Super-Eddington Accretion in the WISE-selected Extremely Luminous Infrared Galaxy W2246—0526

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Abstract

We use optical and near-infrared spectroscopy to observe rest-UV emission lines and estimate the black hole mass of WISEA J224607.56–052634.9 (W2246—0526) at z = 4.601, the most luminous hot, dust-obscured galaxy yet discovered by WISE. From the broad component of the Mg II 2799 Å emission line, we measure a black hole mass of log(MBH/M⊙) = 9.6 ± 0.4. The broad C IV 1549 Å line is asymmetric and significantly blueshifted. The derived MBH from the blueshift-corrected broad C IV line width agrees with the Mg II result. From direct measurement using a well-sampled SED, the bolometric luminosity is 3.6 × 10^45 L⊙. The corresponding Eddington ratio for W2246—0526 is λEdd = LAGN/LEdd = 2.8. This high Eddington ratio may reach the level where the luminosity is saturating due to photon trapping in the accretion flow and may be insensitive to the mass accretion rate. In this case, the MBH growth rate in W2246—0526 would exceed the apparent accretion rate derived from the observed luminosity.

Key words: infrared: galaxies — galaxies: active — galaxies: individual (WISEA J224607.56–052634.9) — galaxies: nuclei — quasars: emission lines — quasars: supermassive black holes

1. Introduction

Discovered by their unusual mid-infrared colors in the Wide-field Infrared Survey Explorer all-sky survey (WISE; Wright et al. 2010), hot, dust-obscured galaxies (Hot DOGs; Eisenhardt et al. 2012; Wu et al. 2012) are hyperluminous infrared galaxies with a wide IR plateau and a steep drop in the far-IR, suggesting a broader dust temperature distribution (Tsai et al. 2015), which we model in C-W. Tsai et al. (2018, in preparation). W2246—0526 is the most luminous Hot DOG yet identified. With Lbol > 3 × 10^14 L⊙, it is well into the extremely luminous infrared galaxy (>10^14 L⊙; Tsai et al. 2015) range and is among the few most luminous galaxies known thus far.

Its superluminous luminosity is not the result of gravitational lensing (Tsai et al. 2015; Díaz-Santos et al. 2016). Accounting for a significant fraction of this luminosity via a starburst would require a star formation rate (SFR) ≳ 10^4 M⊙ yr^-1 (Tsai et al. 2015), but the cool gas and dust supplies needed for such an extraordinary SFR are not in evidence. Instead, the spectral energy distribution (SED) of W2246—0526 is dominated by hot dust (T_dust > 450 K; Tsai et al. 2015), indicative of a dominant active galactic nucleus (AGN). Direct evidence for an accreting supermassive black hole (SMBH) in this system comes from the broad C IV line in its spectrum (Díaz-Santos et al. 2018), which we discuss in further detail below. This makes an obscured AGN the most straightforward power source for W2246—0526, and we assume this is the case for the remainder of this paper.

Like W2246—0526, many hyperluminous Hot DOGs show AGN features in their spectra (P.R.M. Eisenhardt et al. 2018, in preparation). Recently, Wu et al. (2018) detected broad Hα lines in all members of a sample of five hyperluminous Hot DOGs at 1.6 < z < 2.5, finding black hole masses in the range log(MBH/M⊙) = 8.7–9.5. Compared to quasars with similar black hole masses, these Hot DOGs have higher luminosities. The SMBHs in these Hot DOGs are accreting at a rate close to the Eddington limit, suggesting that Hot DOGs represent a transitional phase of high accretion between obscured and unobscured quasars (Wu et al. 2018).

Is W2246—0526 similar to its sibling Hot DOGs? Is its extreme luminosity due to sub-Eddington accretion onto an exceptionally massive SMBH, or to an exceptionally high Eddington ratio for a more typical SMBH mass (Assef et al. 2015; Tsai et al. 2015)? To answer these questions, the virial mass of the SMBH in W2246—0526 needs to be determined. Measuring SMBH mass from C IV profiles is challenging in comparison to Balmer lines, because of large scatter (e.g., Netzer et al. 2007; Shen et al. 2011) and possible bias due to outflows (Gaskell 1982; Murray & Chiang 1997; Leighly 2004). Although the Hα and Hβ lines are stronger and suffer less from Fe II emission blending, for sources at higher redshift (z > 4), such as W2246—0526, only the broad Mg II line is reliable and available from the ground.

