Keck/OSIRIS IFU Detection of a z ~ 3 Damped Lyα Host Galaxy*

Holly M. Christenson¹²³ and Regina A. Jorgenson³

¹ University of California, Riverside, 900 University Avenue, Riverside, CA 92521, USA; holly.christenson@email.ucr.edu
² Western Washington University, 516 High Street, Bellingham, WA 98225, USA
³ Maria Mitchell Observatory, 4 Vestal Street, Nantucket, MA 02554, USA; rjorgenson@mariammitchell.org

Received 2018 October 30; revised 2019 July 18; accepted 2019 July 22; published 2019 September 17

Abstract

We present Keck/OSIRIS infrared IFU observations of the z = 3.153 sub-DLA DLA2233+131, previously detected in absorption to a background quasar and studied with single-slit spectroscopy and Potsdam Multi Aperture Spectrophotometer integral field spectroscopy (IFU). We used the Laser Guide Star Adaptive Optics and OSIRIS IFU to reduce the point-spread function of the background quasar to FWHM ~ 0.15′ and marginally resolve extended, foreground DLA emission. We detect [O iii]λ5007 emission with a flux \( F_{\text{O iii}}^{\lambda5007} = (2.4 \pm 0.5) \times 10^{-17} \text{erg s}^{-1} \text{cm}^{-2} \), as well as unresolved [O iii]λ4959 and H/βλ4861 emission. Using a composite spectrum over the emission region, we measure dynamical mass \( M_\text{dyn} \approx 3.1 \times 10^9 M_\odot \). We made several estimates of star formation rate (SFR) using [O iii]λ5007 and H/βλ4861 emission, and measured a SFR of \( \sim 7.1 \pm 13.6 \dot{M}_\odot \text{yr}^{-1} \). We map [O iii]λ5007 and H/βλ4861 emission and the corresponding velocity fields to search for signs of kinematic structure. These maps allow for a more detailed kinematic analysis than previously possible for this galaxy. While some regions show slightly red and blueshifted emission indicative of potential edge-on disk rotation, the data are insufficient to support this interpretation.

Key words: galaxies: evolution – intergalactic medium – quasars: absorption lines – quasars: individual (HB89 2233+131)

1. Introduction

Studying galaxies at high redshift has always been challenging, given the great distances and natural dimming of galaxies’ light. While some galaxies have now been detected in emission at extremely high redshifts (for example, Genzel et al. 2006), these studies can only probe the highest luminosity, most rapidly star-forming galaxies. These galaxies are likely not representative of the galaxy population as a whole; the bulk of the galaxy population is forming stars at a much more modest rate, and thus cannot be probed directly by extremely high-redshift studies.

To have a complete picture of galaxy formation and evolution, a more representative sample of the galaxy population is needed. Damped Lyα systems (DLAs) are an ideal candidate for probing the typical galaxy population. DLAs contain the bulk of neutral hydrogen in the universe, the raw material for star formation, and are thought to be the progenitors of modern spiral galaxies (Wolfe et al. 2005). DLAs are defined by their column density in neutral hydrogen, and are detected in absorption to background light sources, typically quasars. The first large survey of DLAs was completed by Wolfe et al. (1986) and since then, thousands have been studied in absorption (see Blanton et al. 2017 for an overview). Absorption studies provide detailed information about redshift, neutral hydrogen column density, and metalliclicity. However, nearly all absorption-line studies are inherently limited in scope because they probe only a single line of sight through a given galaxy.

In an effort to remediate the problems inherent with absorption-line-only studies, practitioners have been trying to detect DLA lines directly in emission for many years. This is a tremendously difficult task, given the difficulty of detecting relatively faint foreground emission toward a much brighter background quasar (i.e., Lowenthal et al. 1995; Bunker et al. 1999; Kulkarni et al. 2000, 2006; Christensen et al. 2009). To date, only \( z > 2 \) DLAs have been detected in emission (see Krogager et al. 2017 for a summary). Most of these targets were detected in single-slit observations, requiring fortuitous slit placement and providing limited information on the total fluxes, star formation rates (SFRs), and kinematics of the emission.

