NuSTAR Non-detection of a Faint Active Galactic Nucleus in an Ultraluminous Infrared Galaxy with Kpc-scale Fast Wind

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Abstract

Large-scale outflows are generally considered to be possible evidence that active galactic nuclei (AGNs) can severely affect their host galaxies. Recently, an ultraluminous infrared galaxy (ULIRG) at $z = 0.49$, AKARI J0916248+073034, was found to have a galaxy-scale [O III] $\lambda$5007 outflow with one of the highest energy-ejection rates at $z < 1.6$. However, the central AGN activity estimated from its torus mid-infrared (MIR) radiation is weak relative to the luminous [O III] emission. In this work we report the first NuSTAR hard X-ray follow-up of this ULIRG to constrain its current AGN luminosity. The intrinsic 2–10 keV luminosity shows a 90% upper limit of $3 \times 10^{34}$ erg s$^{-1}$ assuming Compton-thick obscuration ($N_H = 1.5 \times 10^{24}$ cm$^{-2}$), which is only 3.6% of the luminosity expected from the extinction-corrected [O III] luminosity. Using the NuSTAR observation, we successfully identify that this ULIRG has a very extreme case of X-ray deficit among local ULIRGs. A possible scenario to explain the drastic decline in both the corona (X-ray) and torus (MIR) is that the primary radiation from the AGN accretion disk is currently in a fading status, as a consequence of a powerful nuclear wind suggested by powerful ionized outflow in a galaxy scale.

Unified Astronomy Thesaurus concepts: Active galaxies (17); X-ray active galactic nuclei (2035); Ultraluminous infrared galaxies (1735)

1. Introduction

Ultraluminous infrared galaxies (ULIRGs; $L_{IR} > 10^{12} L_{\odot}$) are a population of galaxies that emit nearly all of their energy in the infrared (IR) band (Sanders & Mirabel 1996). The high $L_{IR}$ originates from dust heated by ultraviolet (UV)/optical radiation of vigorous starbursts and/or active galactic nuclei (AGNs). ULIRGs are thought to represent a rapidly growing phase of massive galaxies in the transition from disk to elliptical galaxies, as gas and dust are swept out by starburst- and/or AGN-induced outflows (e.g., Hopkins et al. 2008).

Chen et al. (2020) reported a new follow-up program for sources in the AKARI Far-Infrared Surveyor (FIS) Bright Source Catalogue11 (ver.2) to construct a statistical flux-limited sample of ULIRGs at intermediate redshifts ($z = 0.5$–1). Among the sources, AKARI J0916248+073034 (hereafter J0916a) at $z_{spec} = 0.49$ indicates signatures of an extremely strong ionized-gas outflow in the Subaru/FOCAS long-slit spectroscopic image (with slit width of 0.5, Chen et al. 2019). The [O III] $\lambda$5007 emission line has a FWHM of 1830 km s$^{-1}$ and a shift of $-770$ km s$^{-1}$ relative to stellar absorption lines. The long-slit spectroscopic image shows that the outflow extends to a radius of 4 kpc. The mass-loss and energy-ejection ($\dot{E}_{\text{k}}$) rates are estimated to be $500 M_{\odot}$ yr$^{-1}$ and $10^{42.6}$ erg s$^{-1}$, respectively, implying that J0916a has one of the highest $\dot{E}_{\text{k}}$ ionized outflows among ULIRGs/AGNs at $z < 1.6$ and is comparable to the most powerful outflows in quasars at $z \sim 2$ (e.g., Harrison et al. 2012; Zakamska et al. 2016). Emission-line ratios indicate that the outflow is driven by AGNs.

The strong [O III] emission line ($10^{43.8 \pm 0.5}$ erg s$^{-1}$ after extinction correction12) implies that the AGN is luminous with bolometric luminosity,13 ($L_{bol,\text{[OIII]}}$) of $10^{46.3 \pm 0.5}$ erg s$^{-1}$ using the empirical relationships (Ueda et al. 2015; Ricci et al. 2017b). However, the mid-IR (MIR) radiation originating from dusty torus in the vicinity (∼10 pc) of the supermassive black hole (SMBH) is weak. The 5–38 μm MIR luminosity ($L_{5-38\mu m}$) of J0916a is $10^{44.9 \pm 0.1}$ erg s$^{-1}$, which is integrated using the best-fit spectral energy distribution (SED) of AGN component reported in Chen et al. (2019).14 The corresponding bolometric luminosity with the empirical function (Ichikawa et al. 2019b) is $L_{bol,\text{[OIII]}} = 10^{45.6 \pm 0.1}$ erg s$^{-1}$, which is only 32% of $L_{bol,\text{[OIII]}}$ and would indicate that the central engine of the AGN in

