An AGN with an Ionized Gas Outflow in a Massive Quiescent Galaxy in a Protocluster at $z = 3.09$

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Abstract

We report the detection of an ionized gas outflow from an X-ray active galactic nucleus hosted in a massive quiescent galaxy in a protocluster at $z = 3.09$ (J221737.29+001823.4). It is a type-2 QSO with broad ($W_{50} > 1000$ km s\(^{-1}\)) and strong ($\log(L_{[OIII]}/\mathrm{erg\,s^{-1}}) \approx 43.4$) [O III] $\lambda\lambda$ 4959,5007 emission lines detected by slit spectroscopy in three-position angles using Multi-Object Infra-Red Camera and Spectrograph (MOIRCS) on the Subaru telescope and the Multi-Object Spectrometer For Infra-Red Exploration (MOSFIRE) on the Keck-I telescope. In the all slit directions, [O III] emission is extended to $\sim 15$ physical kpc and indicates a powerful outflow spreading over the host galaxy. The inferred ionized gas mass outflow rate is $22 \pm 3 \, M_{\odot} \, \mathrm{yr}^{-1}$. Although it is a radio source, according to the line diagnostics using H\(\beta\), [O II], and [O III], photoionization by the central QSO is likely the dominant ionization mechanism rather than shocks caused by radio jets. On the other hand, the spectral energy distribution of the host galaxy is well characterized as a quiescent galaxy that has shut down star formation several hundred Myr ago. Our results suggest a scenario that QSOs are powered after the shutdown of the star formation and help complete the quenching of massive quiescent galaxies at high redshift.

Unified Astronomy Thesaurus concepts: Active galactic nuclei (16); Galaxy evolution (594); Protoclusters (1297)

1. Introduction

Giant elliptical galaxies are the dominant population in clusters of galaxies today, and their formation history is one of the most important issues of observational cosmology. According to their tight color–magnitude relation, they are thought to have formed the bulk of their stars in the early universe (e.g., Bower et al. 1992, 1998; Kodama et al. 1998). Massive galaxies with quiescent star formation similar to giant ellipticals today have been now discovered at up to $z = 4$ (e.g., Kubo et al. 2018, 2021; Schreiber et al. 2018; Tanaka et al. 2019; Forrest et al. 2020; Saracco et al. 2020; Valentino et al. 2020). They are characterized by significant Balmer/4000 Å breaks and suppressed emission in the rest-frame UV and far-infrared (FIR). According to the detailed analysis of their star formation histories (SFH) using multiwavelength photometry and deep near-infrared (NIR) spectroscopic observations, they have likely formed via a burst of star formation quenched suddenly and evolved passively for several hundred Myr to a few Gyr; however, it is not yet understood how they were quenched and how they were maintained quiescence when the universe was still rich in gas.

Several quenching mechanisms to suppress the star formation by removing or heating gas have been adopted in cosmological numerical simulations to reproduce massive quiescent galaxies in the early universe (e.g., Weinberger et al. 2017; Donnari et al. 2021). Active galactic nuclei (AGN) feedback is a plausible quenching mechanism (e.g., Naab & Burkert 2003; Boumaud et al. 2005; Hopkins et al. 2006; Sparre & Springel 2016) leading to a well-established relationship between the masses of the supermassive black holes (SMBH) and the bulge luminosities/masses or velocity dispersions of their host galaxies (e.g., Magorrian et al. 1998; Ferrarese & Merritt 2000; Kormendy & Ho 2013). AGN feedback is observed as a quasar (radiative) mode that occurs around the peak of the AGN activity and a radio (kinetic or jet) mode that occurs at a low accretion rate (Fabian 2012); strong outflows from AGNs have been observed (e.g., Rupke & Veilleux 2011; Harrison et al. 2014; Carniani et al. 2015; Harrison et al. 2016; Bae et al. 2017) while radio-loud AGNs are often hosted by giant ellipticals in the local universe (e.g., Best et al. 2005). However, it is still unclear whether AGNs have quenched the star formation; the star formation rates (SFR)
of host galaxies of AGNs range widely (e.g., Rosario et al. 2012; Santini et al. 2012; Shimizu et al. 2015; Mullaney et al. 2015).

Here we present a spatially extended ionized gas outflow from a type-2 AGN in a protocluster at $z = 3.09$ detected with $\lambda\lambda4959,5007$ emission lines. Its host galaxy is well characterized as a massive quiescent galaxy by detecting significant Balmer/4000 Å breaks photometrically. Thus the AGN in this particular object is an excellent target to understand how an AGN worked in a giant elliptical when it has been quenched of star formation. This object is an excellent target to understand how an AGN worked in a protocluster at $z = 3.37$.

Figure 1 shows the rest-frame $UVJ$ color diagram. The magenta filled circle shows the target of this study (J221737.29+001823.4) and open circle shows a massive quiescent galaxy in the same protocluster confirmed in K21 (J221737.25+001816.0). The points and curves show the color evolution tracks for SED models with age between 0.1 and 2 Gyr computed with GALAXEV (Bruzual & Charlot 2003). The black crosses with a dotted curve show the color evolution track for a single-burst star formation model with $A_V = 0$. The blue diamonds and curve show the color evolution track for a constant star formation model with $A_V = 0$. The points are shown at ages 0.5, 1.0, 1.5, and 2.0 Gyr. The black solid line shows the color criterion for quiescent galaxies at $2.0 < z < 3.5$ in Whitaker et al. (2013).