Technological advances made in the past two decades, in form of Integral Field Units (IFUs) on 10 m class telescopes assisted by laser guide star adaptive optics (LGSAO) systems, are now enabling the direct detection of these elusive galaxies. While progress is slow, given the relatively small fluxes and correspondingly long exposures required (see, for example, Jørgenson & Wolfe 2014), this is an important task not only for gaining a complete understanding of the bulk of the high-z galaxy population, but also in preparation for similar studies that will be made possible (and more efficient) with space telescopes such as James Webb Space Telescope.

In this paper, we present observations using the Keck/OSIRIS IFU (Larkin et al. 2006) with LGSAO to target the super Lyman limit system, or sub-DLA, DLA2233+131, with \( N(\text{H}) = 1 \times 10^{20} \text{cm}^{-2} \). We note that this column density is just under the DLA threshold of \( N(\text{H}) = 2 \times 10^{20} \text{cm}^{-2} \), although DLA2233+131 is most often referred to as a DLA in the literature. We will do so here for consistency. DLA2233+131 is a well studied system, first discovered by Sargent et al. (1989), who reported the DLA redshift of \( z = 3.153 \). DLA2233+131 was first detected in emission by Steidel et al. (1995) who performed deep broadband imaging of a sample of Lyman limit systems to search for the counterparts of known Lyman Limit systems. Steidel et al. (1995) report the
detection of R band stellar continuum from a system located 2"/9 from the background quasar Q2233+131. Several more reports of emission followed, including Djorgovski et al. (1996), who report the detection of DLA2233+131 in both stellar continuum and in Ly$\alpha$ line emission located 2"/8 away from the background quasar at PA = 159$^\circ$ from the quasar line of sight.

Warren et al. (2001) and Møller et al. (2002) report Hubble Space Telescope (HST)/NICMOS imaging of DLA2233+131 with magnitude $H_{AB} = 25.05$ located 2"/78 away from the background quasar at PA = 158.6$^\circ$.

Finally, Christensen et al. (2004) used the Potsdam Multi Aperture Spectrophotometer (PMAS) to measure extended Ly$\alpha$ flux of DLA2233+131, with a total flux of $(2.8 \pm 0.3) \times 10^{-16}$ erg cm$^{-2}$ s$^{-1}$ measured over an area 3 $\times$ 5$''$. Christensen et al. (2004) estimate the SFR to be $19 \pm 10$ M$_{\odot}$ yr$^{-1}$, and conjecture that the extended flux may be powered by a star formation fueled outflow from the DLA galaxy. Christensen et al. (2007) perform higher spectral resolution PMAS observations resulting in Ly$\alpha$ flux of $(9.6 \pm 2.5) \times 10^{-16}$ erg cm$^{-2}$ s$^{-1}$, consistent with the previous Djorgovski et al. (1996) measurement (see Table 3 for a summary of previous work).

In this work, we map the flux and velocity field of [O III] and H$\beta$ emission from DLA2233+131 to look for kinematic signatures that may help reveal the underlying nature of the galaxy. The paper is organized as follows. We describe the observations and data reduction process in Section 2. In Section 3 we discuss the details of the analysis of the final spectral cube. We place these results in a larger context in Section 4, before summarizing in Section 5. Throughout the paper, we assume a standard lambda cold dark matter ($\Lambda$CDM) cosmology based on the final nine-year WMAP results (Hinshaw et al. 2013) in which $H_0 = 70.0$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_m = 0.279$ and $\Omega_\Lambda = 0.721$.

2. Observations

Observations were made with the Keck/OSIRIS (Larkin et al. 2006) infrared integral field spectrograph and the Keck I LGSAO system on 2014 July 18, using the broadband KB filter that covers 1965–2381 nm. This wavelength range covers the redshifted wavelengths of [O III] and H$\beta$ emission from DLA2233+131 at $z \sim 3.15$. Unfortunately, H$\alpha$ emission is redshifted out of the observable OSIRIS wavelength range. We used the 100 mas plate scale, giving a 1.6 $\times$ 6$''$/4 field of view. The average spectral resolution for OSIRIS in this configuration is $R \sim 3000$ (100 km s$^{-1}$), with small variations from spaxel to spaxel.