In this paper, we report the detection of broad Mg II emission in W2246—0526. We provide black hole mass estimates from the Mg II and C IV lines. To better determine the Eddington ratio, we also reexamine the luminosity estimate of W2246—0526 with updated photometric data. We present our near-infrared spectroscopy of W2246—0526 in Section 2, together with a description of other data used in this paper. Section 3 gives the SED, luminosity, and line widths based on these data.
Section 4 considers the resulting black hole mass and Eddington ratio. In Section 5, we summarize our work. A redshift \( z = 4.593 \) for W2246–0526 was reported by Tsai et al. (2015), determined from the overall \( \text{Ly} \alpha \) line profile. However, the redshift was revised to \( z = 4.601 \) based on the [C\( \text{II} \)] 157.7 \( \mu \text{m} \) line emission (Díaz-Santos et al. 2016). We adopt \( z = 4.601 \) for W2246–0526 and a cosmology with \( H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1} \), \( \Omega_m = 0.3 \), and \( \Omega_l = 0.7 \).

2. Observations and Data Reduction

2.1. Keck OSIRIS Observation of the Mg II Line

At \( z = 4.601 \), the Mg II 2799 Å line of W2246–0526 falls at 1.567 \( \mu \text{m} \) in the \( H \) band. W2246–0526 was observed with the Keck I telescope on UT 2016 October 21 in the first half of the night using OSIRIS (Larkin et al. 2006) while the originally proposed instrument (MOSFIRE) was being repaired. The weather was clear and the seeing was \( \sim 0.7'' \) over the observation. The spectra were taken with the H\( \beta\) filter covering 1.473–1.803 \( \mu \text{m} \) at 0.5 nm channel\(^{-1} \) resolution. With the \( 4 \times 4 \) dithering used, the \( 17'' \times 6''4 \) field of view of the integrated field unit covered \( 2''0 \times 10''9 \) with 0''1 pixel\(^{-1} \) at a position angle of 337\(^\circ \) centered on W2246–0526. The final spectral resolution of \( \sim 2.5 \) spaxels yielded \( R = \lambda/\Delta \lambda \lesssim 3400 \). Atmospheric wavefront errors were partially corrected with Laser Guild Star Adaptive Optics (LGS-AO) and an \( R = 18.3 \) tip-tilt star 26''8 to the southwest of W2246–0526. The integration time for each individual frame was 900 s, and a total of 4 hr (16 frames) of on-source data was collected.

The OSIRIS data were reduced with the OSIRIS data-reduction pipeline v4.0.0. A custom procedure was used to remove the sky emission using pixels near the science target and frames adjacent in time. About 6% of the data at wavelengths with substantial sky line residual present were clipped. The telluric correction was applied using both the G2V star HD 216516 and the A0V star HD 219833. The flux calibration was done using the G2V star. Including the uncertainties due to calibrator flux, aperture correction, and Strehl ratio, the overall uncertainty in the calibrated fluxes is estimated to be \( \sim 20\% \). The wavelength was calibrated to values in vacuum. The final mosaic data cube was produced using the LGS offsets between frames. Using the 2MASS point source catalog (Skrutskie et al. 2006) and the WFPC3 image in F160W (Díaz-Santos et al. 2016) from the Hubble Space Telescope (HST), we registered the final science data cube with the uncertainty in absolute astrometry estimated to be \( < 0''1 \).

Due to the LGS-AO, the spatial resolution was sufficient to resolve the continuum profile of W2246–0526, with an estimated extent of \( 0''36 \times 0''29 \) at PA = 155\(^\circ \), consistent with the HST observations (Díaz-Santos et al. 2016). The Mg II emission line of W2246–0526 was extracted from the OSIRIS data cube using a 0''3 aperture. An aperture correction was applied to the flux scale of the Mg II spectrum to match the photometry from the HST F160W image. The extracted and flux-corrected spectrum is shown in Figure 1.

2.2. Other Data

For comparison to the SMBH mass estimate from Mg II, we analyze an optical spectrum of the C IV line. To calculate the Eddington ratio, we estimate the luminosity using the observed spectral energy distribution (SED) of W2246–0526 from optical to submillimeter wavelengths. The flux densities and the references are listed in Table 1. These observations are described below.

2.2.1. Keck LIRIS Observation of the C IV Line

As reported in Díaz-Santos et al. (2018), an optical spectrum with one hour of exposure of W2246–0526 was obtained on UT 2013 October 5 using LIRIS (Oke et al. 1995) on the Keck I telescope, with spectral resolution \( \sim 750 \) and a 1''5 slit. Additional details of the observation are reported in Díaz-Santos et al. (2018).