As we noted in K15 and revisit in Section 3.1, the SED of J221737.29+001823.4 is well-fitted by a quiescent galaxy. Figure 1 shows the rest-frame $UVJ$ color diagram to select quiescent galaxies (e.g., Whitaker et al. 2013). The $UVJ$ colors are interpolated from the best-fit SED described in Section 3.1. J221737.29+001823.4 is classified as a quiescent galaxy similar to another massive quiescent galaxy with $z_{\text{spec}} = 3.0922^{+0.009}_{-0.004}$ at R.A., decl. = $22:17:37.25$, +00:18:16.0, only 7’5” ($\approx 60$ in physical kpc) away from the target confirmed in K21. We note that J221737.25+001816.0 is not detected in $[O\text{ III}]$ emission and the Chandra and radio data described below but shows weak $[O\text{ II}]$ emission that can originate in an AGN. Including our studies, several studies have shown the prevalence of massive quiescent galaxies in protoclusters at up to $z = 3.37$ (e.g., Kubo et al. 2013; K21; Shi et al. 2021; McConachie et al. 2021). Such massive quiescent galaxies in protoclusters are the most plausible progenitors of typical giant ellipticals today.

In the SSA22 protocluster, AGNs have been surveyed using Chandra and Spitzer data (Webb et al. 2009), and those hosted by galaxies ranging from Ly$\alpha$ emitters to submillimeter galaxies have been studied (Geach et al. 2009; Lehmer et al. 2009a, 2009b; Webb et al. 2009; Tamura et al. 2010; Kubo et al. 2013; K15; Umehata et al. 2015, 2019; Monson et al. 2021). Among them, J221737.29+001823.4 is not particularly luminous in the X-rays but is the most $[O\text{ III}]$ luminous source observed at this point (K15).

### Table 1

| Items | References |
|-------|------------|
| Photometry | not published (PI: Cowie) |
| Subaru S-Cam $BVRIz'$ | Matsuda et al. (2004) |
| Subaru MOIRCS $JKs$ | Kubo et al. (2013) |
| Subaru nuMOIRCS $K_s$ | K21 |
| HST ACS F814W | in archive (PID9760) |
| Spitzer IRAC & MIPS 24μm | Webb et al. (2009) |
| ALMA 1.2 mm | Umehata et al. (2018) |
| ALMA 3.0 mm | Umehata et al. (2019) |
| VLA 6 GHz | H. Umehata et al. 2022, in preparation |
| VLA 3 GHz | Ao et al. (2017) |
| VLA 1.4 GHz | Chapman et al. (2004) |
| Chandra 0.5–8 keV | Lehmer et al. (2009b) |

| Spectroscopy | |
|------------|----------------|
| Subaru MOIRCS $VPH-K$ | K15 |
| Keck MOSFIRE $H$ and $K$ | Umehata et al. (2019) |
| VLT MUSE | Umehata et al. (2019) |

2. Target and Data

2.1. Target

Table 1 summarizes the data and their reference of the target. Our target is one of the galaxies confirmed by our NIR spectroscopic observations of massive galaxies in a protocluster at $z = 3.09$ in the SSA22 field (Steidel et al. 1998) using Multi-Object Infra-Red Camera and Spectrograph (MOIRCS; Ichikawa et al. 2006; Suzuki et al. 2008) on the Subaru telescope (Kubo et al. 2015 hereafter K15; referred J221737.3+001823.2). Hereafter we call the target as J221737.29+001823.4 adopting the source position measured on the new $K_s$-band image taken with updated MOIRCS (nuMOIRCS; Fabricius et al. 2016; Walawender et al. 2016) (Kubo et al. 2021, hereafter K21) using SExtractor (Bertin & Arnouts 1996). The source is an AGN matching with the X-ray source at a $0.18$ angular separation in the catalog obtained with Chandra in Lehmer et al. (2009a, 2009b). Its redshift is confirmed by detecting the $[O\text{ III}]\lambda\lambda4959,5007$ emission, which shows two peaks corresponding to $z = 3.0851 \pm 0.0001$ and $3.0926 \pm 0.0003$ indicating the complex kinematics of the ionized gas.
2.2. Photometry

Table 2 summarizes the measured magnitudes and fluxes of the target. The $u'$ to 8.0 $\mu$m photometry was taken in the same way as K21. The $u'$ to $K_s$ and F814W-band images are convolved to match the PSF to a FWHM of $\approx 1.0$ arcsec and measured fluxes with a 2.5 $\mu$m diameter aperture. In the IRAC 3.6–8.0 $\mu$m photometry we apply aperture correction computed by using the $K_s$-band image to match with $u'$ to the $K_s$ band (see detail in Kubo et al. 2013). Then we corrected the PSF matched photometry values multiplying the total (Kron flux measured on the nuMOIRCS image) to the aperture photometry ratio in the $K_s$ band. Major emission lines shifting to the bandpasses were checked spectroscopically and subtracted from these broadband measurements. [O II], H$\beta$, and [O III] were subtracted from the H- and K-band fluxes, respectively, while H$\alpha$ and [N II] are shifted out of the bandpasses. Ly$\alpha$ and [C IV] were ignored as they were observed with the Multi-Unit Spectroscopic Explorer (MUSE) on the Very Large Telescope (VLT; Umehata et al. 2019). Indeed, Ly$\alpha$ fluxes of a few $10^{-18}$ erg s cm$^{-2}$ s$^{-1}$ were detected in the narrow-line AGNs at $z \approx 3$ with [O III] fluxes similar to J221737.29+001823.4 (Law et al. 2018). Although J221737.29+001823.4 itself showed no strong Ly$\alpha$, it is likely associated with the extended Ly$\alpha$ nebulae, which indicate the presence of abundant intergalactic gas (Umehata et al. 2019). Thus it is natural to consider that Ly$\alpha$ photons of J221737.29+001823.4 are absorbed and/or scattered by circum/intergalactic media to form the extended Ly$\alpha$ nebulae (e.g., Hennawi et al. 2009), although the detail of Ly$\alpha$ damping mechanism is beyond the scope of this study.