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11 https://www.ir.isas.jaxa.jp/AKARI/Observation/update/20160425_preliminary_release.html
12 The extinction is estimated to be $E(B-V) = 1.0 \pm 0.3$ using Balmer decrement, which is close to the typical amount of dust attenuation in local ULIRGs (e.g., García-Marín et al. 2009).
13 Throughout this Letter we use $L_{\text{bol,indicator}}$ to denote the luminosity in a given band or wavelength range estimated from the employed indicator.
14 There is a mistake in Table 3 of Chen et al. (2019). The reported value of $L_{\text{bol,AGN}}$ was not the bolometric luminosity of AGN, but the total integrated luminosity of the best-fit AGN SED including the torus thermal and scattering radiation and the transmitted primary emission.
J0916a is declining. That is, the AGN is currently less active than it was in its past epoch, while the observed strong [O III] emission with extreme outflow reflects a historical effect of the AGN during its preceding active phase, due to the time-lag between AGN activity in the nuclear region and outflow in the galaxy scale (e.g., Harrison 2017). Recent works have reported the luminosity decline of AGNs within a timescale of $10^3$–$10^4$ years in a population called “fading AGNs” or “dying AGNs” (e.g., Schawinski et al. 2010). This population shows AGN signatures in large spatial scales, e.g., radio jets and/or bright [O III] line in the kpc-scale narrow line region (NLR), but they lack the features in small scales, e.g., weak or absent X-ray (corona) and/or MIR (torus) emission. The faintness in small scales of those objects implies a transient stage that the central engine was active in the past, but currently seems quenched (Kawamuro et al. 2017; Ichikawa et al. 2019c, 2019a; Cooke et al. 2020). The “changing-look AGN” is another population of AGNs which shows drastically declining by an order of magnitude in $10^3$–$10^4$ years (e.g., LaMassa et al. 2015; MacLeod et al. 2016) as their accretion states change from bright (standard disk) phase to faint (radiatively inefficient accretion flow) phase (e.g., Noda & Done 2018; Ruan et al. 2019). Recent X-ray studies of ULIRGs presented that the coronae in ULIRGs could be intrinsically weak compared to normal AGNs (e.g., Teng et al. 2015).

In order to constrain the current activity of the AGN in J0916a, hard X-ray observation over 10 keV is required with its power to penetrate the heavy obscuration in the nuclear region (e.g., Ricci et al. 2015). There is no previous X-ray observation for J0916a and it is not detected in the Swift/BAT 14–195 keV survey due to its faintness at a relatively high redshift. In this letter we report the first hard X-ray follow-up of J0916a with NuSTAR (Harrison et al. 2013). Thanks to a wide energy range over $10$ keV with great sensitivity, NuSTAR makes it capable to directly constrain the intrinsic AGN luminosity in J0916a even in the case with Compton-thick absorption, e.g., gas column density ($N_H$) of at least $1.5 \times 10^{24}$ cm$^{-2}$). Throughout the paper we adopt the cosmological parameters, $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_M = 0.3$ and $\Omega_{\Lambda} = 0.7$.

