Central Engine and Host Galaxy of RXJ 1301.9+2747: A Multiwavelength View of a Low-mass Black Hole Active Galactic Nuclei with Ultra-soft X-Ray Emission

X. W. Shu¹, T. G. Wang², N. Jiang², J. X. Wang², L. M. Sun², and H. Y. Zhou²,3

¹Department of Physics, Anhui Normal University, Wuhu, Anhui, 241000, China; xwshu@mail.ahnu.edu.cn
²Department of Astronomy, University of Science and Technology of China, Hefei, Anhui 230026, China
³Polar Research Institute of China, 451 Jinqiao Road, Shanghai, 200136, China

Received 2016 November 29; revised 2017 January 16; accepted 2017 February 3; published 2017 February 27

Abstract

RXJ 1301.9+2747 is an optically identified very-low-mass AGN candidate with $M_{\text{BH}} \sim 1 \times 10^6 M_\odot$, which shows extremely soft X-ray emission and unusual X-ray variability in the form of short-lived flares. We present an analysis of multiwavelength observations of RXJ 1301.9+2747 in order to study the properties of the active nucleus and its host galaxy. The UV-to-X-ray spectrum in the quiescent state can be well and self-consistently described by a thermal and a Comptonized emission from the accretion disk, with the black body dominating ~70% of the X-rays in the 0.2–2 keV. The same model can describe the X-ray spectrum in the flare state, but the Comptonized component becomes dominant (~80%). The best fit implies an Eddington ratio of ~0.14 and a black-hole mass of (1.7 – 2.8) x $10^6 M_\odot$, in agreement with the estimation from the optical data within errors. However, the best-fitting model under predicts the optical flux for the HST point source by a factor of ~2. The excess of nuclear optical emission could be attributed to a nuclear stellar cluster, which is frequently seen in low-mass AGNs. The X-ray to optical spectral slope ($\alpha_{\text{ox}}$) is lower than in most other active galaxies, which may be attributed to intrinsically X-ray weakness due to very little hot and optically thin coronal emission. We performed a pilot search for weak or hidden broad emission lines using optical spectropolarimetry observations, but no polarized broad lines are detected. The host galaxy appears to be a disk galaxy with a boxy pseudobulge or nuclear bar accounting for ~15% of the total starlight, which is consistent with the general characteristics of the host of low-mass AGNs.

Key words: galaxies: active – galaxies: individual (RXJ 1301.9+2747) – galaxies: nuclei – X-rays: galaxies

1. Introduction

Supermassive black holes (SMBHs) with masses of $M_{\text{BH}} \sim 10^6–10^9 M_\odot$ reside in the center of most bulge-dominated galaxies in the local universe. The discovery of the correlation between BH masses and the stellar velocity dispersions, $\sigma_*$, of their host galaxies ($M_{\text{BH}}–\sigma_*$ relation, Ferrarese & Merritt 2000; Gebhardt et al. 2000), strongly suggests coevolution of galaxies and BHs. However, it is not known when and how this relation is established. In current models of galaxy evolution, SMBHs must have formed from much less massive “seed” BHs and grown up by fast accretion and/or merging (e.g., White & Rees 1978; Volonteri et al. 2003; Begelman et al. 2006). The nature of such seed BHs is thus a major challenge for any cosmological BH growth model.

BHs with masses in the range of $10^5–10^6 M_\odot$ (IMBHs hereafter) are of particular importance. By filling the mass gap between supermassive and stellar-mass BHs, these objects are potential analogs of the seeds of supermassive BHs (e.g., Volonteri 2010; Greene 2012). Recent optical and X-ray observations have yielded a sample of ~200–300 candidate IMBHs, which revealed themselves as active nuclei in small galaxies (Greene & Ho 2004, 2007b; Dong et al. 2012; Kamizasa et al. 2012; Schramm et al. 2013; Reines et al. 2013; Moran et al. 2014), and are beginning to constrain formation and evolution models of seed BHs (Greene 2012). In fact, deviations in the $M_{\text{BH}}–\sigma_*$ relation have been observed in a population of IMBHs (e.g., see the review by Kormendy & Ho 2013). The host galaxies of IMBHs appear very different from their supermassive counterparts. Detailed bulge-disk-bar decompositions of IMBH AGNs have shown that the majority of galaxies have disks and are likely to contain pseudobulges, with very few of them living in classical bulges (Greene et al. 2008; Jiang et al. 2011b), suggesting that a bulge may not be a necessary condition for BH growth and a secular evolution of the low-mass BHs is favored.

Presumably, IMBHs likely have not had the opportunity to become full-grown. The accretion process and the disk-corona geometry around the central IMBH could be markedly different from that around SMBHs in luminous AGNs (e.g., Godet et al. 2012; Miniutti et al. 2013; Jin et al. 2016). Therefore, AGNs with IMBHs provide an excellent diagnostic tool for probing the BH accretion processes in a poorly explored regime of parameter space (e.g., Dewangan et al. 2008; Miniutti et al. 2009; Yuan et al. 2010; Dong et al. 2012; Yuan et al. 2014; Ludlam et al. 2015; Pan et al. 2015; Ho & Kim 2016; Plotkin et al. 2016). They are potential candidates enabling us to test if the accretion physics is the same at all scales from the stellar mass to supermassive BHs (McHardy et al. 2006; Gültekin et al. 2014; Zhou et al. 2015).

The broadband spectral energy distribution (SED) of AGNs are powerful diagnostics on the detailed BH accretion processes as well as the interplay with the host galaxies (e.g., Elvis et al. 1994; Ho 1999; Vasudevan & Fabian 2009; Jin et al. 2012b). Although it is not straightforward to measure the SEDs for low-mass and hence low-luminosity AGNs because of the strong contamination from the hosts, there is increasing observational evidence suggesting the unusual multiband properties for these systems. Chandra and XMM-Newton observations of IMBH AGNs discovered with SDSS have shown that while the soft X-ray spectral properties are consistent with those for AGNs with more massive BHs, the X-ray-to-optical
spectral slopes ($\alpha_{\text{acc}}$) tend to be steeper (on average) than expected for their UV luminosities, suggesting that at least some of them may be intrinsically X-ray weak (Greene & Ho 2007a; Desroches et al. 2009; Miniutti et al. 2009; Dong et al. 2012). Low-mass AGNs with high accretion rates ($L_{\text{bol}}/L_{\text{edd}} \gtrsim 0.1$) have also been found to be very radio-quiet on average (Greene et al. 2006). Yuan et al. (2014) recently extended the study to relatively low Eddington ratio sources ($L_{\text{bol}}/L_{\text{edd}} \sim 10^{-2}$, Plotkin et al. 2016), and found that they tend to be intrinsically X-ray weak, very similar to that of the prototype IMBH AGN NGC 4395. On the other hand, Gültekin et al. (2014) have shown that low-mass BHs do belong to the “fundamental plane of BH accretion,” a correlation between the X-ray, radio continuum emission, and mass of accreting BHs (Merloni et al. 2003; Falcke et al. 2004; Gallo et al. 2012). More recently, Terashima et al. (2012) reported an extreme case of IMBH AGN, 2XMM J123103.2+110648 (J1231 +1106), with a central BH mass as small as $10^5 M_\odot$ (Ho et al. 2012), whose X-ray spectrum completely lacks emission at energies $\gtrsim 2$ keV, and can be described entirely by a soft thermal component of temperature $kT \sim 0.12$ keV. Such an extreme soft excess is unprecedented among AGNs, even at the very-low-mass end (e.g., Dewangan et al. 2008; Desroches et al. 2009; Miniutti et al. 2009; Ai et al. 2011). A similarly extremely soft X-ray spectrum was also found in GSN 069 ($M_{\text{BH}} \sim 1.2 \times 10^6 M_\odot$) by Miniutti et al. (2013). In either case, the pure thermal X-ray spectrum appears to be a close analog to the typical high/soft state in BH X-ray binaries (BHBs), which would suggest a new, and possibly accretion disk dominated, AGN spectral state. The discovery of a $\sim$3.8 hr periodicity from J1231+1106 adds further confidence of the similarity of this ultra-soft AGN to the BHBs (Lin et al. 2013). Lin et al. (2013) claimed that the ultra-soft X-ray spectra in the two objects could be associated with tidal disruption events because both clearly show long-term luminosity evolution, making the nature of their ultra-soft X-ray emission intriguing.

RX J1301.9+2746 (hereafter J1302) is another ultra-soft and highly variable AGN (Sun et al. 2013, hereafter S13). Our detailed analysis of the optical spectrum taken from the SDSS revealed that the galaxy hosts a Seyfert-like nucleus at $z = 0.0237$. Using the width of the [O III] $\lambda$5007 line as a proxy for the stellar velocity dispersion of the host galaxy, we obtained a BH mass of $M_{\text{BH}} \sim 8 \times 10^5 M_\odot$ with an intrinsic scatter of 0.5 dex, placing J1302 in the regime of IMBHs. The source not only shows many similarities to J1231+1106 and GSN 069 (lack hard X-rays and no detectable broad Hα), but is also exceptional in at least two respects: (1) its X-ray light curve clearly shows two distinct states: a long quiescent state and a short flare (or eruptive) state, which differs in count rates by a factor of five to seven; (2) significant detection in the radio (1.4 GHz) with the Very Large Array (VLA; $\sim 7\sigma$). Because of these unique properties, J1302 remains a valuable target for further study. Here we present an analysis of multiwavelength observations of J1302, including X-ray from Chandra/XMM-Newton, optical from HST, ultraviolet (UV) from XMM-Newton/OM, and GALEX, near-to-mid infrared from 2MASS, WISE, and Spitzer, and radio from the VLA, in order to investigate the nuclear SED of J1302 over a wide range in frequency as well as the host galaxy properties. In Section 2, we present the observations and data analysis. The results are discussed and concluded in Sections 3 and 4, respectively.