J221737.29+001823.4 was observed by the Atacama Large Millimeter/submillimeter Array (ALMA) in Band-6 and Band-3, which give upper limits at 1.2 mm and 3 mm (Umehata et al. 2015, 2017, 2018, 2019). J221737.29+001823.4 was also observed by the Karl G. Jansky Very Large Array (VLA) C band (6 GHz), S band (3 GHz; Ao et al. 2017), and L band (1.4 GHz; Chapman et al. 2004), and is detected in 3 and 6 GHz. Here we briefly explain the recent C-band observations (details will be presented in H. Umehata et al. 2022, in preparation). The field of view covers an entire field of ALMA deep survey field in the SSA22 (Umehata et al. 2018), which includes J221737.29+001823.4. Observations were carried out in the A and B configurations covering 4.2–8.2 GHz with a total on-source time of 89 hours. After data reduction and imaging with VLA Common Astronomy Software Applications (CASA), the resultant map has a synthesized beam size of $0''$089 $\times$ $0''$079 ($PA = 24^\circ71$) and an rms level 0.35 mJy beam$^{-1}$ at the phase center. We measure the 3 GHz and 6 GHz fluxes using CASA/imfit. We also put a point-source upper limit at 1.4 GHz. We put an upper limit of Spitzer Multi-Band Imaging Photometer (MIPS) 24 $\mu$m (Webb et al. 2009; see also Kubo et al. 2013). We use the Chandra X-ray flux values listed in Lehmer et al. (2009b). Its radio flux is around the detection limit of the VLA COSMOS 3 GHz survey (Smaili et al. 2017), and the X-ray flux is lower than the detection limit of the Chandra COSMOS Legacy survey (Marchesi et al. 2016). To summarize, J221737.29+001823.4 is an object hardly detected by deep and wide X-ray and radio surveys to date.

2.3. Spectroscopy

The NIR spectroscopic observations were performed using MOIRCS (K15) and Multi-Object Spectrometer For Infra-Red Exploration (MOSFIRE; McLean et al. 2012) on the Keck-I telescope (see Umehata et al. 2019 and H. Umehata et al. 2022, in preparation for details). We show the slit positions in Figure 2. The observations were conducted using three slit position angles, 5 (slit A), 105 (slit B), and 58 (slit C) degrees. For slits A and B, we conducted a K-band spectroscopy for 3.2 and 3.3 h net exposure with MOSFIRE on 2020 September 11 and 12 (Umehata et al. 2019 and H. Umehata et al. 2022, in preparation). For slit A, an H-band spectrum was obtained with 2.5 h exposure with MOSFIRE on 2020 September 11 (see detail in K21). The slit widths were 0''7 for all the MOSFIRE observations. For slit C, we conducted a K-band spectroscopy with 3.8 h exposure with MOIRCS on the Subaru telescope on 2012 October 29 (K15). The location of slit C was offset from the center of the target in order to observe the other two targets simultaneously. The slit width for the MOIRCS observation was 0''8. All observations were conducted in good seeing conditions with FWHM PSF sizes of $0''5$–$0''8$. Both MOIRCS and MOSFIRE observations were performed by two-position mask-nod sequence dither along slits to perform sky subtraction accurately. The calibration of the fluxes was performed using one telluric standard star at similar air masses taken before or after the observations each night. The spectral resolutions for MOSFIRE K (H) and MOIRCS K band at the given configurations were 3620 (3660) and 1700, respectively. Figure 2 pipeline, shows the spectra obtained using the MOIRCS and MOSFIRE. The spectra obtained by both instruments are corrected for slit losses. [O II] $\lambda\lambda$3727, 3729, H$\beta$, and [O III] are detected significantly. Although the observing methods and conditions are not uniform, the H$\beta$ and [O III] fluxes measured at each slit location do not differ greatly. In the case of J221737.25+001816.0 in K21, which was taken with the same masks as both slit A and slit B, the differences between the slit-loss-corrected fluxes from MOSFIRE spectroscopy and the Kron fluxes based on the MOIRCS imaging in H and $K_s$,
bands were $\sim$20%. Thus the flux calibration in this study is almost correctly performed.

### 3. Analysis

#### 3.1. SED Fitting

We used X-CIGALE (Yang et al. 2020), which models the SED of a host galaxy and X-ray-to-radio emission from an AGN simultaneously. The model parameters used in X-CIGALE are summarized in the Appendix. Briefly, we included a stellar population synthesis model with dust attenuation, dust emission, an optical to infrared emission model for an AGN, X-ray power-law emission, and radio synchrotron emission. For stellar population models, we adopted a Chabrier (2003) IMF and a Bruzual & Charlot (2003) model with solar metallicity, and dust attenuation law from Calzetti et al. (2000). We assumed a delayed exponentially declining SFH model described as,

$$\text{SFR}(t) \propto \frac{(t_\psi - t)}{\tau} \times \exp\left(-(t_\psi - t)/\tau\right) \text{ for } 0 \leq t \leq t_\psi,$$

where $t$ is the look-back time, $t_\psi$ is the look-back time onset of star formation, and $\tau$ is the e-folding time at which the SFR peaks. We use the dust emission templates from Dale et al. (2014), which are parameterized by a power-law slope $\alpha$ of $dM_d(U) \propto U^{-\alpha} dU$, where $M_d$ is the dust mass, and $U$ is the radiation field intensity and AGN fraction. The AGN fraction of this component is set to zero as we included another AGN model. X-CIGALE adopts an energy balance principle for the emission from stars, i.e., the energy emitted by dust in the IR corresponds to the energy absorbed by dust in the UV to optical.