We aligned the detector at a position angle of PA = 158$^\circ$.45 east of north (Weatherley et al. 2005) to detect both the quasar and the peak of DL A emission in a single exposure. To maximize on-target efficiency, we used an A-B observing pattern, shifting the quasar and DLA emission pair from the bottom half of the of field of view to the top half of the field of view for each exposure. This observing pattern allowed us to use each alternate exposure as the sky frame for the previous on-target frame. The field of view is effectively halved after sky background subtraction, but the on-source observing time is doubled, increasing the likelihood of detecting faint, extended emission. In total, we obtained 13 $\times$ 900 s exposures, for a total on-source exposure time of 3.25 hr.

We chose a star within 50$''$ with $R < 17$ to make tip tilt corrections. Observations were made in good weather, with effective seeing, after LGSAO corrections, of 0$''$.15.

2.1. Data Reduction and Flux Calibration

Observations were reduced using a combination of the Keck/OSIRIS data reduction pipeline (DRP) and a set of custom IDL routines, similar to the procedures outlined in Law et al. (2007, 2009) and Jorgenson & Wolfe (2014). The DRP was used for standard reduction and extraction of three-dimensional spectral cubes from the raw data.

We then took the following additional steps:

1. **Background sky subtraction.** We used the OSIRIS DRP background sky-subtraction routine to perform the A-B subtraction as previously described.

2. **Second pass sky subtraction.** To reduce the effects of variable skylines, we calculated the median flux value at each spectral channel and subtracted it for each spaxel. This subtraction sets the median flux value to zero for all spectral channels.

3. **Flux calibration and telluric correction.** We applied telluric corrections using the telluric standard observation taken closest in time to the science exposures. We use the 2MASS photometric magnitude of the tip tilt star to flux calibrate the data. First, we calculate the correction factor needed to reproduce the 2MASS magnitude from the observed spectrum of the tip tilt star. We then apply this correction factor to the spectra in each science frame. The uncertainty in the absolute flux calibration of LGSAO observations is estimated at $\sim$30% (see Law et al. 2009 for further discussion).

4. **Mosaicking.** We used the OSIRIS module Mosaic Frames to combine all of the science frames into a single spectral cube, using the peak emission of the quasar to align the individual frames for mosaicking. The frames were combined using the sigma-clipping average routine meanclip2. Because of the A-B observing pattern and subtraction scheme, this final spectral cube contains a positive central region with negative regions to either side. The positive central region is considered the science region, and only positive spaxels were used for the final analysis. The final spectral cube is shown in Figure 1 summed over a $\sim$5 Å wavelength regime centered on [O III] $\lambda$5007 emission. Figure 1 visually highlights the background subtraction scheme and the resulting science region.

5. **Oversampling.** As done in Law et al. (2007, 2009), we oversampled the spectral cube to increase the signal-to-noise ratio (S/N) in each spaxel, so that we may detect faint, extended emission. We spatially resampled the spectral cube to 0''/05 per pixel, and then smoothed with a Gaussian kernel with FWHM = 4 pixels. The smoothing FWHM is approximately equal to that of the quasar’s point-spread function (PSF) in the oversampled cube, 0''/15.

6. **Normalization.** We normalized the continuum in the spectral cube to zero by first choosing a broad noise region on either side of the [O III] $\lambda$5007 emission line, then finding the median continuum value in those two regions for each spaxel. The median continuum value was then subtracted from each spaxel.
7. Wavelength solution. We checked the wavelength solution using a representative summed spectrum of a background sky region of the cube to ensure that known skylines were consistent with those observed. No correction was necessary.

8. Heliocentric correction. We corrected the spectra for the heliocentric motion of the earth using the IRAF package `rvcorrect`. All wavelengths and redshifts are reported in the heliocentric vacuum frame, with redshifts being determined using the rest-frame vacuum wavelengths of the emission lines.