2. Observations and Data

2.1. Spectropolarimetric Observation

Spectropolarimetric observation was made with the CCD Spectropolarimeter (SPOL; Schmidt et al. 1992) at the 6.5 m Multiple Mirror Telescope on 2016 April 3. We used a low-resolution grating (6001 mm$^{-1}$) providing spectral coverage of 4100–8200 Å. An entrance slit of $\sim 1''$ width centered on the nucleus was used to match the seeing. The resulting spectral resolution is $\sim 15$ Å FWHM, corresponding to an FWHM of $\sim 700$ km s$^{-1}$ around the Hα. The total exposure time was 40 minutes. A $\lambda/4$ rotatable achromatic retardation plate was used to provide linear polarization measurements. The data reductions, including bias subtraction, flat-field correction, and cosmic-ray removal, were accomplished with standard procedures using the IRAF script provided by the instrument’s PI Dr. Paul Smith. Stokes $Q$ and $U$ parameters were measured individually and then combined to obtain the degree of polarization.

2.2. Analysis of the HST Images

J1302, as a member of the Coma cluster, was observed by HST/WFPC2 in F814W (roughly the I band of the Johnson system) and F450W (B) filter in a project studying current starburst and post-starburst early-type galaxies in nearby clusters of galaxies on 1997 July 12 (Caldwell et al. 1999). Some results from HST observations have been presented by Caldwell et al. (1999), which reveal J1302 to be an edge-on disk galaxy with a very bright nucleus. Here we examine the HST data in detail in the context of the broadband SED analysis on the nucleus. For ease of rejecting cosmic rays, the total exposure time (1200 s and 800 s for B and I bands respectively) were divided into two equal exposures in the observations of each band. These images are then combined using astrodrizzle to remove cosmic-ray hits and to correct for possible geometric distortion. J1302 was located at the center of PC1 chip and thus the final pixel scale is 0.00455.

Then we try to perform a two-dimensional (2D) decomposition of J1302 using GALFIT (Peng et al. 2002, 2010). The AGN is represented by a point source modeled with the TinyTim PSF, and the host galaxy is modeled by a bulge as a Sérsic $r^{1/n}$ function or a disk as an exponential (Exp) function (equivalent to $n = 1$), or a combination of the two. The sky background was subtracted during astrodrizzle combination, which was confirmed by our residual sky estimation. Other objects, like background galaxies or foreground stars, are masked out. The single Sérsic fitting scheme gives unacceptable large residuals in the image, while the Sérsic + Exp fitting scheme yields a much better result. For example, in our fittings to the HST I-band image, the single Sérsic model yields fit statistics $\chi^2$/dof = 221594/361180, while it is significantly improved using the Sérsic + Exp model with $\Delta \chi^2 = 14804$ for four extra parameters. During the B-band fitting, we have fixed the Sérsic index to be the value given by I band because a totally free fitting yields an unreasonable high index.

The top panels of Figure 1 show the F814W and F450W HST image (left panel) and the GALFIT model (middle column). The best fit yields $m_{\text{AGN}} = 18.1(f_{\text{p}} = 6.4 \times 10^{-17}$ erg cm$^{-2}$ s$^{-1}$ Å$^{-1}$), $m_{\text{bulge}} = 16.4 (f_{\text{p}} = 3.16 \times 10^{-16}$ erg cm$^{-2}$ s$^{-1}$ Å$^{-1}$) with an effective radius of $0''41$, and $m_{\text{AGN}} = 19.0$

http://james.as.arizona.edu/~psmith/SPOL/spolred.html
\( f_{\lambda} = 1.37 \times 10^{-16} \text{ erg cm}^{-2} \text{s}^{-1} \text{Å}^{-1} \), \( m_{\text{bulge}} = 17.6 \) \( f_{\lambda} = 5.29 \times 10^{-16} \text{ erg cm}^{-2} \text{s}^{-1} \text{Å}^{-1} \) with an effective radius of 0.37, for the F814W and F450W, respectively. The residuals after subtracting the model from the original image are shown in the right panel. The weak residuals seen in the central region (~0.15–0.3 arcsec), especially in the F450W HST image, could indicate small-scale structure in the host galaxy (Section 3.3). The bottom panels of Figure 1 show a radial profile plot of the data as well as the best fit model from GALFIT consisting of a central PSF (orange), a Sérsic of \( n = 1.45 \) (red dashed), and an outer
disk (blue dotted–dashed). The residuals at large radii ($r > 5$ arcsec) are likely due to more extended disk emission, which deviates from the adopted exponential profile ($n = 1$). Allowing the Sérsic index of the disk component to vary yields very similar results, indicating that the current HST observations are not sensitive to detect more extended, low surface brightness emission from the galaxy. In fact, previous studies have shown that the disk component is always fitted by an exponential profile, as in nearby inactive galaxies and galaxies with IMBHs, though disk profiles do vary at large radii (e.g., Jiang et al. 2011a).

Parameters of the F814W and F435W fits can be seen in Table 1, which are consistent with each other, except for the magnitudes. Additional checks on the photometry and potential systematic errors are presented in Appendix A.

2.3. X-Ray Observations

J1302 was observed by XMM-Newton EPIC cameras on 2000 December with a total exposure time of 29 ks, and Chandra on 2009 June for about 5 ks. The data were processed following the standard criteria, which is detailed in S13. We found in both XMM-Newton and Chandra observations that the source displays ultra-soft X-ray emission and unusual giant flares in the light curves for a duration of ~2 ks. Though only one and a possible decline of another flare are recorded in the XMM-Newton observation, a very similar flare seen in the Chandra data is suggesting that the flare itself appears repetitive and occurs very frequently in the object. In this paper, we will present a more physical description of the X-ray spectrum of J1302, by jointly fitting the X-ray and UV data (see Section 3.1). We will use principally the XMM-Newton PN data, which have much higher sensitivity. Because the source shows peculiar temporal and spectral behaviors, we attempted to quantify the spectral variability during flares by dividing the data into high and low flux intervals, using a count rate threshold of 0.35 counts s$^{-1}$ for the PN data. We classify the data above the count rate threshold as belonging to the flare state, and those that fall below, to the quiescent state.

2.4. Ultraviolet Observations

2.4.1. XMM-Newton Optical Monitor (OM)

The OM data from XMM-Newton for the J1302 were taken simultaneously with the X-ray observations, using the UVW2 and UVW1 filter, which is centered at 2120 Å and 2910 Å, respectively. The FWHM of the PSF is ~2$''$, or 2.1 pixels. However, only a few OM images (four) were taken and hence we are not able to construct the UV light curve to examine whether the UV flux is variable, i.e., significant flux enhancements as seen in the X-ray. Top panels of Figure 2 show the XMM-Newton/OM UVW2 (left) and UVW1 (right) images. Inspection of the images shows that the source is extended, in particular, in the UVW1 image. In order to determine the AGN and host galaxy contribution

---

### Table 1

GALFIT Decomposition of HST Images

| Filter   | Component | $m$ ± $0.14$ | $M$ ± $0.14$ | $f_i$ ± $0.09$ | $n$ | $r_0$ (pc) | $b/a$ | $c$ |
|----------|-----------|-------------|-------------|---------------|-----|-----------|-------|-----|
| F814W    | PSF       | 18.12       | −16.81      | 0.64          | 0.14| 0.54      | 2.68  |
|          | Sérsic    | 16.39       | −18.67      | 3.16          | 1.0 | 0.41      | 0.34  |
|          | Exp Disk  | 14.50       | −20.56      | 18.0 ± 2.82   | [1.0]| 2.86      | 0.24  |
| F450W    | PSF       | 19.04       | −16.06      | 1.37 ± 0.18   |     |          |       |     |
|          | Sérsic    | 17.57       | −17.34      | 5.29 ± 0.68   | [1.45]| 0.37/178 | 0.52  | 1.49|
|          | Exp Disk  | 16.05       | −18.89      | 21.4 ± 2.762  | [1.0]| 2.69/1280 | 0.24  |

Note. Column (1): HST filter; Column (2): components used in the fitting schemes; Column (3): the integrated magnitudes on the Vega system, not corrected for Galactic extinction. Column (4): the absolute Johnson $I$ and $B$ magnitude after Galactic extinction correction. We assume a power-law continuum $f_i \propto r^{-0.5}$ for the central AGN, an Sb galaxy for the Sérsic component, and an S0 galaxy for the disk, using templates from Kinney et al. (1996). Column (5): flux density in units of $10^{-16}$ erg cm$^{-2}$ s$^{-1}$ Å$^{-1}$. Column (6): the Sérsic index. Column (7): the effective radius of the Sérsic component or scale length of exponential disk, in units of arcsec and parsec, respectively. Column (8): axis ratio. Column (9): diskness (negative)/boxiness (positive) parameter, defined in Equation (3) of Peng et al. (2002). The brackets mean that they are fixed. The formal errors given by GALFIT are all tiny: <0.05 for magnitude and Sérsic index, <0.01 for $r$. 