2.2.2. SCUBA2 450 \( \mu \text{m} \) Observation

SCUBA2 observations with the James Clerk Maxwell telescope (JCMT), as reported by Jones et al. (2014), were obtained on UT 2012 May 23 and 26. During the 450 \( \mu \text{m} \) observations, the CSO 225 GHz sky opacity was \( \tau_{225} \approx 0.05 \), and the corresponding optical depth at 450 \( \mu \text{m} \) was \( \tau_{450/\mu \text{m}} \approx 1 \). However, the two sets of observations identify a point source with a consistent flux density (within 1\( \sigma \)), slightly offset to the southeast from the WISE infrared position of W2246–0526. The position offset (2''4 \( \pm \) 2''2) is consistent with the pointing uncertainty during the observation. The total time per source was 120 minutes using the CV DAISY mode, providing deep
coverage in the central 3′ diameter region. The final map that combines both sets of observations is shown in the left panel of Figure 2.

### 2.2.3. Herschel Observations

Herschel fluxes for W2246—0526 were reported in Tsai et al. (2015). There is a foreground spiral galaxy (SDSS J224608.38−052624.3; Csabai et al. 2003; Beck et al. 2016) at a photometric redshift of \( z = 0.047 \pm 0.024 \) to the northeast of W2246—0526, with a Petrosian diameter of 8.8′ (Figure 2). With the 12″ FWHM beam size for PACS at 160 μm, this could affect the Herschel fluxes of W2246—0526 reported in Tsai et al. (2015). For the SPIRE bands, the larger beam size (18″ to 37″) increases the possibility of flux contamination. This concern has been raised by Fan et al. (2018), who have tried to estimate the contribution of the foreground galaxy to the Herschel photometry with point-spread function (PSF) fitting and SED modeling. However, the estimated flux contamination in this work does not reconcile with the results of the Herschel/PACS Point Source Catalogue (Marton et al. 2017), in which both the foreground galaxy and W2246—0526 are detected using PSF photometry. We remeasured the 160 μm flux density of W2246—0526 by excluding emission from the extended profile of the foreground galaxy by using an irregular polygon aperture, finding \( F_{160\mu m} = 142 \) mJy, 25% less than reported in Tsai et al. (2015). All other Herschel photometry in Tsai et al. (2015) agrees with the results from the Herschel/PACS Point Source Catalogue (Marton et al. 2017) and the Herschel/SPM Point Source Catalogue (Spence et al. 2017) within 1σ, except the flux density for SPIRE at 250 μm, which is \( \approx 2\sigma \) lower than the SPSC value. For consistency, we adopt the SPSC flux at 250 μm. We note that the SPIRE maps all show a point source with a peak within the corresponding FWHM from W2246—0526. Our ground-based JCMT SCUBA2 maps at 450 μm and 850 μm, with beam sizes of 7.5′ and 15′, also show that the observed submillimeter emission is concentrated at W2246—0526 (Jones et al. 2014) with no significant emission detected around the foreground galaxy (see Figure 2, left). W2246—0526 dominates the observed far-IR and submillimeter emission over the adjacent spiral galaxy. Using the peak flux at the pixel of the foreground galaxy center, we estimate the SPIRE band photometry by summing within a 2.25″ diameter aperture.

### Table 1

| Band     | Wavelength | Flux density | References |
|----------|------------|--------------|------------|
| WFC3 F160W | 1.537 μm   | 6.1 ± 0.2 μJy | D16        |
| K band   | 2.159 μm   | 8.9 ± 2.8 μJy | A15        |
| IRAC band 1 | 3.6 μm   | 38 ± 2 μJy   | G12        |
| IRAC band 2 | 4.5 μm   | 33 ± 1 μJy   | G12        |
| WISE band 3 | 12 μm   | 2.5 ± 0.2 mJy | T15        |
| WISE band 4 | 22 μm   | 15.9 ± 1.6 mJy | T15        |
| PACS blue channel | 70 μm   | 37 ± 3 mJy   | T15        |
| PACS red channel | 160 μm  | 142 ± 16 mJy | T15        |
| SPIRE 250 μm | 250 μm  | 107 ± 8 mJy  | T15        |
| SPIRE 350 μm | 350 μm  | 81 ± 12 mJy  | T15        |
| SCUBA 2 450 μm | 450 μm  | 49 ± 12 mJy  | T15        |
| SPIRE 500 μm | 500 μm  | 44 ± 15 mJy  | T15        |
| SCUBA 2 850 μm | 850 μm  | 11 ± 2 mJy   | J14        |
| ALMA 882 μm | 882 μm  | 7.4 ± 0.4 mJy | D16        |
| ALMA 1.2 mm | 1190 μm | 4.8 ± 1.9 mJy | D18

Notes. Reference codes in the last column: A15: Assef et al. (2015); G12: Griffith et al. (2012); D16: Díaz-Santos et al. (2016); D18: Díaz-Santos et al. (2018); J14: Jones et al. (2014); T15: Tsai et al. (2015); T18: this work.