2. NuSTAR Constraint on the Intrinsic X-Ray Luminosity of J0916a

J0916a was observed by NuSTAR on 2020 June 16 and 17 with a total on-source exposure of 105.6 ks (NuSTAR GO cycle-6 program 06108, PI: X. Chen). The data was reduced using the NuSTAR data analysis pipeline (nupipeline, ver.1.9.2) with the latest HEASARC’s calibration database (CALDB, ver.20200720). The South Atlantic Anomaly (SAA) filtering is adopted to reduce the observation time intervals affected by the enhancement of background event rates from passage through the SAA and the so-called “tentacle” region with the nupipeline configuration of saacalc=1 saamode=optimized tentacle=yes. The calculation algorithm “1” was chosen because it provides the best noise removal as shown in the background filtering reports for both of the two observation epochs.\footnote{The default setting saacalc=3 eliminatesource=yes evaluates count rates after the exclusion of the contribution of the brightest sources in the field of view, which could result in noise remnants for this data set, because the object is very weak and the brightest sources can be dominated by noise.\footnote{We also checked the spectrum extracted using a larger radius of 60$''$ with EEF of 90%. The net spectrum shows $-39.6$ counts ($-1.5\sigma$) in 6–24 keV. The difference of estimated fluxes is about 5%, thus having little impact on our conclusion.}} We use the “optimized” mode because it provides a noise removal result that is comparable with the “strict” mode but does not lose large amounts of exposure like the later one does ($\sim 10\%$). After removal of bad time intervals, the final exposure is 37.3 ks (96.6%) and 67.0 ks (99.8%) on source for the first and second observation epochs, respectively. In total, four cleaned events are created from the data obtained by the two focal plane modules (FPMA and FPMB) during the two epochs.

The images from the four cleaned events are merged using the FTOOLS package fmapage and the co-added 6–24 keV image are shown in the left panel of Figure 1. No serendipitous sources are detected in the fields of view of the NuSTAR observations. A circular region with a radius of 30$'$ centered at the optical position of J0916a is employed as the source region, following the suggestion for faint objects in Section 4.3 of the NuSTAR Data Analysis Software Guide.\footnote{A radius of 30$'$ corresponds to a fraction of encircled energy (EEF) of 65%,} No serendipitous objects are detected in the fields of view of the NuSTAR observations. A circular region with a radius of 30$'$ centered at the optical position of J0916a is employed as the source region, following the suggestion for faint objects in Section 4.3 of the NuSTAR Data Analysis Software Guide.\footnote{The default setting saacalc=3 eliminatesource=yes evaluates count rates after the exclusion of the contribution of the brightest sources in the field of view, which could result in noise remnants for this data set, because the object is very weak and the brightest sources can be dominated by noise.\footnote{We also checked the spectrum extracted using a larger radius of 60$''$ with EEF of 90%. The net spectrum shows $-39.6$ counts ($-1.5\sigma$) in 6–24 keV. The difference of estimated fluxes is about 5%, thus having little impact on our conclusion.}}

Figure 1. Left panel: NuSTAR 6–24 keV image in units of counts per pixel. The image is co-added using the FPMA and FPMB data from the two observation epochs, and smoothed using a Gaussian profile with a radius of 2 pixels. The source (circular) and background (annular) regions are shown in orange and blue, respectively. Middle panel: NuSTAR 3–50 keV spectra extracted from the source (orange) and background (blue) regions shown in the left panel. Right panel: estimated 90% upper limit of intrinsic $L_{\text{2–10 keV}}$ with different assumptions of photon index ($\Gamma$) and intrinsic obscuration ($N_H$). The two horizontal lines denote the $L_{\text{2–10 keV}}$ converted from [O III] λ5007 (dashed) and 5–38 μm (dotted) luminosities. The vertical dashed–dotted line shows the threshold of Compton-thick obscuration. The open circle denotes the fiducial estimation in the discussion.
co-added source and background spectra are extracted from the source and background regions. The net spectrum (i.e., source − background) shows −9.9 counts in 3−6 keV, −16.9 counts in 6−24 keV, and 8.5 counts in 24−50 keV, which correspond to −1.1σ, −1.3σ, and 0.6σ, respectively, where σ is estimated from the Poisson noise within the source region in each energy range. Therefore, we conclude that the object is not detected.