9. Determination of spectral resolution. We estimated the spectral resolution by measuring the FWHM of OH-skylines that are near in wavelength to the redshifted [O III] emission lines. We measured the average FWHM of skylines to be $\sim 101$ km s$^{-1}$, very close to the expected average resolution of 100 km s$^{-1}$. Reported velocity dispersions have been corrected for this instrumental FWHM by subtracting it in quadrature.

3. Analysis

In this section, we describe the analysis of the final spectral cube.

3.1. [O III] Flux and Luminosity

Given the extended nature of the [O III] $\lambda$5007 emission, we measure the total [O III] $\lambda$5007 flux in two ways. First, we create a composite spectrum that maximizes the S/N of the detected emission. This composite spectrum, shown in Figure 2, was created by summing the spaxels over a circle of radius 0.5 centered on the peak of [O III] $\lambda$5007 emission, omitting faint and extended emission. From this “S/N-maximizing” spectrum, we report best-fit redshift, line width, and S/N, using a best-fit Gaussian and report the results in Table 1. The uncertainties are calculated by performing a Monte Carlo analysis, in which we perturb the original spectrum using values drawn from a uniform distribution based on the measured noise, and then recalculate the Gaussian fit. We repeat this procedure 10,000 times and consider the standard deviation of the resulting line centroids and line widths to be the uncertainty in the measurements. The noise is taken to be the standard deviation of the residual, after subtracting the Gaussian fit, at $\pm 1\sigma$ around the wavelength of peak emission (region shown in green in Figure 2).

Second, we create a composite spectrum that includes all of the detectable, faint, extended emission to report the maximum total detected flux (albeit with a lower S/N due to the inclusion of increasingly noisy, faint emission regions). This spectrum, summed over a 1.2 $\times$ 0.8 region, includes all observed...
emission while carefully excluding the negative of the quasar emission. We use this second, “flux-maximizing” composite spectrum to report the total detected [O III]λ5007 flux, \(P_{\text{[O III]}}\lambda 5007 = (2.4 \pm 0.5) \times 10^{-17} \text{ erg s}^{-1} \text{ cm}^{-2}\), which corresponds to luminosity \(L_{\text{[O III]}}\lambda 5007 = (2.2 \pm 0.5) \times 10^{42}\).

Finally, we measure an upper limit on the flux of unresolved [O III]λ4959, by fixing the redshift and line width to that of [O III]λ5007. We report this upper limit in Table 2, but note that because the [O III]λ4959 line falls near a strong atmospheric OH emission feature, residuals have increased the noise in this spectral region. Given the canonical ratio of [O III]λ5007/[O III]λ4959 \(\sim 3\), we expect [O III]λ4959 flux \(\sim 8.0 \times 10^{-18}\) erg s\(^{-1}\) cm\(^{-2}\), consistent with the measured limit.

### 3.2. Hβλ4861 Flux and Luminosity

We follow the same procedure for Hβλ4861 as for the [O III] lines, creating a “S/N-maximizing” composite spectrum by summing over a 0.3 x 0.7 square, centered on the same approximate location as the peak of the [O III]λ5007 emission. The resultant spectrum is shown in Figure 3. Based on a Gaussian fit to the emission line in this composite spectrum, we report a best-fit redshift \(z = 3.1518 \pm 0.01\) and measure S/N = 3.1.

We use a flux-maximizing spectrum summed over a 1.0 x 0.775 rectangle to measure the flux of Hβλ4861 emission. We measure \(P_{\text{Hβλ4861}} = (6.8 \pm 3.6) \times 10^{-18}\) erg s\(^{-1}\) cm\(^{-2}\), which corresponds to \(L_{\text{Hβλ4861}} = (6.2 \pm 3.2) \times 10^{41}\) erg s\(^{-1}\) (not corrected for dust). Adopted line diagnostics and flux measurements of Hβλ4861 emission are summarized in Tables 1 and 2, respectively.