### Table 2

Photometric Data of J1302

| Instrument | Wavelength or Energy | log ($\nu L_\nu$/erg s$^{-1}$) | Reference |
|------------|----------------------|-------------------------------|-----------|
| GALEX$^a$  | 1539 Å (FUV)         | 41.86 (41.33)                 | (1)       |
| GALEX$^a$  | 2316 Å (NUV)         | 42.29 (41.06)                 | (1)       |
| XMM$^a$    | 2120 Å (UVW2)        | 41.83 (41.98)                 | (1)       |
| XMM$^a$    | 2910 Å (UVW1)        | 42.39 (41.74)                 | (1)       |
| SDSS       | 3588 Å (u)           | 42.88                         | (2)       |
| SDSS       | 4862 Å (g)           | 43.31                         | (2)       |
| SDSS       | 6289 Å (r)           | 43.39                         | (2)       |
| SDSS       | 7712 Å (i)           | 43.40                         | (2)       |
| SDSS       | 9230 Å (z)           | 43.38                         | (2)       |
| HST$^a$    | 4500 Å (B)           | 43.19 (41.90)                 | (1)       |
| HST$^a$    | 8140 Å (I)           | 43.35 (41.83)                 | (1)       |
| 2MASS      | 1.22 μm (I)          | 43.37                         | (2)       |
| 2MASS      | 1.61 μm (H)          | 43.31                         | (2)       |
| 2MASS      | 2.12 μm (K)          | 43.14                         | (2)       |
| WISE       | 3.4 μm (W1)          | 42.51                         | (1)       |
| WISE       | 4.6 μm (W2)          | 42.12                         | (1)       |
| WISE       | 12 μm (W3)           | 41.46                         | (1)       |
| WISE       | 22 μm (W4)           | <41.70                        | (1)       |
| Spitzer    | 24 μm (MIPS)         | 41.22                         | (3)       |
| VLA        | 20 cm                | 37.19                         | (4)       |
| XMM        | 0.5–2 keV (PN quies- | 41.83                         | (5)       |
|            | cent state)          |                               |           |
| XMM        | 0.5–2 keV (PN flare | 40.45                         | (5)       |
|            | state)               |                               |           |
| XMM        | 2–10 keV (PN)        | <40.31                        | (5)       |

Note. (1) This work; (2) From NED database; (3) Mahajan et al. (2010); (4) Miller et al. (2009); (5) Sun et al. (2013).
quantiatively, we first tried to perform 2D decomposition using GALFIT for the UVW1 filter, which is closer to the 
HST F450W band. However, because the OM UV spatial resolution is worse than the HST, we choose a simple model consisting of an AGN point source and a single Sérsic component. The best-fit Sérsic index of the host galaxy component is slightly larger than in the HST filters with $n = 2.06$. The best-fit effective radius of the host galaxy, as described by the Sérsic component, is also larger than in the F450W filter ($3\,\text{arcmin}^2$ compared to $0\,\text{arcsec}^2$), and the PSF component has a relatively low luminosity. Note that excluding the PSF component results in acceptable residuals, but the Sérsic index is a factor of two higher. This is possibly because the single Sérsic component tends to trace the concentrated light in the PSF-dominated region, which is supported by the fitted smaller effective radius of 2\,\text{arcmin}^2.

Details of the tests of the AGN and host galaxy decomposition with simulations are presented in Appendix B. The flux density from the best-fit (PSF+Sérsic) model is $f_l(2120\,\text{Å}) = 1.45 \times 10^{-17}\,\text{erg cm}^{-2}\,\text{s}^{-1}\,\text{Å}^{-1}$ for the AGN and $f_l(2120\,\text{Å}) = 6.45 \times 10^{-16}\,\text{erg cm}^{-2}\,\text{s}^{-1}\,\text{Å}^{-1}$ for the galaxy, respectively. Note that, given the poor resolution, the PSF component likely consists of some host galaxy light, which is difficult to disentangle. We also performed the AGN and host galaxy modeling in the UVW2, but with parameters for the Sérsic component held fixed, except its magnitude. The results for the UVW2 fits can be seen in Table 6 in the Appendix B.

2.4.2. GALEX

Besides the XMM-Newton OM data, J1302 was also imaged and detected in the near-UV (NUV; $\lambda_c = 2316\,\text{Å}$) and far-UV (FUV; $\lambda_c = 1539\,\text{Å}$) by the GALEX All-sky Imaging Survey on 2009 April, for a total exposure time of 

\[ 0.26\,\text{ks and } 0.18\,\text{ks, respectively. The FWHM of the PSF for the NUV filter is } 4\,\text{arcsec} (\sim 2\text{–}3\,\text{pixels}) \text{ and for the FUV filter is } 5\,\text{arcsec} (\sim 3\text{–}4\,\text{pixels}). \]

The lower panels of Figure 2 show the GALEX NUV and FUV images, which have not been analyzed before. As in the XMM-Newton/OM, the source is extended in both images. We tried to perform similar 2D decomposition of the AGN and galaxy emission using GALFIT. Our GALFIT results show that the PSF component has a flux of $f_l(2316\,\text{Å}) = 3.78 \times 10^{-17}\,\text{erg cm}^{-2}\,\text{s}^{-1}\,\text{Å}^{-1}$ and $f_l(1539\,\text{Å}) = 1.06 \times 10^{-16}\,\text{erg cm}^{-2}\,\text{s}^{-1}\,\text{Å}^{-1}$, and the Sérsic has a flux of $f_l(2316\,\text{Å}) = 6.39 \times 10^{-16}\,\text{erg cm}^{-2}\,\text{s}^{-1}\,\text{Å}^{-1}$ and $f_l(1539\,\text{Å}) = 3.58 \times 10^{-16}\,\text{erg cm}^{-2}\,\text{s}^{-1}\,\text{Å}^{-1}$, respectively. Since the NUV band of GALEX surrounds the OM UVW2 filter, the flux gives us the opportunity to check for long-term variability in the UV. We find that the flux density derived from XMM-Newton/OM UVW2 is a factor of $\sim 9$ higher than that from GALEX NUV for the point source, meaning that there is a variability for the J1302 nucleus in the UV. However, it should be noted that the GALEX PSF component may consist of considerable host galaxy light due to its poorer resolution (\sim 5', or 2.4 kpc), and vice versa. In this case, the GALFIT decomposition is very uncertain and one has to treat the results with caution.

2.5. Radio Observations

As part of the deep VLA 1.4 GHz imaging of Coma cluster, J1302 was observed with VLA on 2006 June. The VLA observations were performed in its B configuration, reaching 22\,$\mu$Jy in the deepest part, or $L_{1.4\,\text{GHz}} \sim 1.3 \times 10^{20}\,\text{W} \text{Hz}^{-1}$ for galaxies at the distance of Coma (Miller et al. 2009). As shown in Figure 3, J1302 was near the edge of the mosaic (\sim 20' from the edge, where the local noise level is high), and detected at a level of $\sim \sigma$. The peak and integrated 1.4 GHz flux density is $779 \pm 106$ and $866 \pm 197\,\mu$Jy (Miller et al. 2009), corresponding to radio luminosity at 1.4 GHz of $L_{\nu} \sim 1.6 \times 10^{27}\,\text{erg s}^{-1}$. With the same configuration, J1302 was not detected by Faint Images of the Radio Sky at Twenty cm (FIRST) using VLA, with a $\sigma$ limiting flux of $950\,\mu$Jy/beam (Figure 3, right). This upper limit is consistent with the above reported flux by Miller et al. (2009), thus it is not apparent whether the source is variable or not.

With an FWHM of \sim 5', VLA observations cannot resolve the radio emission, preventing further studies on its origin in J1302. However, as we discussed below, the radio emission
from J1302 is likely associated with an AGN, and could not be produced by a single BHB, because the highest previous known is around $\nu P_\nu \sim 10^{33}$ erg s$^{-1}$ (Corbel et al. 2013), far less than what is observed. A young radio supernova remnant can also be ruled out since the VLA flux density at 1.4 GHz has no evidence of being declined in more than a decade (from 1995 to 2006), which would be otherwise detected in the FIRST survey. The origin of the radio emission from circum-nuclear star formation is also impossible. J1302 was detected in 24 $\mu$m with a flux of 1.01 mJy (see Section 2.5). Based on the local galaxy templates (Chary & Elbaz 2001), the predicted FIR luminosity is $\sim 10^{9} L_\odot$. In combination with the radio power, the FIR/radio ratio ($q_{\text{IR}}$) is estimated to be $\sim$1.6, much less than the typical value of 2.6 for star-forming galaxies (Ivison et al. 2010), suggesting a significant radio excess probably due to the presence of an AGN in J1302.