Spectral analysis is not feasible as the spectrum is dominated by background. In order to estimate the upper bound of the X-ray luminosity, we employed a fixed, putative torus model of Ikeda et al. (2009) following Ichikawa et al. (2019a), which takes into account a torus-absorbed and Compton-scattered power-law component, a reflected continuum, and an accompanying fluorescent iron Kα line. Only the normalization of the power-law component is set as a free parameter. The cut-off energy of the power-law component is fixed to 360 keV. The opening angle of the torus is fixed to 60°, which reflects a typical covering factor for X-ray selected AGNs (e.g., Stalevski et al. 2016; Ichikawa et al. 2019b). An inclination angle of 80° is selected as J0916a is identified as a Seyfert 2 galaxy from its optical spectrum. We consider two values of photon index (Γ), i.e., 1.8, which is a typical value of normal Seyfert galaxies (e.g., Ricci et al. 2017b), and 1.5, as shown in the harder spectra found in several ULIRGs (Teng et al. 2014, 2015; Oda et al. 2017). Galactic absorption of NH = 2.6 × 10^20 cm^{-2}, which is given by the FTOOLS package nh, and intrinsic obscuration with NH from 10^{23} to 10^{26} cm^{-2} are employed in the estimation. We estimate the upper limit of the intrinsic 2−10 keV luminosity (L_{2−10 keV}) by simulating artificial spectra with the above assumed models to achieve net counts of 3σ in 6−24 keV range. The estimated 3σ upper limits with different assumptions of Γ and NH are then converted to 90% upper limits, considering that the 90% confidence level corresponds to 1.645σ for a normal distribution. The results are shown in the right panel of Figure 1.

In the Discussion, we consider the estimated 90% upper limit, L_{2−10 keV} < 3.0 × 10^{43} erg s^{-1} with Γ = 1.5 and NH = 1.5 × 10^{24} cm^{-2}, as a fiducial value unless otherwise stated. The X-ray studies of ULIRGs (Teng et al. 2014, 2015; Iwasawa et al. 2017, 2018; Oda et al. 2017; Tombesi et al. 2017; Xu et al. 2017; Toba et al. 2020) show that NH varies in a range from 10^{22} cm^{-2} (e.g., IRAS F051892524) to 3 × 10^{24} cm^{-2} (e.g., IRAS F131205453), hence NH = 1.5 × 10^{24} cm^{-2} is a reasonable assumption to account for Compton-thick obscuration.

Using the empirical relation of Lehmer et al. (2010), the estimated L_{2−10 keV} contributed by high-mass X-ray binaries (HMXBs) in the host galaxy is ∼2 × 10^{42} erg s^{-1} with stellar mass of 10^{13} M_{⊙} and star formation rate of 1000 M_{⊙} yr^{-1}, which is much lower than the 90% upper-limit L_{2−10 keV}. Therefore, hereafter we ignore the contribution of HMXBs and consider the 90% upper limit L_{2−10 keV} as the upper bound of AGN X-ray luminosity.

3. Discussions

3.1. X-Ray Faintness Relative to NLR Emission

Figure 2 (left panel) shows the intrinsic L_{2−10 keV} and extinction-corrected L_{[OIII]} of J0916a compared to six well-studied nearby (z < 0.1) ULIRGs from Teng et al. (2014, 2015) and Oda et al. (2017). Four of the referred ULIRGs show Compton-thin obscuration, i.e., IRAS F051892524 (hereafter F05189), Mrk 231, Mrk 273, and Superantennae (IRAS F192547245, hereafter SA); the other two ULIRGs host a Compton-thick level absorber, i.e., IRAS F131205453 (hereafter F13120) and UGC 5101. The corrected L_{[OIII]} of the referred ULIRGs are collected from Veilleux et al. (1999; F05189 and Mrk 273), Buchanan et al. (2006; SA), Moustakas & Kennicutt (2006; UGC 5101), and Singh et al. (2011; Mrk 231). The [O III] detection is not available for F13120 and we employ the L_{[OIII]} converted from L_{[OIV]} with the typical ratio of Seyfert 2 galaxies (LaMassa et al. 2010). The contribution to L_{[OIII]} from star formation in the ULIRGs is estimated using the empirical relation of starbursts (Gürkan et al. 2015), which is only 0.5%−2% of the total L_{[OIII]} Thus, we ignore the star formation contamination and consider that the L_{[OIII]} fully accounts for AGN activity.

In order to compare J0916a and other ULIRGs to normal AGNs, we also include the catalog of the Swift-BAT AGN Spectroscopic Survey (BASS DR1; Koss et al. 2017). In total, 243 AGNs are selected with signal-to-noise ratio (S/N) > 3 for Hα, Hβ, and [O III] emission lines, which consists of 135 Seyfert 1 galaxies (including Seyfert 1.2 to 1.9) and 108 Seyfert 2 galaxies. The corrected L_{[OIII]} and L_{2−10 keV}, which are converted from the Swift 14−195 keV luminosity and empirical ratio of Ricci et al. (2017b), are shown in the left panel of Figure 2 with 68% (1σ) and 95% (2σ) distribution contours.