* The Herschel/PACS 160 μm and SPIRE 250 μm measurements are updated. See text for details.

b Flux within 1″ diameter aperture.

c Sum of W2246—0526 and the extended emission.

The observed bolometric luminosity of W2246—0526 is \( L_{bol} = 3.6 ± 0.3 \times 10^{44} \) L⊙, using the observed flux density measurements listed in Table 1. This estimate follows the methodology of Tsai et al. (2015) by integrating a power law interpolated between photometric data. We assume that essentially all of this luminosity comes from a quasar shrouded within a dust cocoon. Hot dust dust dominates the energy output, as indicated by the SED. Because of the high luminosity, the dust sublimation radius is \( \sim 15 \) pc for W2246—0526 (Barvainis 1987; Tsai et al. 2015), substantially larger than the radius of the broad line region (\( \sim 1.3 \) pc, based on Bentz et al. 2009). Thus the thermal dust emission cannot vary dynamically within the light-crossing rest-frame timescale of \( \sim 50 \) years, or \( \sim 280 \) years in the observed frame. This timescale is even longer for the dust emission at the longer wavelengths of theSED plateau. Therefore we do not anticipate observable variability in the bolometric luminosity of W2246—0526.

### 3. Analysis

#### 3.1. SED and Luminosity

The SED of W2246—0526 is shown in Figure 3, based on the updated photometric data listed in Table 1. Unlike optical QSOs in which a large fraction of energy escapes at UV wavelengths, most of the energy from W2246—0526 is seen at rest-frame infrared wavelengths (>1 μm). The broad Mg II and C IV emission lines observed in W2246—0526 provide direct evidence for the presence of an AGN, and the infrared emission most plausibly arises from hot dust obscuring the AGN. The rest-frame UV and optical continuum emission, which is assumed to be primarily from the host galaxy of the obscured AGN, contributes <1% of the total luminosity. Like other Hot DOGs, the infrared SED of W2246—0526 shows this plateau but, interestingly, also shows a dip with respect to other Hot DOGs at rest-frame \( \sim 12.5 \) μm (70 μm in the observed frame). This prompts us to suggest that silicate absorption may be affecting the SED.

At \( z = 4.601 \), the broad 9.7 μm silicate absorption feature overlaps with the 60–85 μm bandpass of the PACS 70 μm filter and can account for the dip in the SED if the strength of the absorption in W2246—0526 is comparable to that in the heavily enshrouded nucleus of NGC 4418 (Roche et al. 1986; Spoon et al. 2001), the ultraluminous infrared galaxy Arp 220 (Polletta et al. 2007), or the hyperluminous infrared galaxy IRAS 08572+3915 (Spoon et al. 2007; Vega et al. 2008; Efstathiou et al. 2014). In Figure 3, we plot a template of the silicate absorption in NGC 4418 scaled to match the observed 70 μm photometry (for clarity we omit showing the relatively weak 9.66 μm H2 0–0 S(3) emission line).
3.2. Mg II Emission Line Width

The observed Mg II 2799 Å emission line and the line model are shown in Figure 1, which covers the spectrum at rest-frame wavelengths between 2630 Å and 3220 Å. The signal-to-noise ratio of the continuum and the Mg II line (within FWHM from the line center) are 1.4 and 7.7 per spectral element (0.8 Å, rest), respectively.

The Mg II doublet line profile was fit after modeling the blended Fe II line complex and a power-law continuum. The profile of the Fe II complex used templates from Tsuzuki et al. (2006). Least-squares model fitting was done using the Levenberg–Marquardt algorithm as implemented in IDL MPFIT (Markwardt 2009). Excluding the Mg II region, we stepped through a grid of Fe II widths with FWHM = 0 to 18,000 km s\(^{-1}\) and a 600 km s\(^{-1}\) step size, finding the best-fit continuum (given in the Figure 1 caption) and Fe II model strength. We then fit the residual with a single Gaussian model for the Mg II line, iterating up to 20 times until the parameters stay unchanged to floating-point precision.

Although the signal-to-noise ratios are not high, they do not significantly affect the reliability for the line profile measurements, because of the broad line width. The best-fit model yields a Gaussian with an FWHM of 3300 ± 600 km s\(^{-1}\) and a blueshifted velocity offset of \(\Delta v = 1600 ± 300\) km s\(^{-1}\) with respect to the [C II] redshift (Díaz-Santos et al. 2016).