We obtained a radio-loudness parameter, $R \sim 6$, which is defined as the ratio of the flux densities between 6 cm and optical 4400 Å. The latter is the flux for the nuclear point source as derived from the GALFIT-decomposition of the HST B-band image, while the radio flux at 6 cm is estimated from the observed 1.4 GHz flux by assuming a spectral index of $\alpha = 0.8$ ($f_\nu \sim \nu^{-0.8}$). Thus J1302 is formally radio quiet, because a radio-loud object is usually defined to have $R \gtrsim 10$ (Kellermann et al. 1989). However, it should be noted that our estimate on the radio loudness by the extrapolation is uncertain because it depends strongly on the radio spectral index, which is unknown. Recent studies have shown that the radio spectral indices are in the range of $\alpha \sim 0.5$–0.9 (e.g., Greene et al. 2006; Wrobel & Ho 2006; Nyland et al. 2012; Reines & Deller 2012; Gültekin et al. 2014). Assuming a radio spectral index of $\alpha = 0.5$ for J1302 will yield a factor of $\sim 1.5$ increase in the value of radio loudness. The $R$ value for J1302 is slightly higher than the majority of the low-mass AGNs studied by Greene et al. (2006), which have upper limits in the range of $R < 0.68$–9.9, but comparable to the measurements in the extended sample of AGNs with low-mass BHs (Greene & Ho 2007b; Gültekin et al. 2014), $0.5 < R < 60$ with a median value of $\sim$7. Note that only 11 of the objects are detected in the FIRST survey ($\sim$6%, Greene & Ho 2007b), suggesting that low-mass AGNs may have a low incidence of radio activity, though deeper radio observations are required to reach a firm conclusion.

2.6. Infrared Observations

J1302 was detected at 24 $\mu$m, as part of the Spitzer/MIPS survey program of the Coma cluster. The 80% completeness limit of the survey is $\sim 0.33$ mJy. By using a 21" aperture photometry (corrected by a factor of 1.29 for total), the 24 $\mu$m flux for J1302 was estimated to be 1.05 mJy (Mahajan et al. 2010). This corresponds to a star formation rate (SFR) of 0.064 $M_\odot$ yr$^{-1}$ (Elbaz et al. 2010), if assuming that the AGN has little contribution to the 24 $\mu$m flux.

J1302 is also included in the Wide-field Infrared Survey Explorer (WISE; Wright et al. 2010) source catalog. WISE has mapped the whole sky in four bands centered at 3.4, 4.6, 12, and 22 $\mu$m (W1, W2, W3, W4), with an angular resolution of 6''1, 6''4, 6''5, and 12''0. J1302 is detected with a high S/N in W1 and W2, while it is marginally detected in W3 and not detected in W4. The average magnitude over the set of observations is $W1 = 12.58$ mag (2.85 mJy), $W2 = 12.558$ mag (1.62 mJy), $W3 = 11.295$ mag (0.88 mJy), and $W4 < 8.6$ mag (2.89 mJy).

The upper limit on the W4 flux is consistent with the observed 24 $\mu$m flux with Spitzer/MIPS.

To construct the broadband SED of J1302, we also took near-infrared magnitudes from the 2MASS Point Source Catalog (Skrutskie et al. 2006) in the $J$ (13.31 mag), $H$ (12.67 mag), and $K_s$ (12.336 mag) bands. The corresponding flux density is 7.55 mJy, 8.73 mJy, and 7.76 mJy, respectively. Given the poor resolution, the 2MASS magnitudes include flux from both the AGN and the host galaxy.

3. Results and Discussion

We have combined the photometric data described in the previous section to construct the broadband SED for J1302 (Table 2). This is one of the most complete SEDs available for low-mass AGNs (e.g., Moran et al. 1999, 2005; Thornton et al. 2008; Jiang et al. 2013). The result, plotted in $\nu L_\nu$ units and corrected for Galactic absorption, is displayed in Figure 4. The SED template from an S0 galaxy is overplotted for comparison because it is consistent with the classification of J1302 from ground-based imaging. Thanks to the high-resolution HST data obtained, we can partially reveal the nuclear SED of J1302. As Figure 4 shows, the optical nuclear SED is at least 10 times weaker than that of the host galaxy. A comparison with the median SEDs of radio-quiet and radio-loud quasars (Elvis et al. 1994) suggests that the SED of J1302 differs dramatically from those of quasars, particularly from the UV to the X-ray. The obvious big blue bump in optical/UV as seen in typical quasars is not observed in J1302, which is likely shifted to higher frequencies. While possible source variability is present in the UV, the XMM-Newton/OM measurements appear to agree roughly with the disk black-body (BB) model, which can well fit the X-ray data (S13). Further characterization of the optical-to-X-ray data will be presented in the next section.
3.1. X-Ray Spectral Properties

As we found in S13, the X-ray spectrum of J1302 is extremely steep ($\Gamma > 7$ in the quiescent state), which is unprecedented among AGNs. Modeling the quiescent state spectrum with a disk BB yields an effective disk temperature of $kT \sim 40$ eV, which is comparable to the expectation from the standard accretion disk model (Yuan et al. 2010; S13). The fitted disk temperature is, however, in remarkable contrast to the canonical temperatures of $\sim$0.1–0.2 keV found for the soft X-ray excess in AGNs, which are too high to conform to the disk model prediction (e.g., Crammey et al. 2006; Ai et al. 2011). The dominance of thermal disk emission in the spectrum is by analog with BHBs in their high/soft state, suggesting that the source has a high Eddington ratio ($\gtrsim 0.1$). If explaining the ultra-soft X-ray emission with the Comptonization of seed photons from the disk, an even higher Eddington ratio of $\gtrsim 0.3$ will be implied (Done et al. 2007). In combination with the observed luminosity, the BH mass may be at an order of $\sim 10^5 M_\odot$, consistent with the estimation from optical (S13). The quiescent state, however, requires an additional steep power law ($\Gamma \sim 4$) contributing to $\sim 15\%$ of the total luminosity, presumably arising from the Comptonization by transient heated electrons in the corona. It is possible that the additional power-law component likely increases in luminosity during the flare state, resulting in a hardening of the X-ray spectrum.

Here, we consider simultaneous fits to the X-ray and UV data for the two flux states, using a more physical model, namely the OPTXAGNF model in XSPEC (Done et al. 2012; Jin et al. 2012b). It assumes that the gravitational energy released in the disk is emitted as a color corrected BB down to a coronal radius $r_{\text{cor}}$, while within this radius the available energy is distributed between two Comptonization components: a soft one via Comptonization in an optically thick cool corona to account for the observed soft X-ray excess and a hard one in an optically thin hot corona to model the standard X-ray power-law emission above 2 keV. The key aspect of this model is that the optical/UV luminosity constrains the mass accretion rate through the outer disk, provided there is an independent estimate of the BH mass. The parameters of the OPTXAGNF model are the BH mass ($M_{\text{BH}}$), the Eddington ratio ($L_{\text{bol}}/L_{\text{Edd}}$), the dimensionless BH spin ($a_*$), coronal radius ($r_{\text{cor}}$) marking the transition from BB emission to a Comptonized spectrum, the outer radius of the disk ($R_{\text{out}}$ in units of $R_g$), the electron temperature ($K_T$) and the optical depth ($\tau$) for the soft Comptonization component, the fraction of the power within $r_{\text{cor}}$, which is emitted in the hard Comptonization component ($f_{p_2}$), and the normalization.

However, as we mentioned in Section 2.4.2, the NUV flux from GALEX, which is not simultaneous with the X-ray data, is found to be a factor of $\sim 9$ lower than that observed with XMM-Newton/OM. This is likely due to the uncertainty in image decompositions. Therefore, only the XMM-Newton/OM data are used in our spectral fits. However, there are too many parameters to constrain, and the UV data are not sufficient to remove the degeneracies, so we assumed a non-rotating Schwarzschild BH, and fixed the outer radius at $10^5 R_g$, the hard power-law index at $\Gamma = 1.8$. In our fittings to the quiescent state, we also fixed the coronal radius to $10 R_g$ which is the typical value for AGNs (Jin et al. 2012a), as it is found pegged to the maximum value of $100 R_g$ allowed in the OPTXAGNF model. In fact, spectral-timing and reverberation studies are suggestive of a physically small corona of $<10 R_g$ above the central BH in AGNs (e.g., Fabian et al. 2009; Wilkins et al. 2015). Compact coronae with radii less than 10$R_g$ have also been inferred from X-ray microlensing analyses of some bright quasars (e.g., Chartas et al. 2009; Reis & Miller 2013). Both Galactic absorption (fixed at $N_H = (7.5 \times 10^{20})$ cm$^{-2}$) and intrinsic absorption from the host galaxy are allowed in the final model. We accounted for the Galactic extinction by setting $E(B-V) = 1.7 \times 10^{20}$ cm$^{-2}$. This model provides a good description of the UV and X-ray data with a reduced $\chi^2$/dof $= 26.4/40$. The parameters for the OPTXAGNF fit are shown in Table 3. The best fit implies a BH mass of $M_{\text{BH}} = 2.8 \times 10^5 M_\odot$ and an Eddington ratio of $L_{\text{bol}}/L_{\text{Edd}} = 0.14$, which are in agreement with those derived from the optical spectrum in S13. Therefore, if the OPTXAGNF model is correct to explain the observed X-ray spectrum for J1302, then a low-mass BH accreting at a high Eddington rate can be inferred.