### 3.3. SFR Estimation

The SFR is typically estimated using Hα emission, as in the Kennicutt (1998) calibration that relates \(L_{\text{Hα}}\) to SFR:

\[
\text{SFR}(M_\odot \text{ yr}^{-1}) = 7.9 \times 10^{-42} \times L_{\text{Hα}} \text{ (erg s}^{-1}) \tag{1}
\]

Unfortunately, for DLAs+131 the Hα emission is redshifted out of the Keck/OSIRIS filter range. Therefore, we estimate the SFR using [O III] or Hβ emission. There are three ways that we can estimate the SFR:

1. Adopt the standard Balmer ratio, Hα/Hβ = 2.8, to convert \(L_{\text{Hβ}}\) to \(L_{\text{Hα}}\), and then proceed with the Kennicutt (1998) relation. With this method, we find a SFR of \(13.6 \pm 7.1 M_\odot \text{ yr}^{-1}\).

2. Follow the method outlined in Suzuki et al. (2015) and assume that [O III]/Hα \(\sim 2.4\) (the maximum value for local star-forming galaxies), then proceed with the Kennicutt (1998) relation to estimate a lower limit SFR. With this method, we find that the lower limit of the SFR is \(\sim 7.1 \pm 1.6 M_\odot \text{ yr}^{-1}\).

3. Follow the method outlined in Weatherley et al. (2005) and assume that [O III]/Hα \(\sim 1.67\) for DLAs+131, then proceed with the Kennicutt (1998) relation. With this method, we find a SFR of \(\sim 10.3 \pm 2.5 M_\odot \text{ yr}^{-1}\).

Each of these methods comes with their own set of assumptions and large inherent uncertainties. However, we note that the three methods provide estimates that agree within errors (except the Suzuki et al. 2015 method, which is a lower limit). There is no clear argument for which method is the most accurate. Kennicutt (1992) found a large scatter between \(L_{\text{Hα}}\) and \(L_{\text{[O III]}}\) for a sample of nearby galaxies, and recommended against using [O III] emission as an indicator of SFR at all for this reason. On the other hand, Weatherley et al. (2005) suggest that differences in metallicity and ionization parameter within the sample of galaxies could account for this scatter. Furthermore, Weatherley et al. (2005) calculate [O III]/Hα as a function of these parameters using relations from Kewley & Dopita (2002), and then estimate [O III]/Hα for DLAs+131 by using its known metallicity and assuming ionization parameters similar to Lyman break galaxies. We have estimated the SFR of DLAs+131 with each of these methods and present a comparison to other measurements in Section 4.

We note that the ratio of Hα/Hβ, used in the first method of calculating a SFR, is sensitive to dust extinction. However, as DLAs are relatively low-metallicity systems, with typical

### Table 1

Line Diagnostics of DLAs+131

| Quantity      | Units       | Measured          |
|---------------|-------------|-------------------|
| \(z_{\text{[O III]}}\lambda 5007\) & … & 3.14927          |
| \(\Delta v_{\text{[O III]}}\lambda 5007\) & [km s\(^{-1}\)] & 110               |
| \(\text{FWHM}_{\text{[O III]}}\lambda 5007\) & [km s\(^{-1}\)] & 141 ± 1          |
| \(\text{FWHM}_{\text{Hβ}}\lambda 5007\) & [km s\(^{-1}\)] & 99 ± 1.6         |

**Notes.**

\(^{a}\) The [O III]λ4959 line is taken to have the same redshift and FWHM as the [O III]λ5007 line.

\(^{b}\) Velocity difference between \(z_{\text{Hβ}}\) and the given transition.

\(^{c}\) Effects of instrumental smoothing taken out in quadrature.

\(^{d}\) Hβ emission is unresolved after instrumental smoothing.