We adopted models of rest-frame UV to IR emission from an AGN according to Fritz et al. (2006). Here we fixed the parameters at default values of X-CIGALE except for position angle ($\psi$) and AGN fraction. The parameters fixed here can affect the mid-IR (MIR) SED shape, but this is out of the scope of this study as the MIR flux of our target is not well constrained. The X-ray power law is parameterized by a photon index $\Gamma$. The Fritz et al. (2006) and X-ray models are constrained not to have an optical to X-ray luminosity ratio significantly different from the empirical values (Just et al. 2007). The radio synchrotron emission in X-CIGALE is parameterized with a power-law spectral slope $\alpha$ where radio flux $F_\nu \propto \nu^{-\alpha}$, with radio–IR correlation $q_{IR}$ (Helou et al. 1985).

We did not include the nebular emission in X-CIGALE that is useful for modeling young star-forming galaxies but not important for a massive quiescent galaxy like our target. Our target has strong nebular emission lines from an AGN, which is not included in the AGN model templates, and their contributions to the SED were subtracted in advance. Low-mass X-ray binaries (LMXB), high-mass X-ray binaries (HMXB), and hot gas from a host galaxy were also considered for the X-ray model, but according to the recipe adopted in X-CIGALE, their contribution to X-ray luminosities are expected to be 2 or more orders of magnitude lower than that of the AGN X-ray luminosity of our target. As shown in Figure 2, as it is hard to determine the systemic redshift of the host galaxy, hereafter we adopt $z = 3.085$ to calculate the physical properties. We also ran X-CIGALE with a fixed position angle $\psi = 0^\circ$, where the contribution of the AGN is negligible at rest-frame UV to optical wavelength.
3.2. Emission Lines Fitting

As shown in Figure 2, all [O III] line profiles have significantly redshifted tails. Hβ shows no significant emission from a broad-line region (FWHM > 2000 km s⁻¹). We measured the fluxes and line profiles of the emission lines by fitting them with combinations of Gaussian profiles. The composites of two or three Gaussian profiles are often used to fit the [O III] line profiles of AGNs (e.g., Harrison et al. 2014; Zakamska & Greene 2014). Zakamska & Greene (2014) found that three-component Gaussian models are better than two- or one-component Gaussian models for 400 out of 568 obscured AGNs found in the Sloan Digital Sky Survey (SDSS). According to Villar-Martín et al. (2011), such a three-component Gaussian model consists of two narrow components and one very broad (FWHM ≥ 1000 km s⁻¹) component. Such a broad component can appear as a distinct tail in a spectrum, but it was not identified well in our target maybe due to the low sensitivity. As we describe later, the line profiles of our target are approximated well by combinations of the two narrow Gaussian profiles without another very broad component. Thus to compare the line properties properly with literatures, we fitted each [O III] with a combination of two Gaussian components.

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### Table 3  SED Parameters

| Model   | Parameter Value (free $\psi$) | Value ($\psi = 0$) |
|---------|------------------------------|--------------------|
| Stellar | $\gamma_{\text{max}}$/Gyr | 1.68 ± 0.29 | 1.40 ± 0.04 |
|         | $\tau_{\text{max}}$/Myr | 45 ± 54 | 200 ± 0 |
|         | $E(B-V)$/mag | 0.12 ± 0.04 | 0.09 ± 0.02 |
|         | age$_{\text{bol}}$/Gyr | 1.59 ± 0.29 | 1.00 ± 0.36 |
|         | $M_0/10^{10} M_\odot$ | 9.91 ± 1.67 | 6.22 ± 0.33 |
|         | SFR/M$_\odot$ yr$^{-1}$ | 0.05 ± 0.02 | 3.41 ± 0.84 |
| Dust    | $\alpha$ | 0.71 ± 0.70 | 0.14 ± 0.11 |
| Fritz06 | $\psi$/deg | 51 ± 3 | 0 |
| X-ray   | $L_{\text{AGN}}$ | 0.16 ± 0.16 | 0.14 ± 0.14 |
|         | $\Gamma$ | 0.67 ± 0.20 | 0.65 ± 0.21 |
|         | log($L_{2-10 \text{keV}}$/erg s$^{-1}$) | 43.2 ± 0.1 | 43.2 ± 0.1 |
| Radio   | $q_{\text{IR}}$ | 0.61 ± 0.28 | 0.61 ± 0.27 |
|         | $\alpha$ | 0.61 ± 0.18 | 0.73 ± 0.22 |
|         | log($L_{1.4 \text{GHz}}$/erg s$^{-1}$ Hz$^{-1}$) | 31.05 ± 0.06 | 31.08 ± 0.09 |

Notes.

a The errors are calculated with X-CIGALE.
b Calculated with a fixed position angle $\psi = 0$.
c The stellar mass weighted age.