Figure 3(a) shows the best-fit OPTXAGNF model for the X-ray quiescent data (red solid line), alongside different SED components. The thermal emission from the accretion disk dominates the X-ray spectrum at the quiescent state by accounting for $\sim 72\%$ of the total flux in the 0.2–2 keV, while the Comptonization from low-temperature corona contributes $\sim 27\%$. The best-fit electron temperature and optical depth for the soft Comptonization component is $K_T \sim 0.1$ keV and $\tau \sim 18$, respectively. They are consistent with the average values, i.e., $\langle K_T \rangle \sim 0.3$ and $\langle \tau \rangle \sim 13$, in the study of a large sample of type 1 AGNs by Jin et al. (2012a), suggesting that the Comptonization by an optically thick corona could account for, at least partially, the observed soft excess emission. The high-temperature optically thin Comptonization component, however, contributes to only $\sim 1\%$ of the X-ray flux. This suggests that J1302 may differ from many other AGNs in its environment surrounding the central engine, i.e., lacking the standard optically thin electron population in corona. It may be possible that J1302 the hot disk corona is strongly suppressed due to the formation of the jet given its detection in the radio, as found in BHBs during their high/soft state. However, because the high-temperature Comptonization to produce the power-law emission that dominates above 2 keV is

---

### Table 3 Best-fit OPTXAGNF Model

| Model Component | Parameter | Quiescent | Flare |
|-----------------|-----------|-----------|-------|
| Extinction      | $E(B-V)$  | 0.0128$^a$| 0.0128$^a$ |
| Absorption      | $N_H$ ($10^{20}$ cm$^{-2}$) | 1.08($<1.7$) | 1.62($<3.3$) |
| optxagnf        | $M_{\text{BH}}$ ($M_\odot$) | $2.8 \times 10^5$ | $1.7 \times 10^5$ |
|                 | log $L_{\text{bol}}/L_{\text{Edd}}$ | $-0.84\pm 0.12$ | $-0.82\pm 0.48$ |
|                 | $\epsilon_{\text{cor}}(R_g)$ | $10^7$ | $21.2(\pm 11.8)$ |
|                 | log $R_{\text{out}}(R_g)$ | $5.0^\circ$ | $5.0^\circ$ |
|                 | $K_T$ (keV)$^b$ | $0.11 \pm 0.04$ | $0.13 \pm 0.03$ |
|                 | $\tau$ | $18.0 \pm 0.0$ | $24.2 \pm 4.4$ |
|                 | $f_{p_2}$ | $0.07 \pm 0.02$ | $0.18 \pm 0.18$ |

### Notes

$^a$ The parameters are fixed during the fittings. For the flare state spectral fittings, the errors on BH and log $L_{\text{bol}}/L_{\text{Edd}}$ are derived by fixing the corona breaking radius.

$^b$ The 90% confidence errors are calculated with the BH mass fixed.
still consistent with the data, future longer observations at higher energies than our XMM-Newton data are needed to better constrain the coronal parameters. We note that, by extrapolating the best-fitting model to the optical emission from the HST point source, the model under predicts the point source, the model under predicts the flux at a factor of ∼2, as shown in Figure 5. This is likely due to the emission from nuclear star clusters (NSCs), for which we will discuss in detail in Section 3.3.1

The X-ray data for the flare state along with the best-fit OPTXAGNF model are shown in Figure 5(b), and the best-fit parameters are summarized in Table 3. It was found that when fixing the coronal breaking radius $r_{\text{cor}} = 10R_g$, as we did for the quiescent data, spectral fits with the OPTXAGNF model result in an extremely large optical depth, which is approaching the maximum value of $\tau = 100$ allowed in the model. The large optical depth is indicative of more low-energy photons being upscattered by the Comptonization process. We then allowed the corona radius to vary in the spectral fits, and the best fit yields a more extended corona of $r_{\text{cor}} = 21.2R_g$, with a 90% confidence lower limit at $11.8R_g$. In this situation, it is possible that the configuration of the corona is changed before and during the flare, e.g., a layer of warm, optically thick material over the surface of the accretion disk may arise for a short period. Although the physical condition on the corona is unclear, it has been suggested that the magnetic reconnection may play a critical role in accelerating the non-thermal electrons associated with the corona, which could be responsible for the X-ray flares (e.g., Wang et al. 2001; Wilkins et al. 2015; Li et al. 2016). In the flare state, the best fit of the OPTXAGNF model suggests that the X-ray spectrum is dominated by the low-temperature Comptonization component, which accounts for ∼80% of the total emission in the 0.2–2 keV.

3.2. Broadband Continuum Properties

3.2.1. The Ratio of Optical/UV to X-Rays

As we have seen in the above section, J1302 appears to have different disk-corona geometries compared to other AGNs. In order to gain insights into the unusual X-ray properties of J1302, we turn to now the analysis of the optical-to-X-ray flux ratio. Given the extremely weak hard X-ray emission, the ratio in this object may be unusually large compared to previously known AGNs. The optical-to-X-ray flux ratio is often parameterized by $\alpha_{\text{ox}}$, which is defined as the effective spectral index between 2500 Å and 2 keV.\(^5\) To calculate the monochromatic 2500 Å flux, we used the XMM/OM flux at ∼2120 Å (UVW2),\(^6\) assuming a UV spectral index of $\alpha = -0.9$ ($S \propto \lambda^{\alpha}$). The XMM/OM data, which are taken simultaneously with the X-ray observations allow for a more reliable measurement of $\alpha_{\text{ox}}$. The X-ray monochromatic flux at 2 keV is estimated from the best-fitting spectral model (S13), since it is not detected directly. In Figure 6, we plot the $\alpha_{\text{ox}}$ versus $L_{2500}$ Å. It is well known that AGNs are increasingly X-ray weak for higher UV luminosities. Such a relation for the optically selected AGNs is shown by the solid line and the dotted line is the 1σ scatter (Steffen et al. 2006). J1302 is displayed as a red filled square in the flare and quiescent state, respectively. It shows that the $\alpha_{\text{ox}}$ for J1302, like some low-

\[ \alpha_{\text{ox}} = \log(f_{\lambda_{\text{X}}} / f_{\lambda_{\text{UV}}}) / \log(f_{\lambda_{\text{X}}} / f_{\lambda_{\text{UV}}}) = 0.384 \alpha_{\text{ox}}. \]

\[ \alpha_{\text{ox}} = \log(f_{\lambda_{\text{X}}} / f_{\lambda_{\text{UV}}}) / \log(f_{\lambda_{\text{X}}} / f_{\lambda_{\text{UV}}}) = 0.384 \alpha_{\text{ox}}. \]

Figure 6. Optical-to-X-ray spectral index $\alpha_{\text{ox}}$ vs. 2500 Å luminosity for J1302 (red filled squares). The low-mass AGNs from Dong et al. (2012) are shown by open circles, while the open triangles represent upper limits. The solid line and dotted lines represent the relation and the 1σ scatter given by Steffen et al. (2006). The symbol “1” represents the low X-ray state data for J1302, while “2” is for the high state. For comparison, we plot two ultra-soft AGNs, J1231 +1106 (blue filled circles) and GSN 069 (green star), and low-mass AGNs from Plotkin et al. (2016) (filled squares) and from Yuan et al. (2014; filled triangles).

Figure 5. (a) X-ray (quiescent state) to UV SED fitted with the physical model of OPTXAGNF (red), consisting of a modified accretion disk emission (green dashed), a soft X-ray Comptonization for the soft X-ray excess (blue dotted), and a hard X-ray Comptonization component (orange dotted–dashed). The GALEX data are not used in the spectral fittings because they are not taken simultaneously and are a factor of ∼9 lower than the OM ones. The HST optical data and the corresponding best-fit stellar population model (gray curve) are also shown for comparison. (b) The same OPTXAGNF fit but for the X-ray data in the flare state (red crosses). The X-ray spectrum in the quiescent state is shown in black for comparison.
mass AGNs with high Eddington ratios (Dong et al. 2012), falls below the low-luminosity extrapolation of the previously found $\alpha_{\text{ox}} - L_{2500}$ Å relation. In particular, J1302 in the quiescent state is significantly (hard) X-ray weak compared to typical AGNs (>10 times weaker than expected with respect to its optical/UV emission). The $\Delta \alpha_{\text{ox}} = \alpha_{\text{ox}} - \alpha_{\text{ox,exp}} = -0.46$ and $-0.99$ for the flare and quiescent state (see Table 4) corresponding to being X-ray weaker than $\alpha_{\text{ox,exp}}$ at the 4.90 σ and 10.67 σ level, respectively (e.g., Plotkin et al. 2016). For comparison, we also plot the $\alpha_{\text{ox}}$ for the ultra-soft AGNs J1302+2746 and GSN 069 (Terashima et al. 2012; Minniti et al. 2013), which are found to be significantly lower than the extrapolation of the $\alpha_{\text{ox}} - L_{2500}$ Å relation, indicating similar hard X-ray weakness.