### Table 2

Summary of Results for DLAs+131

| Quantity      | Units       | Measured          |
|---------------|-------------|-------------------|
| \(P_{\text{[O III]}}\lambda 5007\) & [erg s\(^{-1}\) cm\(^{-2}\)] & \((2.4 \pm 0.5) \times 10^{-17}\) |
| \(L_{\text{[O III]}}\lambda 5007\) & [erg s\(^{-1}\)] & \((2.2 \pm 0.5) \times 10^{42}\) |
| \(\text{SFR}_{\text{[O III]}}\lambda 5007\) & \([M_\odot \text{ yr}^{-1}]\) & 10.3 ± 2.5         |
| \(P_{\text{[O III]}}\lambda 4959\) & [erg s\(^{-1}\) cm\(^{-2}\)] & \((2.0 \pm 7.5) \times 10^{-18}\) |
| \(L_{\text{[O III]}}\lambda 4959\) & [erg s\(^{-1}\)] & \((1.8 \pm 6.8) \times 10^{41}\) |
| \(P_{\text{Hβ}}\lambda 3861\) & [erg s\(^{-1}\) cm\(^{-2}\)] & \((6.8 \pm 3.6) \times 10^{-18}\) |
| \(L_{\text{Hβ}}\lambda 3861\) & [erg s\(^{-1}\)] & \((6.2 \pm 3.2) \times 10^{41}\) |
| \(\text{SFR}_{\text{Hβ}}\lambda 3861\) & \([M_\odot \text{ yr}^{-1}]\) & 13.6 \pm 7.1       |
| \(M_{\text{dyn}}\) & \([M_\odot]\) & \(3.1 \times 10^9\) |
| \(M_{\text{gas}}\) & \([M_\odot]\) & \((3.8 \pm 0.0) \times 10^9\) |
| \(f_{\text{gas}}\) & \(\sim 60\%\) &               |

**Notes.**

\(^{a}\) 1σ uncertainties are determined after subtraction of the Gaussian model.

\(^{b}\) \(\text{SFR}_{\text{[O III]}}\) calculated by assuming Hα/[O III]λ5007 \(\sim 0.6\) (Weatherley et al. 2005) and then using the empirical relationship between L(Hα) and SFR in Kennicutt (1998).

\(^{c}\) \(\text{SFR}_{\text{Hβ}}\) calculated by assuming a standard Balmer ratio and then using the empirical relationship between L(Hα) and SFR in Kennicutt (1998).
metallicities $\sim 1/30$th solar (Rafelski et al. 2012), they are generally considered to be unaffected by dust. Furthermore, Rafelski et al. (2012) found that the $[\alpha/Fe]$ ratio of DLAs is relatively constant at low metallicity, noting the absence of expected effects from dust depletion in their sample. While DLA2233+131 has a metallicity of $\sim 1/10$th solar (see Section 4.1), and is therefore more metal-rich than the typical DLA, it is still relatively metal-poor with respect to solar, and therefore we consider the assumption $H\alpha/H\beta = 2.8$ to be reasonable.

3.4. Spatial Mapping of Intensity, Velocity, Velocity Dispersion, and S/N

To map the emission and search for kinematic signatures, we fit a Gaussian to the expected location of emission in each individual spaxel in the science region of the data cube and compared the chi-squared result to that of a fit with no emission line. We require a minimum of $1\sigma$ for detection. Additionally, we perform a visual inspection of the spectrum in each spaxel, and reject spaxels where the spectrum appears to be dominated by noise features or spikes, or where the emission features are not well fit by a Gaussian. If no line is detected or any quality check is failed, we do not report a detection and the spaxel is black in the emission maps. All spaxels where we find a credible detection are displayed in Figures 4 and 5.

For spaxels where emission is detected, we calculate a best-fit flux, velocity (relative to the best-fit redshift determined from the composite spectrum of the emission region), velocity dispersion, and S/N. Velocity dispersion values have been corrected for the instrumental resolution by subtracting instrumental FWHM in quadrature. In this way, we generated two-dimensional maps of the $[O \text{ III}]$ λ5007 and $H\beta$λ4861 emission, which we present in Figures 4 and 5. These figures show an intensity map (top left), velocity map (bottom left), velocity dispersion map (bottom right), and S/N (top right) in $[O \text{ III}]$λ5007 and $H\beta$λ4861, respectively. The average FWHM of the PSF is 0\"$15$, indicated by the white bar. The FWHM was measured from the image of the quasar. The quasar is 2\"3 from the center of DLA emission, which corresponds to a physical distance of 17.8 kpc. The location of the quasar is outside the field of view of the maps and is not shown.