3.3. C IV Emission Line Width

At \(z = 4.601\), the C IV line shifts to \(~8674\) Å. As noted in Díaz-Santos et al. (2018), the C IV line in W2246–0526 is highly asymmetric, broad, and significantly blueshifted relative to this ALMA-derived [C II] redshift. Following an approach similar to that used by Shen et al. (2008, 2011) and Jun et al. (2017), we model the C IV line of W2246–0526 with two components, as shown in Figure 4. The signal-to-noise ratios of the continuum and the C IV line are 4.2 and 13.4 per spectral element (2.1 Å, rest), respectively.

As we did for Mg II, we first solved for a power-law continuum (given in the Figure 4 caption) and the Fe II line complex (using the template from Vestergaard & Wilkes 2001), as well as the He II–1640 Å line. The strength of the Fe II complex was matched to that of the Fe II around the Mg II region using overlapping wavelengths in the templates, and the Fe II line widths were set to be identical for the Mg II and C IV regions.

The narrower Gaussian component has an FWHM = 1600 ± 140 km s\(^{-1}\), blueshifted by 3000 ± 80 km s\(^{-1}\) with respect to the system redshift, while the broader component has FWHM = 9000 ± 140 km s\(^{-1}\) and is blueshifted by 3420 ± 70 km s\(^{-1}\). The composite double-Gaussian profile has FWHM = 5900 ± 100 km s\(^{-1}\) and a blueshift of 3300 ± 70 km s\(^{-1}\). This blueshift of the C IV line profile in W2246–0526 is significantly higher than the median blueshift observed in SDSS QSOs (median of 890 km s\(^{-1}\) for 492 quasars at 4.5 < \(z\) < 4.7; Shen et al. 2011) and is more comparable to the median blueshift of 2520 km s\(^{-1}\) for nine quasars at \(z \geq 6.4\) that have C IV emission line measurements (Mazzucchelli et al. 2017).

4. Results and Discussion

4.1. Mg II-based SMBH Mass

Masses of the SMBH in AGNs are usually determined from the measurements of broad emission lines, assuming virialized gas motion. This approach was established via variability monitoring (reverberation mapping; see, e.g., Peterson 1993) and subsequently calibrated to single-epoch measurements of the H\(\beta\) line width and 5100 Å continuum (e.g., Wandel et al. 1999; Kaspi et al. 2000; Vestergaard 2002) and extended to other line widths. For objects at \(z > 1\), the H\(\beta\) line is redshifted into the infrared, stimulating the use of the broad Mg II line...
from optical spectroscopy for SMBH mass determination (McLure & Jarvis 2002; Onken & Kollmeier 2008; Trakhtenbrot & Netzer 2012; Marziani et al. 2013). Advances in near-IR instrumentation have made near-IR spectroscopy of distant objects feasible, enabling the Balmer lines to be used for SMBH measurement at $z \sim 2.5$–3.5 (e.g., Wu et al. 2018). At $z > 3.5$, the Mg II line is also observed at >1 μm, and Mg II is usually used for black hole mass ($M_{\text{BH}}$) measurements of objects at the highest redshifts (Wu et al. 2015; Bahados et al. 2018). The calibration of Mg II-determined SMBH masses with respect to those from Hβ has been established (McLure & Dunlop 2004; Wang et al. 2009; Shen et al. 2011; Jun et al. 2015; Suh et al. 2015). In this paper, we adopt the Mg II-based SMBH mass formulation from Equation (10) of Wang et al. (2009):

$$\log \left( \frac{M_{\text{BH}}}{M_\odot} \right) = (7.13 \pm 0.27) + 0.5 \log \left( \frac{L_{3000}}{10^{44} \text{ erg s}^{-1}} \right) + (1.51 \pm 0.49) \log \left( \frac{\text{FWHM}_{\text{Mg II}}}{1000 \text{ km s}^{-1}} \right),$$

where $L_{3000}$ is the monochromatic luminosity at rest-frame 3000 Å, and $\text{FWHM}_{\text{Mg II}}$ is the FWHM of the Mg II line profile (given in Section 3.2).

Because of the high extinction in W2246−0526, estimates of $L_{3000}$ from the rest-UV continuum are uncertain. Instead, we use $L_{3000} \sim 0.19 \times L_{\text{bol}}$ based on the empirical unobscured AGN SED model of Richards et al. (2006). For $L_{\text{bol}} = 3.6 \times 10^{44} L_\odot$, $L_{3000} = 2.6 \times 10^{47} \text{ erg s}^{-1}$. The observed rest-frame 3000 Å continuum flux in W2246−0526 is only about 0.02 of the anticipated value from this template. With the Mg II FWHM of $3300 \pm 600 \text{ km s}^{-1}$, this yields $\log(M_{\text{BH}}/M_\odot) = 9.6 \pm 0.4$. The error range includes the 1σ systematic uncertainties from Equation (1) and from the Mg II profile fitting. The statistical uncertainty of $M_{\text{BH}}$ due to the Mg II line width uncertainty is 0.05 dex.