A similar perspective comes from comparing the hard X-ray luminosity with optical line emission, e.g., [O III], because the two are strongly correlated in unobserved AGNs (e.g., Heckman et al. 2005; Panessa et al. 2006). The hard X-ray (2–8 keV) and [O III] line luminosity relation is shown in Figure 7(a). We include the best-fitting relation from a sample of Seyfert galaxies with high BH masses (e.g., Panessa et al. 2006), and the low-mass AGN sample from Dong et al. (2012) for comparison. The intrinsic 0.5–2 keV luminosity of J1302 is $L_{\text{0.5–2 keV}} \sim 1.2 \times 10^{42}$ erg s$^{-1}$, while the 2–8 keV luminosity is $L_{\text{2–8 keV}} \lesssim 2.03 \times 10^{40}$ erg s$^{-1}$. J1302, together with the other two ultra-soft AGNs, do lie below the relation defined by the higher luminosity sources. According to this correlation, the observed upper limit on $L_{\text{2–8 keV}}$ implies that the hard X-ray emission in J1302 is at least five times fainter than in typical AGNs. Note that given the low luminosity of the J1302 nucleus, a fraction of the [O III] line luminosity may be associated with the star formation process. Using the [O III]/H$\beta$ ratio of ~0.54 dex for galaxies (Moustakas et al. 2006), we obtained an SFR of ~0.21 $M_\odot$ yr$^{-1}$, assuming that the [O III] line is due to star formation activity. This SFR is a factor of three larger than that obtained from the IR luminosity (Section 2.6), suggesting that most, if not all, of the [O III] line is ionized by AGN emission. This is supported by the observed ratios of the narrow lines [O III]/H$\beta > 4.8$ and [N II]/H$\alpha = 2.3$, which place J1302 into the Seyfert regime on the BPT diagram of Kewley et al. (2006). Subtracting the SFR contribution from the [O III] luminosity, the hard X-ray emission for J1302 is still three times fainter than typical AGNs.

We argue that the X-ray weakness of J1302 is not due to intrinsic absorption, though it has been proposed to play a role in some IMBH AGNs (e.g., Dong et al. 2012; Yuan et al. 2014). J1302 displays a highly variable soft X-ray emission (S13), and its X-ray spectra show no evidence of any significant intrinsic X-ray absorption. Comparing the 0.5–2 keV emission with the strength of the [O III] line further supports this, as illustrated in Figure 7(b). The ratio of soft X-ray to [O III] luminosity can be used as an indicator of X-ray absorption. Obscured AGNs fall off the correlation being under-luminous in X-rays for a given [O III] luminosity. As can be seen, J1302 does lie within the $L_{\text{X}}/L_{\text{[O III]}}$ relation defined by unabsorbed type 1 AGNs, both of high and low BH mass. Another trend can be seen is that J1302, especially at its quiescent state, extends the $L_{\text{X}}/L_{\text{[O III]}}$ relation down to the lower luminosity regime for low-mass AGNs (Yuan et al. 2014).

The above analysis strongly suggests that J1302 is intrinsically X-ray weak, though the true nature of which is unclear. One possibility is that J1302 may represent an extreme case of a low BH mass but high Eddington ratio system in which the standard hard X-ray corona is absent or unable to efficiently up-scatter the disk photons (e.g., Leighly et al. 2007; Minniti et al. 2013). When the Eddington ratio is high ($L_\text{bol}/L_\text{Edd} \gtrsim 0.3$), the structure of the standard thin accretion disk changes to a geometrically and optically thick slim accretion disk, where outflow and/or disk-wind becomes important. In this situation, a dense, highly ionized “failed wind” produced by overionization could fall into the corona and thus may quench the hard X-ray emission through bremsstrahlung (Proga 2005).

3.2.2. Intrinsic Lack of BLR?

Note that, like the other two ultra-soft AGNs, J1302 is unabsorbed in the X-rays but does not show any broad Balmer lines in the optical, suggesting that this AGN may lack the BLR or that the corresponding emission lines are much weaker than in typical AGNs, as suggested by Minniti et al. (2013). This is puzzling and in apparent contradiction with the unification model of AGNs (Antonucci 1993). The contradiction might be attributed to a patchy torus, which could block most of the BLR emission while enabling the occasional leakage of the central X-ray emission. If this is the case for J1302, we would expect X-ray spectral transitions, i.e., from unabsorbed to heavily obscured (to be testified with future X-ray observations). Meanwhile, we also expect a hidden BLR. We have therefore conducted a pilot search for weak or hidden broad emission lines (BELs) in J1302 using optical spectropolarimetry. The results are shown in Figure 8. Although a small polarization (including instrumental one) is detected, no polarized broad H$\alpha$ or H$\beta$ is seen, suggesting that J1302 may intrinsically lack a BLR. However, the spectral

### Table 4

| Name          | Morph. | $z$ | log($M_\text{BH}$) ($M_\odot$) | $\Gamma$ | log($L_{0.5–2 \text{ keV}}$) (erg s$^{-1}$) | log($L_{\text{[O III]}}$) (erg s$^{-1}$) | log($L_{\text{[O III]}}$) (erg s$^{-1}$) | $\alpha_{\text{ox}}$ | $\Delta \alpha_{\text{ox}}$ | Reference |
|---------------|--------|----|-------------------------------|---------|----------------------------------------|----------------------------------------|----------------------------------------|----------------|------------------------|-----------|
| RX J1301–2746 | disk   | 0.024 | 5.9 | 7.1(4.4) | 40.45 (41.8) | 39.64 | 37.6 | -2.04 | -0.99 [10.67] | 1 |
| 2XMM          | disk   | 0.119 | 5 | 4.8 | 42.13 (42.5) | 40.22 | ... | -1.89 | -0.77 [8.33] | 2, 3 |
| J1231+1106    |        |        |    |        |                        |                        |                        | (-1.68) | (-0.57) [6.18] | 2          |
| GSN 069       |        | 0.018 | 6.08 | 6.7 | 42.08 | 40.32 | ... | -2 | -0.89 [9.53] | 4 |

Notes.

a Parentheses show the values corresponding to flare state.

b The difference between $\alpha_{\text{ox}}$ and the value expected from the Steffen et al. (2006) $\alpha_{\text{ox}} - L_{2500}$ Å relation. The statistical significance of the $\Delta \alpha_{\text{ox}}$ is shown in square brackets. (1) S13, (2) Ho et al. (2012), (3) Terashima et al. (2012), (4) Minniti et al. (2013).
resolution of our observation is not high, which may not be efficient to detect broad Hα in polarization if its FWHM is less than 700 km s\(^{-1}\). In addition, because the object was observed in a relatively short (40 min) exposure and the S/N is poor in the spectropolarimetry data, deeper spectropolarimetric observations are needed to firmly exclude the presence of weak or hidden BELs.

Models have suggested that if the BLR is part of an outflow, or disk-wind, it is unable to form once the AGN accretion rates fall below the critical value of \(\sim10^{-3}\) (Nicastro 2000; Elitzur & Ho 2009). In this scenario, J1302 appears to be a puzzling “true” Seyfert 2 candidate with an Eddington ratio much higher than the critical value for the BLR disappearance. Miniutti et al. (2013) proposed that the lack of BLR in GSN 069, another ultra-soft AGN similar to J1302, may be attributed to the lack of hard X-ray emission in a two-phase BLR model, or an evolutionary scenario in which the BLR has not fully formed. Such an idea can be tested in J1302 by detecting and following the evolution of the hard X-ray emission (if present). The (quasi)-simultaneous optical/UV spectroscopic campaign may be useful to confirm/dissimply the above interpretation.

3.3. Host Galaxy Structure and BH–Host Connection

From our GALFIT decompositions, we conclude that the host galaxy can be well fitted in both HST filters by a Sérsic profile with \(n \sim 1.5\) and \(r_e \sim 0''41\) at \(r < 2''\), and an exponential profile (equivalent to the \(n = 1\) Sérsic function, which is usually used to describe the disk at the outer region, see Figure 1). The structure of the inner region of the host galaxy remains complicated due to the slight excess of emission between \(~0.2\) and 0.5 arcsec in the F435W filter, which could be attributed to the PSF mismatch. Looking at the inner region, there is a significant vertical “X”-shaped structure in the residual image (Figure 1). Such a structure has also been reported by Caldwell et al. (1999), and is not unusual for Milky Way mass galaxies in the local universe (Laurikainen et al. 2014), which is confirmed by the N-body simulation as a natural evolutionary result from a pure disk galaxy (Li & Shen 2012). By excluding the AGN emission, we find that the inner Sérsic component contributes \(\sim15\%\) of the total flux of the host galaxy. Such a ratio between the bulge and total light (\(B/T\)) is consistent with the median value (\(B/T = 0.16\)) found for the galaxies hosting low-mass BHs (Jiang et al. 2011b). The flatter index (\(n < 2\)) and small \(B/T\) suggest the bulge of J1302 to be a pseudobulge. Because the pseudobulges are believed to be formed by secular processes driven by disk instabilities, including the slow rearrangement of material by bars, oval disks, and spiral structure, the presence of a low-mass AGN in J1302 seems to support the hypothesis that low-mass BHs evolve secularly and are most likely not fueled by major mergers (Kormendy & Kennicutt 2004).