The ratio, L_{2−10 keV} / L_{[OIII]}, can be considered as an indicator of the current X-ray faintness in the nuclear region relative to the past AGN activity. All of the ULIRGs (except for F13120) in Figure 2 (left panel) show lower L_{2−10 keV} / L_{[OIII]} compared to the normal AGNs. If we adopt a modified faintness ratio, f_X = L_{2−10 keV} / L_{[OIII]} where L_{X,[OIII]} is the 2−10 keV luminosity converted from L_{[OIII]} using the empirical relation of normal AGNs (Ueda et al. 2015), then the referred ULIRGs (except for F13120) possess an average f_X of 10%, implying a general trend of X-ray deficit in the ULIRGs. J0916a shows f_X < 3.6% assuming NH = 1.5 × 10^{24} cm^{-2}, which is even lower than the lowest f_X = 5.2% of SA in the referred ULIRGs. The f_X of J0916a can be much lower (<1.6%) if we consider Compton-thin absorption.

19 We employ the intrinsic L_{2−10 keV} from MYTorus model fitting in Teng et al. (2014).
20 Because the reported L_{2−10 keV} of SA in Teng et al. (2015) was estimated without intrinsic obscuration, we replace with the result of Brightman & Nandra (2011) for SA.
21 We employ the intrinsic L_{2−10 keV} from “Model II” fitting in Oda et al. (2017).
22 As the Balmer decrement is not available, the L_{[OIII]} of Mrk 231 is not corrected and shown as the lower limit in Figure 2.
23 Note that the converted L_{[OIII]} of F13120 could be underestimated because the average L_{[OIII]} / L_{[OIV]} ratio of the four ULIRGs (F05189, Mrk 273, SA, UGC 5101), ~1.0 dex, seems higher than the ratio of Seyfert galaxies (0.59 dex; LaMassa et al. 2010).
The horizontal and vertical dotted lines show the median values of BASS DR1 AGNs. Other legends are the same as in the left panel. J0916a is the most extreme ratio of Seyfert 2 galaxies (the 68% empirical).

Figure 2. Left panel: intrinsic $L_{2-10 \text{ keV}}$ vs. corrected $L_{[\text{OIII}]}$ of J0916a compared to ULIRGs (Teng et al. 2015; Oda et al. 2017) and normal AGNs from the BASS DR1 sample (Koss et al. 2017). The red circle and downward arrow show the upper limit $L_{2-10 \text{ keV}}$ of J0916a estimated assuming Compton-thick ($N_H = 1.5 \times 10^{24} \text{ cm}^{-2}$) and Compton-thin obscuration ($10^{20} \text{ cm}^{-2}$), respectively. The blue square and rightward arrow of F13120 denote the converted $L_{[\text{OIII}]}$ from $L_{[\text{OIII}]}$ using an empirical ratio of Seyfert 2 galaxies (LaMassa et al. 2010) and an average $L_{[\text{OIII}]/L_{[\text{OIII}]}}$ of the other ULIRGs, respectively. The blue square and rightward arrow of Mrk 231 denote the uncorrected and corrected $L_{[\text{OIII}]}$ with a typical dust extinction of Seyfert 1 galaxies (LaMassa et al. 2010), respectively. The orange contours show the 68% (1σ) and 95% (2σ) distribution ranges of the Swift-BAT AGN Spectroscopic Survey (BASS DR1) AGNs (gray dots). The gray dashed and dotted lines show the empirical $L_{2-10 \text{ keV}}$/$L_{[\text{OIII}]}$ relation from Ueda et al. (2015) and the $-1$ dex position under the relation, respectively. Right panel: $L_{2-10 \text{ keV}}/L_{5-38 \mu m}$ vs. $L_{5-38 \mu m}/L_{[\text{OIII}]}$. A small $y$-value denotes the corona ($<0.1 \text{ pc}$) fading compared to torus ($<0.1 \text{ pc}$), while a small $x$-value denotes the torus fading compared to NLR ($1-10 \text{ kpc}$). The horizontal and vertical dotted lines show the median values of BASS DR1 AGNs. Other legends are the same as in the left panel. J0916a is the most extreme ULIRG with both fading corona and torus relative to the normal AGN sample.