The Richards et al. (2006) SED model assumes the emission from a quasar is isotropic. However, the unobscured quasars used to construct the SED presumably have a surrounding dusty torus with a low inclination and a covering factor that intercepts and reprocesses some of the quasar emission so that it appears again in the IR. Thus the $L_{\text{bol}}$ from the SED model would be overestimated by $(1 + CF_u)$, where $CF_u$ is the covering factor for the unobscured quasars used in Richards et al. (2006), and $L_{3000}$ would represent a larger portion of the true $L_{\text{bol}}$. For W2246−0526, which has a well-determined $L_{\text{bol}}$, this suggests using a ratio of $L_{3000}/L_{\text{bol}}$, which is $(1 + CF_u)$ larger. The covering factor cannot be higher than 1 (especially for an unobscured quasar sample), so using Equation (1), this correction would increase $\log(M_{\text{BH}}/M_\odot)$ by <0.15. Both of these terms are smaller than other estimates of the overall systematic uncertainty, which are up to 0.3 dex (Denney et al. 2009; Wang et al. 2009; Jun et al. 2015).

### 4.2. C IV-based $M_{\text{BH}}$ Estimate

The C IV line profiles of AGNs often show an enhanced blue wing, significantly different from their Hβ line profiles. This highlights the issue of the virial assumption for C IV and results in a large and biased offset when comparing C IV-based $M_{\text{BH}}$ estimates to those based on Hβ and Mg II (Netzer et al. 2007; Shen et al. 2011). In addition, the broad C IV 1549 Å feature is often substantially blueshifted with respect to the system rest frame (e.g., Richards et al. 2002), especially for high-luminosity objects (Baskin & Laor 2005). The blueshift is usually attributed to the wind component of the broad line region, or outflow (Gaskell 1982; Murray & Chiang 1997; Leighly 2004). Nevertheless, because of the accessibility of the C IV line from the ground for the quasars over a large range of redshift ($1.3 \lesssim z \lesssim 5$), efforts have been made to calibrate...
Velocities are shown with respect to the independent Gaussian $\mathrm{C\ IV\ 1488,\ 1551\ Å}$ emission line profiles (orange and magenta dashed lines), the He $\mathrm{II\ 1640\ Å}$ line (orange solid line), the Fe $\mathrm{II\ line\ complex}$ (brown solid line), and a power-law continuum ($F_I [10^{-19} \text{ erg s}^{-1} \text{ cm}^{-2} \text{ Å}^{-1}] = 38.00 \times (\lambda/1350 \text{ Å})^{-1.784}$; cyan solid line). Velocities are shown with respect to the [C II] redshift of $z = 4.601$. The middle panel shows the composite of the two Gaussian models (FWHM $= 9000 \pm 100$ km s$^{-1}$, blueshifted by $3300 \pm 70$ km s$^{-1}$) overlaid on the observed spectrum after subtracting the other model components. The residual spectrum is presented in the lower panel.

$\mathrm{C\ IV-based\ } M_{\mathrm{BH}}$ estimates to $\mathrm{H}\beta$-based values in Type 1 AGNs (Vestergaard & Peterson 2006; Assef et al. 2011; Shen et al. 2011; Denney 2012; Denney et al. 2013; Runnoe et al. 2013; Park et al. 2017), although $\mathrm{C\ IV}$ is not considered as reliable as $\mathrm{Mg\ II}$ (Fine et al. 2010; Jun et al. 2015; Mejia-Restrepo et al. 2016). Motivated by the significance of the $\mathrm{C\ IV}$ asymmetry in a principal component analysis of AGNs (Sulentic et al. 2007), a simple correction to the $\mathrm{C\ IV-based\ } M_{\mathrm{BH}}$ estimate has recently been suggested (Brotherton et al. 2015; Coatman et al. 2016, 2017; Jun et al. 2017). This correction calibrates the FWHM of the $\mathrm{C\ IV}$ line to the expected virial $\mathrm{C\ IV}$ FWHM from the Balmer line widths using the $\mathrm{C\ IV}$ blueshift.