### 4.2. AGN Luminosity

Table 4 lists the strength, line center and line width at each slit position. Using the largest flux value at slit B, J221737.29+001823.4 has a [O III] luminosity of $L_{\text{[O III]}} = 43.28 \pm 0.01$. The observed luminosity is $L_{\text{bol}} = 43.2 \pm 0.1$. Thus $L_{\text{[O III]}}$ is more than 10 times larger than that expected from the empirical X-ray to [O III] luminosity relation for type-1 AGNs in the local universe (e.g., Ueda et al. 2015). Furthermore, our target has a flat X-ray SED ($\Gamma = 0.67 \pm 0.20$), which suggests significant absorption in the X-rays where $\Gamma \approx 1.8$ is typical (e.g., Yang et al. 2016; Liu et al. 2017). We then estimated the intrinsic X-ray luminosity based on the [O III] luminosity. Adopting the X-ray to [O III] luminosity relation for Seyfert-1 AGNs in the local universe (Ueda et al. 2015), J221737.29+001823.4 has an intrinsic X-ray luminosity of $L_{\text{X}} = 44.4$. Applying the X-ray to bolometric correction as in Marconi et al. (2004), the source has a bolometric luminosity of $L_{\text{bol}} = 46.0$, which would make it a moderately luminous QSO. Assuming a scaling relation between the black hole mass and the host galaxy stellar mass of $M_{\text{BH}} \approx 0.002 M_\bullet$, following Aird et al. (2012), J221737.29+001823.4 may have $M_{\text{BH}} \approx 2 \times 10^8 M_\odot$ and Eddington luminosity $L_{\text{Edd}} = 1.3 \times 10^{46} M_{\text{BH}}/M_\odot \approx 2.6 \times 10^4$ erg s$^{-1}$. Thus it may have a relatively large Eddington ratio of $L_{\text{bol}}/L_{\text{Edd}} \sim 0.4$.

### 4.3. Radio Emission

The 1.2 mm flux to IR luminosity $L_{\text{IR}}$ relation for the SED library in Danielson et al. (2017), the conservative upper limit of $L_{\text{IR}}$ is $\sim 0.9 - 2.0 \times 10^{11} L_\odot$, taking the 95% confidence interval. It corresponds to SFR $< 9 - 21 M_\odot$ yr$^{-1}$ using the $L_{\text{IR}}$ to SFR conversion in Kennicutt & Evans (2012). Hereafter we use $L_{\text{IR}} = 2.0 \times 10^{11} L_\odot$ and SFR = $21 M_\odot$ yr$^{-1}$ as a conservative upper limit.

### Figure 4

Left: 6 GHz image of the target. The image size is 4" by side. The red filled ellipse shows the beam size at 6 GHz. Right: The 3, 6, and 9σ contours (red) of the 6 GHz are overlaid on the $K_s$-band image of the target. The blue line shows the position angle measured at 6 GHz.

Table 4  [O III] Line Profile

| Slit  | $z$ | $V_{\text{offset}}$ (km s$^{-1}$) | FWHM$_{\text{corr}}$ (km s$^{-1}$) | fraction$^a$ |
|------|-----|-----------------------------|-------------------------------|-----------|
|      | (1) | (2)                         | (3)                          | (5)       |
| A    | 3.0832 | 10.0002                    | 242±21                      | 0.68±0.04 |
| B    | 3.0905 | 10.0005                    | 229±25                      | 0.67±0.04 |
| C    | 3.0848 | 10.0005                    | 147±98                      | 0.81±0.08 |

Notes.

a The velocity offset of this component from the brighter component.
b The fraction of this component in the total flux.
component sizes after deconvolution of the beam are (0.99 ± 0.05) × (0.52 ± 0.05) arcsec and PA = 151°2 ± 4°6. There is also a diffuse component with an orientation different from that of the bright central source. The source lies at the low-power end of the distribution for compact steep spectrum radio galaxies (e.g., Gelderman & Whittle 1994; O’Dea 1998), which are believed to be young systems evolving into more extended radio galaxies or systems with spatial growth restricted by the dense interstellar medium (ISM). The radio position angle is different from the slit directions for NIR spectroscopy, and then it is not clear whether the [O III] traces the radio morphology. However, the similar spatial extents of [O III] and radio emission can indicate their physical connection though both are limited by the observational depths.

### 4.4. Outflow

Although the small notches of the spectra left from the model spectra indicate more complex kinematics, each spectrum is well approximated by a combination of two Gaussian profiles. The obtained spectra have large relative asymmetries 0.07–0.15 and line widths of ≈1000 km s⁻¹. The spatial extent of [O III] (≈15 kpc in Figure 2) of J221737.29+001823.4 is much larger than the typical size of a massive quiescent galaxy at high redshift (a few physical kiloparsec; e.g., Shibuya et al. 2015), though the size of the host galaxy cannot be evaluated robustly because the K_s-band image can be significantly contaminated by [O III] emission. These line profiles observed at each slit indicate a significant outflow of ionized gas spread over the host galaxy. Such galactic wide-scale outflows of ionized gas have been observed among AGNs in the local universe and at high redshift (e.g., Harrison et al. 2014; Genzel et al. 2014; Harrison et al. 2016; Law et al. 2018; Kakkad et al. 2020).

Table 5 summarizes the ingredient of each spectrum. At all slit locations, a spectrum consists of two narrow components. The redshifts of the bluer components at slits A and B match with that of [O II] within errors, while the redshifts of both components at slit C are redder than [O II]. Therefore, J221737.29+001823.4 consists of one component also detected with [O II] at z ≈ 3.0832 (i) and at least two redshifted components (a bluer component at slit C (ii) and a redder components at slits A, B, and C (iii), at the resolution of this study). Comparing with local AGNs with [O III] line width as wide as J221737.29+001823.4 in literature (Villar-Martín et al. 2011; Fu et al. 2012; Zakamska & Greene 2014), J221737.29+001823.4 has components with narrower line widths and a larger velocity offset between the first and second brightest components. Then the wide line widths of the whole line profiles of J221737.29+001823.4 are due to the large velocity offsets of the two components, while those are due to broad components for most of the type-2 AGNs. The broader components found in such type-2 AGNs are generally blueshifted from the narrower components and regarded as highly disturbed outflowing gas. In the case of J221737.29+001823.4, component (iii) seen at all slit positions likely comes from the gas near the central SMBH. As the emission lines are spatially extended at all slit directions, components (i) and (ii), which dominate the emission-line fluxes at slits A and B and slit C, respectively, likely come from the outflowing extended emission-line region. The narrower line width indicates that the outflowing gas is not highly perturbed like typical type-2 AGNs with wide line widths. Maybe the outflowing gas of this system is not disturbed because of young age or lack of intergalactic gas to interact, or because the wing of the gas is highly attenuated by dust.

