an emission line arises around 5530 Å on the blue side with an FWHM of $1700 \pm 200 \, \text{km s}^{-1}$, larger than that of H$_\alpha$ by a factor of 4 (the lower panel in Figure 2). All of the exposures obtained in the two nights show the same emission feature and similar velocity dispersions, so it is unlikely an artifact or cosmic rays. This emission line is too broad to be a nebular line, and it is probably not an Fe II emission line because Fe$^+\text{II}$ ion emits through a huge number of multiplets scattered across the blue side of the spectrum (Baldwin et al. 2004; Shapovalova et al. 2012). Since the relative shift is $10 \, \text{Å} \pm 2 \, \text{Å}$ between two nights of observation, the emission line is unlikely to be related to the accretion disk. It has been reported that the N II λ5530 and λ5535 emission lines have been detected for Ae/Be stars (Mathew et al. 2010; Mathew & Subramaniam 2011). However, no other features are found to support the existence of an Ae/Be star, such as Fe II or O I emission lines. More spectra with a high signal-to-noise ratio (S/N) are needed to draw a conclusive result.

The spectrum of M81 ULS1 shows a gap between the red and blue sides due to the low response on the edges of CCDs, and the S/N on the red side is very low. Further, deeper spectroscopic observations with coverage of $\sim 5000$–$9000 \, \text{Å}$ could present the complete spectrum with high S/N on the red side, which will enable us to characterize the secondary.

The authors thank Prof. Bregman for his constructive comments on the manuscript. Some of the data presented in this paper were obtained from the Mikulski Archive for Space Telescopes (MAST). The authors acknowledge support from the National Science Foundation of China under grants NSFC-11273028 and NSFC-11333004, and support from the National Astronomical Observatories, Chinese Academy of Sciences under the Young Researcher Grant.

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