As noted in Section 3.3, the $\mathrm{C\ IV}$ line in W2246–0526 is highly asymmetric, broad, and significantly blueshifted relative to the [C II] redshift. Using the composite Gaussian model and adopting the correction of Coatman et al. (2017),

$$F_{\mathrm{FWHM}} = \frac{F_{\mathrm{FWHM Measured}}} {0.36 \pm 0.03\times (\lambda_{\mathrm{FWHM}} \text{ [km s}^{-1}]) + (0.61 \pm 0.04),}$$

(2)

we obtain a corrected FWHM for the broad $\mathrm{C\ IV}$ component of $F_{\mathrm{FWHM}} = 3300 \pm 400$ km s$^{-1}$, which is a factor of 1.8 smaller than the FWHM derived from our two-component analysis.

To estimate the black hole mass, we adopt the methodology of Coatman et al. (2017):

$$\log\left(\frac{M_{\mathrm{BH}}}{M_\odot}\right) = 6.71 + 2 \log\left(\frac{\mathrm{FWHM}_{\mathrm{C\ IV\ Corr}}}{10^{-4} \text{ km s}^{-1}}\right) + 0.53 \log\left(\frac{L_{1350}}{10^{44} \text{ erg s}^{-1}}\right).$$

Here, $L_{1350}$ is the monochromatic luminosity at 1350 Å and is estimated to be $L_{1350} \sim 0.26 \times L_{bol} = 3.6 \times 10^{47}$ erg s$^{-1}$ using the AGN template of Richards et al. (2006).

Using the corrected value for the broad $\mathrm{C\ IV}$ component, this yields $\log(M_{\mathrm{BH}}/M_\odot) = 9.6 \pm 0.4$ including systematic uncertainty, which is nearly identical to the $M_{\mathrm{BH}}$ estimated using the Mg II line. The agreement of the $M_{\mathrm{BH}}$ estimate using the $\mathrm{C\ IV}$ profile with that from the Mg II line measurement may be coincidental. It has been argued that a large component of the broad $\mathrm{C\ IV}$ emission line is observed to not reverberate for nearby AGNs, based on reverberation mapping studies (e.g., Denney 2012).

4.3. $M_{\mathrm{BH}}-M_{\mathrm{sph}}$ Relation

From a sample of five Hot DOGs with $M_{\mathrm{BH}}$ measurements, Wu et al. (2018) found that the ratio of $M_{\mathrm{BH}}$ to the stellar mass in the spheroidal component of the host galaxy ($M_{\mathrm{BH}}/M_{\mathrm{sph}}$) in these systems is closer to the $M_{\mathrm{BH}}-M_{\mathrm{sph}}$ relation seen in local active galaxies (Bennert et al. 2011) than are the ratios seen in $z \sim 1.3$ quasars.

We estimate the bulge mass in W2246–0526 from $K$ and 4.5 μm photometry using the synthesized elliptical galaxy SED template from the GRASIL code (Silva et al. 1998) to represent the spheroidal component, omitting the 3.6 μm data point, which may be significantly elevated by the Hα emission line (see Figure 3). In Figure 3, the brown solid line shows the SED of an elliptical galaxy at an age of 1.3 Gyr with $M_{\mathrm{sph}} = 1.1 \times 10^{12} M_\odot$. This can be considered as an upper limit of the bulge mass of W2246–0526. This value is similar to the $\log(M_{\mathrm{sph}}/M_\odot) = 11.9$ value expected from the local $M_{\mathrm{BH}}-M_{\mathrm{sph}}$ relation (Bennert et al. 2011):

$$\log\left(\frac{M_{\mathrm{BH}}}{M_\odot}\right) = -3.34 \pm 1.91 + (1.09 \pm 0.18) \times \log\left(\frac{M_{\mathrm{sph}}}{M_\odot}\right).$$

This suggests that W2246–0526 has an $M_{\mathrm{BH}}-M_{\mathrm{sph}}$ relation similar to that of the Hot DOGs shown in Figure 9 of Wu et al. (2018).

4.4. Eddington Ratio and Black Hole Accretion

In Wu et al. (2018), we argue that Hot DOGs are on the high-luminosity tail for a given $M_{\mathrm{BH}}$ with respect to SDSS QSOs because they achieve the highest accretion rates, implying that they are accreting material at the highest rates possible. To illustrate this, in Figure 5, we plot Eddington ratio ($\lambda_{\mathrm{Edd}} = L_{\mathrm{AGN}}/L_{\mathrm{Edd}}$) versus $M_{\mathrm{BH}}$. With $\log(M_{\mathrm{BH}}/M_\odot) = 9.6 \pm 0.4$ and $\log(L_{\mathrm{bol}}/L_\odot) = 14.6$, the Eddington ratio of W2246–0526 is $\lambda_{\mathrm{Edd}} = 2.8^{+0.7}_{-0.9}$ (statistical uncertainty), the highest of all the Hot DOGs for which we have so far obtained $M_{\mathrm{BH}}$ measurements (Wu et al. 2018) and putting the SMBH of W2246–0526 well into the super-Eddington accretion region.
The total uncertainty for the \( \lambda_{\text{Edd}} \) as shown by the dotted error bars in Figure 5 for W2246–0526, is 0.4 dex, dominated by the systematic uncertainty of \( M_{\text{BH}} \). This systematic uncertainty also applies to all objects at \( z > 4 \) in Figure 5.