Here we estimate the mass outflow rate of J221737.29+001823.4 following Fiore et al. (2017), using the [O III] W_{60,corr} and the spatial extent and H_β luminosity for slit A, which are similar to those for slits B and C. Based on the H_β luminosity, the mass of the outflowing ionized gas is estimated as

\[ M_{H_\beta} = 7.8 \times 10^7 \left( \frac{L_{H_\beta}}{10^{44}} \right)^{-1} \left( \frac{\eta}{10^3} \right)^{-1}, \]

following Osterbrock & Ferland (2006) and Carniani et al. (2015), where \( \eta = \frac{n_e}{n_H} \) (set to unity, which is a conservative lower limit); a gas temperature \( T = 10^4 \) K is assumed. Adopting \( n_e = 200 \) cm⁻³ following Fiore et al. (2017), we find \( M_{H_\beta} = 7.2 \times 10^7 M_\odot \).

The mass outflow rate of ionized gas is calculated as,

\[ \dot{M} = 3 \times v_{\text{max}} \times M_{H_\beta}/R, \]

where \( v_{\text{max}} \) is the wind maximum velocity, and \( R \) is the radius at which the mass outflow rate is computed. \( v_{\text{max}} \) is defined as \( W_{60,\text{corr}}/1.3 \), and \( R \) is defined as the maximum radius at which the high-velocity gas is detected. Here we use half of the extent of [O III] for each slit, \( \approx 7.1 \) kpc, corrected of the spatial resolution with FWHM PSF of \( \approx 4.5 \) kpc on average. We find a mass outflow rate \( 22 \pm 3 M_\odot \text{yr}^{-1} \). Its mass loading factor \( \eta = \dot{M}/\text{SFR} \) is around unity at lower limit. \( \dot{M} \) Note that our estimate does not include outflowing gas at a neutral or molecular state. Including them, the total mass outflow rate and thus \( \eta \) could be a few to 10 times larger than that of the ionized gas (e.g., Rupke & Veilleux 2013; Carniani et al. 2015; Fiore et al. 2017; Fluetsch et al. 2019).

| Slit  | line         | \( z_{50} \)   | \( W_{60,\text{corr}} \) (km s⁻¹) | Rel. asym. | Flux (10⁻¹⁷ erg cm⁻² s⁻¹) | [OIII]λ3727/λ3729 |
|------|--------------|---------------|---------------------------------|------------|--------------------------|------------------|
| (1)  | (2)          | (3)           | (4)                             | (5)        | (6)                      |                  |
| A    | [OIII]λ5007  | 3.0856±0.0002 | 1174±133                        | 0.14±0.03  | 21.0±0.8                |                  |
|      | H_β          |               |                                 |            |                          |                  |
|      | [OIII]λ3727, 3729 | 3.0852±0.0002 | 354±128                        | 0.15±0.04  | 22.7±0.9                |                  |
| B    | [OIII]λ5007  | 3.0852±0.0002 | 1148±146                       | 0.15±0.03  | 22.7±0.9                |                  |
|      | H_β          |               |                                 |            |                          |                  |
| C    | [OIII]λ5007  | 3.0857±0.0006 | 903±254                        | 0.07±0.11  | 19.9±1.6                |                  |
|      | H_β          |               |                                 |            |                          |                  |
We compared the mass outflow rate, AGN bolometric luminosity, SFR, and specific SFR (sSFR) of J221737.29+001823.4 with results in Fiore et al. (2017) who summarized the outflow properties of QSOs at low and high redshift in the literature, and Leung et al. (2019) who investigated the outflow properties for X-ray AGNs at 1.4 < z < 3.8 in Figure 5. We correct the mass outflow rate in Leung et al. (2019) adopting the equation in Fiore et al. (2017). The dashed line in the central panel shows η = 1.

Figure 5. Mass outflow rate vs. AGN bolometric luminosity $L_{\text{bol}}$ (left), and SFR (center) and sSFR (right) of the host galaxy. The filled magenta circle shows J221737.29+001823.4. The black crosses and filled squares show the QSOs at low and high redshift from Fiore et al. (2017). The blue filled circles show AGNs in Leung et al. (2019). We correct the mass outflow rate in Leung et al. (2019) adopting the equation in Fiore et al. (2017). The dashed line in the central panel shows η = 1.

Figure 6. Left: O32 vs. R23 indices. The filled magenta circle with error bars shows the target. The filled black contour shows the distribution of star-forming galaxies from the SDSS (based on the MPA-JHU catalog; Brinchmann et al. 2004; Kauffmann et al. 2004; Tremonti et al. 2004). The blue contour shows the distribution of AGNs selected from the SDSS. Both the star-forming galaxies and AGNs are selected based on the BPT diagram. The green tracks show the photoionization model from Groves et al. (2004). The models with α = −2, log $U = −3, −2, −1, 0, \text{and} Z = 0.25, 0.5, 1, \& 2 Z_e$ are shown. The red tracks show the shock ionization model from Allen et al. (2008). The models with $n = 1000 \text{ cm}^{-3}, Z = Z_e, v = 100, 250, 500, \& 1000 \text{ km s}^{-1}, \text{and} B = 0.1, 10, 100, \& 1000 \mu G$ are shown. Right: Similar to the left panel but for the $[\text{O III}]\lambda5007/\text{H}\beta$ vs. $[\text{O III}]\lambda\lambda 3726+3729/\text{H}\beta$ line diagnostics.