We measure the S/N of the line detection in each spaxel by subtracting the Gaussian fit from the spectrum and taking the standard deviation of the residual to be the noise in that spaxel. The S/N is the ratio of the amplitude of the best-fit Gaussian in that spaxel to the measured noise.

In some spaxels, the instrumental resolution is greater than the FWHM of the Gaussian fit to the emission line, resulting in a nonreal value when we remove instrumental resolution in quadrature. Emission in these spaxels is unresolved. We are able to measure intensity, velocity, and S/N, but not velocity dispersion. For this reason, these spaxels are black in the velocity dispersion maps.

4. Results

In this section, we place these measurements in the context of previous observations of DLA2233+131 and other high-$z$ DLAs and sub-DLAs. We summarize these current results in Table 2.

4.1. Metallicity

In the literature, DLA2233+131 is most commonly referred to as having a metallicity of $[Fe/H]\text{^4} = -1.4$, based on the estimation of Lu et al. (1997) from their Keck/HIRES spectrum. We reanalyzed the Keck/HIRES spectrum and followed the procedure of Rafelski et al. (2012) for estimating DLA metallicities. Unfortunately, transitions of the preferred ions of O, S, Si and Zn are either saturated, heavily blended, or not covered in the Keck/HIRES spectrum, leaving us to estimate the metallicity from the unsaturated FeII transition (see Figure 6). We use the AODM technique (Savage & Sembach 1991) and measure $[Fe/H] = -1.36 \pm 0.02$. We then apply the Rafelski et al. (2012) $\alpha$-enhancement correction to find $[M/H] = [Fe/H] + 0.3 \text{ dex} = -1.06$, confirming that this is a relatively metal-rich system, given the typical DLA

\[^4\text{We use the standard shorthand notation for metallicity relative to solar, } [M/H] = \log(M/H) - \log(M/H)_{\odot}.\]
metallicity of [M/H] \sim -1.5 \ (Rafelski \ et \ al. \ 2012). We note that the potential depletion of Fe, which is larger in higher metallicity systems, may mean that this estimation is, strictly speaking, a lower limit on the metallicity of this system.

4.2. Discrepancy with Previous Flux Measurements

We note that the flux we measure is not in agreement with that of Weatherley et al. \(2005\), who measured \([\text{O\ III}]\lambda5007\) flux of \((6.78 \pm 0.5) \times 10^{-17} \ \text{erg s}^{-1} \ \text{cm}^{-2}\) (compare with our measurement, \(F_{\text{[O III]}}^{\lambda5007} = (2.4 \pm 0.5) \times 10^{-17} \ \text{erg s}^{-1} \ \text{cm}^{-2}\)). This discrepancy may be due to the location of the DLA emission. The emission region is very close to the edge of the field of view. It is possible that the observations presented here do not capture the full extent of emission, resulting in a flux measurement that is lower than that of Weatherley et al. \(2005\).

Given this discrepancy, we perform two additional tests of the fidelity of the flux estimation. First, we model the potential loss of flux due to the DLA emission being close to the edge of the science region. In this model, we assume that there is a faint, extended “arm” of emission that mirrors the “arm” we observe to the left of the central core of emission. We measure the flux in the summed spectrum of the left “arm” to be \((6.4 \pm 2.3) \times 10^{-18} \ \text{erg s}^{-1} \ \text{cm}^{-2}\). This summed spectrum is taken over a 0.75 \times 1''2 area directly to the left of, and just excluding the central core of the emission region. We assume that an equal amount of flux may be located outside the field of view to the right of the DLA, and add it to the original flux measurement. This results in an estimated total flux of \((3.0 \pm 0.55) \times 10^{-17} \ \text{erg s}^{-1} \ \text{cm}^{-2}\), with a 1\(\sigma\) upper limit, accounting for the additional \sim 30\% flux calibration uncertainty, of \(4.7 \times 10^{-17} \ \text{erg s}^{-1} \ \text{cm}^{-2}\). This adjusted flux estimate is in better agreement with that of Weatherley et al. \(2005\).