For galaxies with classical bulges, BH masses have been found to correlate with bulge luminosity (the \(M_{\text{BH}}-L_{\text{bulge}}\) relation, e.g., Marconi & Hunt 2003). Considering that pseudobulges have quite different properties from those rapidly formed classical bulges, we may expect differing BH scaling relations as well, which are observed with small galaxy samples with dynamical BH masses (Greene et al. 2008). We discuss shortly the connection between the BH in J1302 and the bulge luminosity of its host galaxy. The lack of detectable BELs from either direct or polarized optical lights prevents us from estimating the mass of the central BH using the conventional virial method. If we employ the \(M_{\text{BH}}-\sigma\) relation at the low-mass end by Xiao et al. (2011) and use the velocity dispersion traced by narrow lines, we find a BH mass of \(M_{\text{BH}} = 8 \times 10^5 M_\odot\) for J1302 (S13). For the estimation of an absolute magnitude for the bulge, we use the F435W B-band magnitude of the corresponding Sérsic component, which yields \(M_B \sim -17.34\) for the host galaxy. Extrapolating the Graham (2007) \(M_{\text{BH}}-L_{\text{bulge}}\) relation down to a lower luminosity, we find a predicted mass of \(M_{\text{BH}} = 2.5 \times 10^7 M_\odot\), which is a factor of \(>30\) higher than the current estimate. Adopting the recently revised \(M_{\text{BH}}-L_{\text{bulge}}\) relation by McConnell & Ma (2013), we obtain a
predicted mass of $M_{\text{BH}} = 1.8 \times 10^7 M_\odot$ (assuming a conversion factor of $B - V = 0.9$ for the bulge lights, Benz et al. 2009). Using the $I$-band absolute magnitude and the Bentz et al. (2009) $M_{\text{BH}} - L_{\text{bulge}}$ relation in a similar higher BH mass of $M_{\text{BH}} = 2.2 \times 10^7 M_\odot$. Note that the pseudobulge in J1302 may contain younger stars, which would affect the estimate on the $B$-band bulge luminosity. We find $B - I = 1.33$ mag for the host galaxy, which is close to the typical color of S0/Sab galaxies found in Fukugita et al. (1995), $B - I \sim 1.8$ mag, suggesting that the correction for age or mass-to-light ratio to the bulge luminosity is small. Therefore, with large uncertainty associated with the BH mass measurement, J1302, like other pseudobulges containing low-mass BHs (Greene et al. 2008; Jiang et al. 2011b), appears to deviate from the $M_{\text{BH}} - L_{\text{bulge}}$ relation of classical bulges and elliptical galaxies.

3.3.1. Nature of the Extra Lights in the Optical

As we mentioned in Section 3.1, fitting the XMM-Newton UV and the X-ray emission of the AGN model, we identified the presence of a significant optical excess in the HST bands, though this model accounts for the X-ray emission very nicely. The unresolved morphology from the HST suggests that the optical excess emission comes from a very compact region of $r < 47$ pc, which is likely associated with an NSC. The coexistence of NSCs within BHs is not unusual and has been inferred for many low-mass AGNs (e.g., Seth et al. 2008, 2010). For example, it has already been demonstrated that the first two prototypes of this kind, NGC 4395 and POX 52, have both an AGN and an NSC in their centers (Filippenko & Ho 2003; Thornton et al. 2008).

We attempted to fit the optical excess in the SED (XMM-Newton/UVW1, HST/F435W, and HST/F814W) using stellar population models representing emission from a stellar cluster. We used the Maraston (2005) simple stellar population models, which are constructed assuming the Salpeter initial mass function. These models provide spectra over a finely spaced age and metallicity grid. However, the metallicity ($Z$) of the stellar population could not be constrained and so we froze it to solar values because it is the approximate midpoint of the metallicity range in the Maraston (2005) model. The best-fit model is shown in Figure 5 (gray curve). The age of the stellar population was found to be $\sim 80$ Myr. Changing the metallicity to lower values results in higher ages. For instance, fixing metallicity at $Z_\odot = 0.02 Z_\odot$ and $Z_\odot = 2 Z_\odot$ yields a stellar age equal to 300 Myr and 65 Myr, respectively. Note that previous studies have found significant evidence for multiple stellar populations in NSCs (e.g., Siegel et al. 2007; Seth et al. 2010), but the statistics of our data are insufficient to allow us to attempt to fit for an additional stellar contribution.

Although the formation mechanisms for NSCs are still under debate, they may lead to the formation of central BHs. One possibility is that NSCs are created from gas accretion onto the nucleus due to disk gas dynamics (Bekki et al. 2006). This in situ scenario is favored by observations that NSCs in spiral galaxies have complicated star formation histories, suggesting frequent episodic star formation (Walcher et al. 2006; Rossa et al. 2006). Indeed, Caldwell & Rose (1997) have shown that J1302 is a very strong post-starburst galaxy with a post-starburst age of 500 Myr, based on the presence of enhanced Balmer absorption lines compared to those in normal galaxies (see also S13). It is quite possible that the formation of central BH in J1302 was connected with the starburst event. The presence of a young stellar population with ages up to $\sim 300$ Myr around the J1302 nucleus seems to reconcile this picture, indicative of further gas accretion onto the nucleus. If our interpretation of the optical excess component with NSC is correct, we could expect its mass to be of the same order as BH, i.e., $\sim 1 \times 10^7 M_\odot$. Future high-resolution observations with integral field unit spectroscopy will be helpful to construct a dynamical model to estimate the mass (and mass-to-light ratio) of the NSC and of a central BH inside it.

4. Conclusions

We have conducted a follow-up multiwavelength study of the nuclear and host galaxy properties of J1302, a newly discovered low-mass galaxy that displays extremely soft and variable X-ray emission. We have shown that the UV-to-X-ray SED can be well and self-consistently described by thermal emission from an optically thick accretion disk around a BH, with an optically thin Comptonized emission from corona. The derived parameters ($M_{\text{BH}}$ and $n$) from modeling agree with the independent estimates based on the optical data. We thus consider the ultra-soft X-ray emission could be a signature of X-rays from an accretion disk around an IMBH.

The source appears intrinsically X-ray weak, especially in the quiescent state, with hard X-ray emission at least three times fainter than in typical AGNs. The lack of hard X-ray emission may be connected with the absence of broad optical lines in J1302. We performed a pilot search for weak or hidden BELs using optical spectropolarimetry observations. Although a small polarization is detected, no polarized broad $H_\alpha$ (or $H_\beta$) is seen, indicating that J1302 likely intrinsically lacks a BLR. J1302 is detected significantly in the radio, which is most likely related to the accreting low-mass BH. However, the radio emission is not strong enough to qualify the source as radio loud.

We performed a comprehensive analysis of the HST images in $B$ and $I$ bands to quantify the structure and morphology of the host galaxy. The galaxy is an isolated, nearly edge-on S0 galaxy with a minor optical excess in the morphology, which is most likely related to the accreting low-mass BH. However, the radio emission is not strong enough to qualify the source as radio loud.

This work was supported by Chinese NSF through grants 11573001, 11233002, 11421303, 11603021 and National Basic Research Program 2015CB857005. X.S. acknowledges support from the Fundamental Research Funds for the Central Universities (WK3440040001), Anhui Provincial Natural Science Foundation (1608085QA06), and the Open Research Program of Key Laboratory of Space Astronomy and Technology, CAS (KLSAT201601). J.W. acknowledges support from the CAS Frontier Science Key Research Program (QYZDJ-SSWSLH006). This work has made use of the data obtained through the Telescope Access Program (TAP) in 2016A.
Appendix A

Test on the HST AGN-to-galaxy Decomposition

Due to the complex galaxy morphology observed with HST, our GALFIT decompositions may introduce potential systematic errors. We have looked at images and identified the possible bar structures, which can be seen in Figure 1. In fact, our fittings with PSF+sersic models are quiet good, except for the large residuals at large radius \((r > 5\, \text{arcsec})\). The disk component is always fitted by an exponential profile, as in nearby inactive galaxies and galaxies with IMBHs, though disk profiles do vary at large radii (Jiang et al. 2011a). Therefore, we investigated the effect of possible systematic biases due to the variations of the outer disk profile. For simplicity, we choose to work on the HST F814W image. We first allowed the Sérsic index for the outer disk component to vary in our fits, but found similar results. This is perhaps because HST is not able to detect the extended, lower surface brightness emission component of the galaxy when the exposure is not deep (e.g., van Dokkum et al. 2015). We then turned to the SDSS I-band image, which has a larger field of view with very good

Figure 9. One-dimensional surface brightness distribution of the SDSS I-band data for J1302, along with that for the best-fit PSF (blue solid line) and the Sérsic component (red dashed).
measurements of the sky background (Gunn et al. 1998). This is important in studying the extended galaxy morphology, particularly the low-surface-brightness structure like galactic disk (e.g., Pohlen & Trujillo 2006; Erwin et al. 2008; Jiang et al. 2013). We found the disk can be modeled with a Sérsic component but with a slightly higher index of $n = 1.59$.