We compared the mass outflow rate, AGN bolometric luminosity, SFR, and specific SFR (sSFR) of J221737.29+001823.4 with results in Fiore et al. (2017) who summarized the outflow properties of QSOs at low and high redshift in the literature, and Leung et al. (2019) who investigated the outflow properties for X-ray AGNs at 1.4 < z < 3.8 in Figure 5. We used the upper limit on SFR from the 1.2 mm flux (< 21 M$_\odot$ yr$^{-1}$) and the stellar mass estimated assuming ψ = 0 to obtain sSFR as a conservative limit. J221737.29+001823.4 is not a special object; its ionized gas mass outflow rate is similar to those of AGNs with similar bolometric luminosities. As previous studies have shown, the SFRs of AGNs with strong outflows range widely from quiescent (sSFR < 10$^{-10}$ yr$^{-1}$) to starbursting.

4.5. Emission Line Diagnostics

We show the emission line diagnostics of J221737.29+001823.4 measured at slit A in Figure 6. The left panel shows O32 versus R23, where O32 and R23 are defined as log ([O III] / [O II]) and log ([([O III]+[O II])] / Hβ), respectively. The right panel shows the $[\text{O III}]\lambda 5007/\text{H}\beta$ versus $[\text{O II}]\lambda\lambda 3726,3729/\text{H}\beta$ line diagnostics. The magenta filled circle shows the line ratio of J221737.29+001823.4. The blue and red diamonds show the line ratios of the bluer and redder components. The black filled contour and blue contour show the star-forming galaxies and AGNs, respectively, selected from the SDSS using spectroscopic data products from the Max Planck Institute for Astrophysics and Johns Hopkins University.
5. Discussion

We identified a QSO in a quiescent galaxy that plausibly stopped star formation several hundred Myr ago, which is analogous to the so-called post-starburst galaxies selected with Balmer absorption features caused by A-type stars in the local universe though in our target we hardly detect Balmer absorption features with the current facilities. Post-starburst galaxies often show significant emission lines likely attributed to an AGN rather than star formation (e.g., Yan et al. 2006; Schawinski et al. 2007; Wild et al. 2010; Alatalo et al. 2016). Similarly, massive quiescent galaxies at high redshift sometimes show weak [OII] or [OIII], which are thought to originate in AGNs (e.g., Lemaux et al. 2010; Schreiber et al. 2018; Saracco et al. 2020; K21). However, QSOs with [OIII] as luminous as our target are rarely found in the local universe (Jarvis et al. 2019). The QSOs hosted by quiescent galaxies at high redshift have not been studied in detail previously, but they may not be so unusual given the presence of QSOs with low sSFR and strong outflows (e.g., Fiore et al. 2017; Leung et al. 2019).

In the case of J221737.29+001823.4, photoionization by AGN is likely the dominant excitation mechanism but shocks can also be the dominant excitation mechanism of strong emission lines of post-starburst galaxies (Alatalo et al. 2016). The type-2 QSOs with broad and luminous [OIII] at $z < 0.2$ is or in Harrison et al. (2014) which were further studied in Jarvis et al. (2019) share several properties with J221737.29+001823.4; they have log$(L_{\text{OIII}}/\text{erg s}^{-1}) = 42-43.2$, [OIII] line FWHM = 800–1800 km s$^{-1}$, log$(L_{\text{H}\beta}/\text{erg s}^{-1}) = 30.3-31.4$, compact radio sizes (1.25 kpc), small $q_{\text{BH}} = 1-2$, and low SFR of $\leq 50$ $M_\odot$ yr$^{-1}$, and thus are classified as radio-quiet QSOs. Jarvis et al. (2019) suggested a scenario in which low-power radio jets are confined by the ISM for a long time and efficiently affect the ISM over a large volume and result in strongly ionized gas outflows (e.g., Mukherjee et al. 2016).

How to power a QSO in a quiescent galaxy like J221737.29+001823.4? As radio-quiet QSOs are generally star-forming (e.g., Best & Heckman 2012; Panessa et al. 2019), it is not surprising that there is abundant gas to fuel central SMBHs. However, J221737.29+001823.4 has likely been quenched for several hundred Myr. One interesting issue is the origin of the gas supply to power a QSO. As J221737.29+001823.4 is at high redshift, cold gas supply can be still abundant although star formation should be kept quenching according to the observed SED.

Another possible supply of gas to power a QSO is mass loss from evolved stars following a starburst (Norman & Scoville 1988; Ciotti & Ostriker 2007; Kauffmann & Heckman 2009). In this scenario, the mass loss from asymptotic giant branch (AGB) stars can result in a rise in AGN at 100–300 Myr after the starburst and may explain some observed time delay of AGNs found in the local universe (e.g., Davies et al. 2007; Kauffmann & Heckman 2009; Wild et al. 2010) while the mass loss from supernova explosions (SNe) supplies gas at early times during which the mass accretion to central SMBHs is not efficient because the velocity of the gas ejected by SNe is several thousand km s$^{-1}$. At late times, mass loss from AGB stars becomes dominant. As the speed of the gas ejected as planetary nebulae is several tens km s$^{-1}$, they can more easily accrete into the central SMBH.