Eddington ratios this large may attain a saturation level suggested by theoretical models (Wang & Zhou 1999; Watarai et al. 2000; Mineshige et al. 2000). At high accretion rates, radiation pressure may dominate the accretion flow geometry, making the accretion disk “slim” (Abramowicz et al. 1988). In these models, the fast radial transportation of mass in the accretion flow geometry can trap most photons, preventing them from escaping, and carrying them inward to the SMBH. This photon-trapping accretion makes the radiation efficiency inversely proportional to the mass accretion rate. As a result, the luminosity of a super-Eddington accreting black hole may reach saturation at an apparent Eddington ratio of \( \lambda_{\text{Edd}} \sim 2 \). The bolometric luminosity will increase much more slowly than the accretion rate, and the \( M_{\text{BH}} \) can increase much faster than the growth rate under the Eddington limit. In this scenario, the actual accretion rate of W2246–0526 may be higher than the observed \( \lambda_{\text{Edd}} \) suggests.

Although they have similarly high luminosities, as shown in Figure 5, the \( \lambda_{\text{Edd}} \) of W2246–0526 may have reached saturation while the QSO J0100+2802 has not. The difference in the \( \lambda_{\text{Edd}} \) of the sources is significant, considering only the statistical uncertainties from the measurements, but may not be when including systematic uncertainties in the \( M_{\text{BH}} \) estimate. We speculate that the difference between the sources, if real, is due to the much higher obscuration (and thus more material to accrete) in W2246–0526 or due to a different accreting geometry such as mass inflow from merging events. In this context, it is intriguing to note that recent ALMA observations of W2246–0526 of dust continuum emission at rest 212 \( \mu \)m reveal bridges of dusty, metal-enriched material connecting three companions to the central galaxy (Díaz-Santos et al. 2018), implying that a multiple merger is in progress. Díaz-Santos et al. (2018) estimate that accretion rates of as high as \( M \sim 900 M_\odot \) yr\(^{-1} \) onto the central core of W2246–0526 could be underway, sufficient to power the high luminosity of W2246–0526, which has a BH accretion rate of \( 24 M_\odot \) yr\(^{-1} \) if a radiation efficiency of 0.1 is assumed.

5. Conclusion

We report observations of broad Mg II and C IV lines in the \( z = 4.601 \) source W2246–0526, the most luminous galaxy known, providing clear evidence for the presence of an AGN in the system. The FWHM of Mg II is 3300 km s\(^{-1} \). Using the well-determined bolometric luminosity and an AGN template to estimate the 3000 \( \AA \) continuum luminosity, we measure the black hole mass log(\( M_{\text{BH}}/M_\odot \)) = 9.6 ± 0.4. The broad (5900 km s\(^{-1} \)) C IV line is significantly blueshifted (by 3300 km s\(^{-1} \)), and we
estimate the corresponding $M_{\text{BH}}$ for this line using an empirically calibrated correction for the FWHM based on the blueshift. This method yields $\log(M_{\text{BH}}/M_{\odot}) = 9.6 \pm 0.4$, in good agreement with the Mg II estimate.

We reevaluate the bolometric luminosity of W2246−0526 considering the possible contribution of a nearby foreground galaxy. SCUBA2 450 $\mu$m observations show that W2246−0526 dominates the far-IR flux. Using an ALMA 252 GHz continuum map, we estimate the contribution from the foreground galaxy is <10%. The updated estimate of $L_{\text{bol}}$ based on power-law interpolation of the well-sampled SED, is $3.6 \times 10^{14} L_{\odot}$. The SED shows a dip near rest 10 $\mu$m that is suggestive of silicate absorption.

The Eddington ratio in W2246−0526 is 2.8. Theoretical arguments suggest the luminosity may be saturating in this super-Eddington regime and may be insensitive to the mass accretion rate. In this scenario, the $M_{\text{BH}}$ growth rate may hence exceed the apparent accretion rate derived from the observed luminosity.

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