3.2. Fading AGN Central Engine Indicated by Both Faint Corona and Torus Radiation

The MIR emission from the dusty torus can be used as an intermediate indicator of AGN activity with its spatial scale (=10 pc) between X-ray emitting corona (<0.1 pc; Dai et al. 2010) and NLR (1–10 kpc), and it traces AGN activity over the last 10 years (e.g., Ichikawa & Tazaki 2017). In order to make a fair comparison to J0916a, we collect the optical-IR photometries from the Sloan Digital Sky Survey (SDSS), the Two Micron All Sky Survey (2MASS), the Wide-field Infrared Survey Explorer (WISE), the Spitzer Space Telescope, the Infrared Astronomical Satellite (IRAS), and AKARI for the six referred ULIRGs, and then perform SED fitting with CIGALE (Boquien et al. 2019) following the configuration of Chen et al. (2019). The $L_{5-38 \mu m}$ of the referred ULIRGs are integrated with the best-fit AGN SEDs including the torus thermal and scattering radiation as well as the transmitted primary emission. The $L_{5-38 \mu m}$ of the BASS AGN sample are adopted from Ichikawa et al. (2019b).

The right panel of Figure 2 shows the values of two ratios, i.e., $L_{2-10 \text{ keV}}/L_{5-38 \mu m}$ and $L_{5-38 \mu m}/L_{[\text{OIII}]}$. A low $L_{2-10 \text{ keV}}/L_{5-38 \mu m}$ relative to normal AGNs suggests that there is AGN fading in the core region (0.1 pc compared to 10 pc), while a low $L_{5-38 \mu m}/L_{[\text{OIII}]}$ denotes that there is AGN fading in the circumnuclear region (10 pc compared to several kpc). With this diagram the ULIRGs can be separated into three groups: 1) F13120 shows the properties similar to normal AGNs; 2) SA and Mrk 231 possess decayed coronae but their tori are still luminous; 3) the other four ULIRGs including J0916a show both faint corona and torus radiation. However, the fading ratios of F05189, Mrk 273, and UGC 5101 are moderate and within the 95% (2σ) distribution range of the BASS AGN sample. J0916a locates at a unique position out of the 95% range of the BASS sample, which indicates that both of its core (corona) and circumnuclear (torus) AGN emission are drastic declining.

3.3. Powerful Outflow with Fading Central Engine: the Cumulative Effect of AGN Feedback can be Limited

A possible scenario to explain both of the faintness in corona (X-ray) and torus (MIR) in J0916a is that the primary radiation from the AGN accretion disk is currently in a fading status. Suggested by the connection between the multi-phase outflows observed in nearby ULIRGs such as Mrk 231 (Feruglio et al. 2015) and F05189 (Smith et al. 2019), the powerful galaxy-scale ionized outflow in J0916a could imply an ultrafast nuclear wind when the [O III] outflow was launched with a super-Eddington accretion. The Eddington ratio ($\lambda_{\text{Edd}}$) is estimated to be 5.7, with the bolometric luminosity converted from $L_{[\text{OIII}]}$ and the mass of SMBH ($2.7 \times 10^8 M_\odot$) estimated using the stellar mass of the host galaxy. The nuclear wind could blow out the surrounding gas and dust, weaken the

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24 To be compared, the $\lambda_{\text{Edd}}$ estimated from $L_{\text{bol,torus}}$ and $L_{\text{bol,corona}}$ are 1.4 and <0.3, respectively.
The development of corona and torus, and suppress the fueling to the SMBH.

With the extent of the [O III] outflow (4 kpc) and the maximum outflow velocity (∼2000 km s⁻¹), the fading process could happen in an outflow-traveling timescale of ∼2 Myr, or a light-traveling timescale of ∼10⁴ years. The fading timescales are much shorter than the duration of starburst in ULIRGs, i.e., ∼100 Myr (e.g., Hopkins et al. 2008), implying that although the AGN can drive a powerful, fast wind in the galaxy, e.g., the outflow velocity of J0916a even exceeds the escape velocity of the host halo (Chen et al. 2020), it can be decayed in a relatively short period, and the cumulative effect of AGN feedback on the stellar build-up in the galaxy can be limited as indicated by the high star formation rate of 1000 M⊙ yr⁻¹.