As the SFH of massive quiescent galaxies at high redshift is believed to be more bursty than that of local star-forming
galaxies (e.g., Schreiber et al. 2018; Forrest et al. 2020; Saracco et al. 2020; Valentino et al. 2020; Kubo et al. 2021), after the starburst, a large amount of gas should be supplied from evolved stars in a short timescale. We calculated the gas production from the mass loss of stars in J221737.29+001823.4 using GALAXEV (Bruzual & Charlot 2003) assuming a constant starburst for 50 Myr, which forms a stellar mass of $5 \times 10^{10} M_\odot$ or half the stellar mass of J221737.29+001823.4, where the lifetimes of SMGs are found to be 40–200 Myr (Greve et al. 2005; Tacconi et al. 2006; Toft et al. 2014). There is a supply of $\gtrsim 10 M_\odot$ yr$^{-1}$ gas from the mass loss of stars at all times within $\sim 1$ Gyr from the beginning of the starburst. Using the equation adopted by Wild et al. (2010), the black hole accretion rate (BHAR) of our target is estimated from the [O III] luminosity as $4 \times 10^{-10} \times L_{[\text{OIII}]}/L_\odot \approx 2 M_\odot$ yr$^{-1}$; this is reduced if a part of [O III] is induced by radio jets. This corresponds to 20% of the mass loss from stars expected for J221737.29+001823.4. We note that Ciotti et al. (2010) predicted that 2% of the recycled gas is used to fuel the central SMBH. From the above, a substantial amount of AGN luminosity can be fueled naturally by the mass loss from stars, but we cannot reject the possibility of an external supply of gas from the circum/intergalactic media to fuel the central SMBH.

6. Conclusion

We have identified a massive quiescent galaxy hosting a QSO with ionized gas outflows by detecting redshifted [O III] $\lambda\lambda$ 4959,5007 emission lines. Large line widths ($W_{50} > 1000$ km s$^{-1}$) measured at the three slit positions indicate the presence of a powerful outflow in multiple directions. Given the quiescent SED of the host galaxy, we conclude that we are witnessing a QSO arising several hundred Myr after the quenching of the starburst. According to the emission line diagnostics, most of the emission line flux likely results from radiative heating by the QSO rather than radio jets.

Our results suggest a new aspect of the role of AGNs in galaxy evolution at high redshift. In one popular galaxy and SMBH coevolution scenario, it is believed that a central SMBH is grown with the star formation of a host galaxy, QSO-driven outflows remove gas from a host galaxy and quench its star formation, after which the accretion rates onto the central SMBHs decline and radio jets regulate the star formation of a host galaxy. Indeed there are dusty starburst galaxies and obscured AGNs that are believed to be the previous steps of QSOs in this $z = 3.09$ protocluster. On the other hand, in this case, we find that a QSO appears several hundred Myr after the quenching of star formation. The presence of a powerful outflow suggests that there remains a significant supply of gas to power a QSO after quenching. Taken together, it is possible that the progenitors of giant ellipticals may become strong QSOs both before and after quenching. We suggest a scenario in which once a QSO and/or stellar feedback initially quench star formation, subsequent accretion onto the SMBH of residual gas can power a QSO effectively, and this late-time QSO further completes quenching.

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Appendix

X-CIGALE Parameter

Table A1 lists the parameters adopted in X-CIGALE. The details of the parameters are described in Yang et al. (2020).
The AGN fraction of this component is set to zero. The extinction law of Calzetti et al. (2000) is used for AGN model. The photon indices of LMXB and HMXB are 1.56 and 2.0, respectively. The extinction law of Calzetti et al. (2000) is used for AGN model. The photon indices of LMXB and HMXB are 1.56 and 2.0, respectively.

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Bruzual, G., & Charlot, S. 2003, SSP model, Chabrier (2003) IMF, and solar metallicity between equatorial axis and line of sight (ψ) = 0.01 to 0.60 with 10 deg steps (=90 for type-1 and 0 for type-2), AGN fraction=0.0 to 1.0 with 0.1 steps. The extinction law of polar dust is that of Calzetti et al. (2000), E(B - V) for extinction in polar direction = 0.2, 0.4, & 0.6, temperature of the polar dust = 100 K, and emissivity index of the polar dust = 1.6.

## Table A1

| Component | Model |
|-----------|-------|
| SFH | sfh-delayed model without any additional burst. r_{main} = 5, 10, 20, 50, 100, 200, 500, & 1000 Myr. |
| stellar population | Modified Calzetti et al. (2000) attenuation model. E(B - V)_{main} = 0 to 1 with 0.2 steps. |
| dust attenuation | The E(B - V) of stellar continuum is 0.44 times the E(B - V)_{main}. |
| nebular emission | Dale et al. (2014) dust emission model. α = 0.0625, 0.2500, 1.0000, & 2.0000. The AGN fraction of this component is set to zero. |
| AGN (Fritz06) | Fritz et al. (2006) model. r_{ratio} = 60.0, τ = 1.0, Γ = 0.0, opening_angle of the dust torus = 100, angle between equatorial axis and line of sight (ψ) = 0.01 to 0.60 with 10 deg steps (=90 for type-1 and 0 for type-2), AGN fraction=0.0 to 1.0 with 0.1 steps. The extinction law of polar dust is that of Calzetti et al. (2000), E(B - V) for extinction in polar direction = 0.2, 0.4, & 0.6, temperature of the polar dust = 100 K, and emissivity index of the polar dust = 1.6. |
| radio free parameters | Power-law slope α = 0.4 to 2.0 with 0.2 steps, maximum deviation of alpha_{ox} from the empirical relation = 0.2. The photon indices of LMXB and HMXB are 1.56 and 2.0, respectively. |

| IR for radio model. Thus free parameters are eight in total. |

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