There are no systematic residuals left as can be see from the one-dimensional surface brightness distribution (Figure 9). We then fixed the Sérsic index at $n = 1.59$ and refitted the model to the HST F814W image. We found that most parameters remain unchanged in our fits, except for the magnitudes. Though the residuals at large radii disappear (Figure 10, right panel), the fit

---

**Figure 10.** GALFIT decomposition of the HST F814W image of J1302 by fixing the index of disk component at $n = 1$ (exponential profile, upper) and $n = 1.59$ (lower). A comparison of the one-dimensional surface brightness distribution of the two is shown in the bottom panel.
becomes worse in the inner region where the PSF and central bulge dominate. A comparison of results by fixing $n = 1$ (exponential profile) and $n = 1.59$ can be found in Figure 10 and Table 5. Since the difference between magnitudes of the AGN and galaxy component is less than 0.3 mag, we conclude that our fits are not introducing major systematic errors.

**Appendix B**

**Test on the AGN-to-galaxy Decomposition in the UV**

Having established the central point source and pseudobulge detections in the *HST* optical, we try to perform similar image decomposition of the AGN and host galaxy of J1302 in the UV using GALFIT. Although the UV images have a low spatial resolution ($\sim 2''$) compared with the *HST* optical, they are still very useful for us to understand its host galaxy and put further constraint on the SED of the AGN (Section 3.1). We chose to first work with the *XMM-Newton* OM UVW1 image ($\lambda_0 = 2910$ Å), which is closest to the *HST* F450W filter and has a better resolution than the *GALEX*. The UVW1 PSF is constructed from the field of 3C273 by stacking five bright, isolated point sources from the catalog of Page et al. (2012). As for the *HST*, the host galaxy is represented by a Sérsic profile and we performed the fittings with PSF+Sérsic, allowing all parameters to vary. The image decomposition is shown in Figure 11. The fit is good with a reduced $\chi^2$/dof = 1.1, and the best-fit parameters for the galaxy, i.e., Sérsic index, axis ratio, and position angle, are all close to that obtained from the *HST*. Note that fitting with a single Sérsic profile leaves acceptable residuals, but the fit statistics is worse (the difference of $\chi^2$ is 13, Table 6). In addition, the Sérsic index ($n = 4.28$) is much larger than that obtained from the *HST* optical ($n = 1.45$), suggesting that a more concentrated light distribution is

![Figure 11. *XMM-Newton* OM UVW1 AGN-to-host decomposition of J1302. The first column shows the observed image of the galaxy. The second column shows the best-fit galaxy (top, parameterized by a single Sérsic profile) and AGN (bottom, parameterized by a single PSF) components as extracted by GALFIT. The third column shows the corresponding residual after subtraction of the Sérsic (PSF). The residual image after both components being subtracted is shown on the right.](image)

![Figure 12. Comparison between the simulated AGN-to-galaxy ratio and that measured by GALFIT. The red filled circle represents the best-fit AGN fraction of 22.5% for J1302 in the UVW1. The dotted-dashed line is the one-to-one relation.](image)
required, which may be due to the presence of unresolved AGN emission.

Since the XMM-Newton/OM spatial resolution is much worse than the HST, we sought to test the robustness of our AGN+galaxy image decomposition. To do so, we used GALFIT to simulate a point source along with a Sérsic profile host galaxy, with total flux adding up to the measured flux in the OM/UVW1. We create a large set of simulated galaxies with profiles assumed to be the best-fit Sérsic model obtained above, varying the total integrated flux of the central point source from $m = 24.7$ to 19.7 mag. The magnitude range represents point sources with fluxes from $\sim 0.9$ to 1/100 of the host galaxy flux. We then place these models randomly on empty regions of the real UVW1 image, trying to measure their properties in the presence of photometric noise. Note that when the AGN emission exceeds 70% of the host galaxy, the fitting yields an unphysically high value of Sérsic index ($n > 10$). In this case, we set constraints on the Sérsic index $n$ to values within 0.7–6 to avoid catastrophic fitting results. Figure 12 summarizes the results of these simulations, plotting the input AGN fraction against the measured fraction from the simulated images. We find that the decomposition method is able to recover the AGN flux with $\sim 80\%$ accuracy at $m_{\text{AGN}} \lesssim 22.2$, corresponding to the $\gtrsim 10\%$ of the galaxy flux. At $m_{\text{AGN}} \gtrsim 22.2$, the fittings tend to overestimate the AGN flux. For instance, the measured AGN fraction is a factor of four higher than the input value at $m_{\text{AGN}} \sim 24.7$. We also performed the AGN and galaxy decomposition for the XMM-Newton/OM UVW2 image ($\lambda_c = 2120$ Å), which is shown in Figure 13. Since the galaxy is marginally resolved in the UVW2, we fit its profile with the same Sérsic model as that of UVW1 image, but with all parameters held fixed except its magnitude. The results of the decomposition are shown in Table 6. Note that the total flux (AGN+Sérsic) from our GALFIT decomposition in the both filters is in good agreement with the aperture photometry from the XMM-Newton/OM UV catalog (Page et al. 2012).

![Figure 13](image-url)  
\textbf{Figure 13.} Same as Figure 11, but for the OM UVW2 filter.

### Table 6  
\textbf{GALFIT Decomposition of OM UV Images}

| Filter ($\lambda$) | Component | Magnitude ($\lambda_c = 2120$ Å) | $f_\lambda$ | $n$ | $n^\prime$/kpc | $b/a$ | PA | $\chi^2$/dof |
|-------------------|-----------|-------------------------------|---------|---|---------------|--------|----|--------------|
| UVW1 2910 Å       | PSF       | 21.29 ± 0.19                  | 1.45 ± 0.44 | ... | ...           | ...   | ... | ...          |
|                   | Sérsic    | 19.67 ± 0.06                  | 6.45 ± 0.68 | 0.26 ± 0.37 | 3.57 ± 0.16/(1.68 ± 0.08) | 0.3 ± 0.01 | ... | 57.3 ± 0.8 | 1861/1670 |
|                   | Single Sérsic | 19.37 ± 0.03              | 8.50 ± 0.23 | 4.28 ± 0.4 | 2.75 ± 0.14/(1.29 ± 0.07) | 0.3 ± 0.01 | 57.3 ± 0.8 | 1874.1/1673 |
| UVW2 2120 Å       | PSF       | 23.04 ± 0.07                  | 3.47 ± 0.58 | ... | ...           | ...   | ... | ...          |
|                   | Sérsic    | 24.42 ± 0.2                   | 2.45±0.79 | [2.06] | [3.75] | [0.3] | [57.3] | 1792/1674 |

\textbf{Note.} Column (1): XMM-Newton OM filter. Column (2): components used in the fitting schemes. Column (3): the magnitudes measured from the UV counts assumed that the photometric zero point is $m_0 = 20$, not corrected for Galactic extinction. Column (4): flux density in units of 10$^{-16}$ erg cm$^{-2}$ s$^{-1}$ Å$^{-1}$. Column (5): the Sérsic index. Column (6): the effective radius of the Sérsic component, in units of arcsec and kiloparsec, respectively. Column (7): axis ratio. Column (8): position angle (degree). Column (9): the fit statistics.

$^a$ The brackets mean that they are fixed.

References

Ai, Y. L., Yuan, W., Zhou, H. Y., Wang, T. G., & Zhang, S. H. 2011, \textit{ApJ}, 727, 31

Antonucci, R. 1993, \textit{ARA&A}, 31, 473

Begelman, M. C., Volonteri, M., & Rees, M. J. 2006, \textit{MNRAS}, 370, 289

Bekki, K., Couch, W. J., & Shiroya, Y. 2006, \textit{ApJL}, L133

Bentz, M. C., Peterson, B. M., Pogge, R. W., & Vestergaard, M. 2009, \textit{ApJL}, 694, L166

Caldwell, N., & Rose, J. A. 1997, \textit{AJ}, 113, 492

Caldwell, N., Rose, J. A., & Dendy, K. 1999, \textit{AJ}, 117, 140

Chartas, G., Kochanek, C. S., Dai, X., Poindexter, S., & Gamire, G. 2009, \textit{ApJ}, 693, 174

Chary, R., & Elbaz, D. 2001, \textit{ApJ}, 556, 562

Corbel, S., Coriat, M., Brocksopp, C., et al. 2013, \textit{MNRAS}, 428, 2500

Crummy, J., Fabian, A. C., Gallo, L., & Ross, R. R. 2006, \textit{MNRAS}, 365, 1067

Desroches, L.-B., Greene, J. E., & Ho, L. C. 2009, \textit{ApJ}, 698, 1515

Dewangan, G. C., Mathur, S., Griffiths, R. E., & Rao, A. R. 2008, \textit{ApJ}, 689, 762

Done, C., Davis, S. W., Jin, C., Blaes, O., & Ward, M. 2012, \textit{MNRAS}, 420, 1848

Done, C., Gierliński, M., & Kubota, A. 2007, \textit{A&A}, 15, 1

Dong, R., Greene, J. E., & Ho, L. C. 2012, \textit{ApJ}, 761, 73