3.4. Other Possibilities and Future Work

In the above discussion a Compton-thick level absorber, N_H = 1.5 × 10⁻³ cm⁻², is assumed, which accounts for the heavy obscuration in ULIRGs (e.g., Teng et al. 2015). However, it is hard to rule out the possibility of a very Compton-thick absorber, e.g., N_H ∼ 10²⁵ cm⁻², located on the line of sight and shielding the X-ray emitting corona. Significant constraint on the nuclear gas column density in J0916a exceeds the capability of the current X-ray instruments due to its faintness at a relatively high redshift. Sub-millimeter (submm) observations of dust emission with a high spatial resolution, e.g., the Atacama Large Millimeter/submillimeter Array (ALMA), provide an alternative method to study such heavily obscured environment in galaxies (e.g., Scoville et al. 2015). Note that although a very Compton-thick absorber may explain the observed X-ray faintness in J0916a, we still need other scenarios for the explanation on the MIR faintness of the torus.

Recent studies have shown that the weakness of X-ray emission is associated to high λ_{Edd} (e.g., Toba et al. 2019) and fast disk winds (e.g., Zappacosta et al. 2020), in which the X-ray deficit does not suggest the fading of the primary accretion disk radiation, but could be explained with the weakening of corona when the disk inner edge moves inward, or the cooling of corona due to the dense, so-called “failed wind.” In these scenarios, the high λ_{Edd} = 5.7 of J0916a from its extended [O III] emission could reflect not only the past, but also the current AGN activity, i.e., the AGN is still active. However, the expected L_{5-38 μm} in this active scenario could be over three times brighter than the observed value, considering that the covering factor of torus keeps nearly constant with λ_{Edd} > 0.03 (Ricci et al. 2017a). With the observed low L_{5-38 μm}/L_{[OIII]} we tend to adopt the fading scenario as discussed in Section 3.3, although it is difficult to rule out the active scenario due to the uncertainty in the estimation of NLR radiation. In this work the [O III] λ5007 line is used as the indicator of AGN NLR radiation. Compared to the IR [O IV] 25.9 μm emission line, [O III] emission is more likely contaminated by the ionized gas surrounding young O/B type stars, and is more sensitive to dust extinction. We estimate the amount of star formation contamination in the total L_{[OIII]}, which is only 0.6% and can be ignored. However, the uncertainty in the extinction estimation due to the weakness of the Hβ line can result in a variation of 0.5 dex in the corrected L_{[OIII]}. A high-quality optical spectrum is required to reduce the uncertainty of extinction correction, which will be achieved with the awarded Gemini/Gemini Multi-Object Spectrograph Integral Field Unit (IFU) follow-up for J0916a. The IFU observation can also help us to better constrain the extent the size of the outflowing region.

In addition to the fading AGN scenario where the central AGN activity indicated by X-ray and MIR radiation is finally quenched, there is another possibility that the AGN in J0916a may brighten up again as shown in the “changing-look AGNs” (CLAGNs), which have strong variability by an order of magnitude and can rebrighten when their accretion states change from faint phase to bright phase in a timescale of 1–10 years (e.g., Ricci et al. 2020). If J0916a has a CLAGN and its X-ray emitting corona would recover L_{2-10 keV} of ∼9 × 10^{44} erg s⁻¹ as expected from the corrected L_{[OIII]}, then the AGN can be significantly detected by NuSTAR, e.g., S/N > 7 in 3–20 keV with an exposure of 100 ks in a Compton-thick case (N_H ∼ 10²⁴ cm⁻²). Therefore, the future NuSTAR follow-up is necessary to test the CLAGN scenario. The submm observation with a high spatial resolution, e.g., ALMA, can be also helpful to constrain the CLAGN scenario. Considering the spectral coverage of ALMA at z = 0.49, CO J = 4–3 line can be employed as a tracer of molecular gas in J0916a. The spatial resolution of ALMA can reach 0.01″ at Band 7 with the maximum baselines of 16.2 km, which provides the capability to determine the molecular gas reservoir in the circumnuclear region (100–200 pc) of the AGN. If the ALMA observation reveals that the cold molecular gas has been cleaned up in the circumnuclear region, the possibility of AGN rebrightening could be reduced without fueling to the SMBH.

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