Second, we verify the flux calibration by calculating the flux of the observed standard star using the same procedure we apply to the DLA emission (see Section 2.1, bullet point 3). As a result, we reproduce the 2MASS magnitude of the standard star to within 10\%.

4.3. Star Formation Rate

We estimate the SFR in three different ways using \([\text{O\ III}]\) and \(\text{H}\beta/\text{H}\alpha\) luminosities: one by using the standard Balmer ratio to convert \(\text{H}\beta\) to \(\text{H}\alpha\) luminosity, and two by assuming a value of \([\text{O\ III}]\)/\(\text{H}\alpha\) (described in detail in Section 3.3). We find SFR values ranging from \(7.1 \ M_\odot \ \text{yr}^{-1}\) to \(13.6 \ M_\odot \ \text{yr}^{-1}\).

There are two previous estimates of SFR for this galaxy. With the method outlined above, Weatherley et al. \(2005\) find that DLA2233+131 has a SFR of \(28 \ M_\odot \ \text{yr}^{-1}\), and suggest that this method is accurate to within a factor of 2. The discrepancy between the Weatherley et al. \(2005\) measurements and those presented here stems from a difference in measured flux as discussed in Section 4.1.

Christensen et al. \(2004\) also provides an estimate of the SFR, but based on measured \(\text{Ly}\alpha\) flux and the assumption that \(\text{Ly}\alpha/\text{H}\alpha\sim 10\). This assumption makes it possible to convert
Lyα flux to Hα flux and calculate the SFR based on the Kennicutt (1998) relation. Christensen et al. (2004) measure a SFR of \( \sim 19 \pm 10 M_\odot \text{yr}^{-1} \). The estimates presented here (and the lower limit based on Suzuki et al. 2015) are in agreement with this measurement.

There are some estimates of SFRs for other DLAs in the literature. For redshift \( 2 \leq z \leq 3 \), DLAs have SFRs spanning \( 2 M_\odot \text{yr}^{-1} \) to \( 17 M_\odot \text{yr}^{-1} \). (Fynbo et al. 2010; Péroux et al. 2012; Krogager et al. 2013; Jorgenson & Wolfe 2014; Srianand et al. 2016). The measurements presented here are well within the range of previously measured SFR for DLAs.

4.4. Dynamical Mass Estimate

We estimate the dynamical mass within the radius of [O iii] λ5007 emission using Equation (2) from Law et al. (2009),

\[
M_{\text{dyn}} = \frac{C \sigma_{\text{net}}^2 r}{G},
\]

where \( C = 5 \) for a uniform sphere (Erb et al. 2006), \( \sigma_{\text{net}} = 42.0 \text{ km s}^{-1} \), and \( r \) is the radius of emission. \( \sigma_{\text{net}} \) is an overall velocity dispersion, measured from the Gaussian fit to the [O iii] λ5007 composite spectrum (see Section 3.1 and Figure 2 for a description of the composite spectrum).

We estimate visually that the radius of emission for this DLA is 0′′2, or 1.5 kpc. We use [O iii] λ5007 emission to estimate the emission radius because it is the strongest line we observe. Estimating the radius of emission using the less-extended [O iii] λ4959 or Hβ λ4861 emission would be likely to underestimate the dynamical mass. Based on this estimate of emission radius, we find dynamical mass \( M_{\text{dyn}} = 3.1 \times 10^9 M_\odot \).

There are few estimates of dynamical mass for DLAs and sub-DLAs in the literature: Srianand et al. (2016) found \( M_{\text{dyn}} \sim (1 - 6) \times 10^9 M_\odot \) for a DLA at \( z = 2.9791 \), Jorgenson & Wolfe (2014) and Krogager et al. (2013) measured \( M_{\text{dyn}} \sim 6.1 \times 10^9 M_\odot \) and \( M_{\text{dyn}} \sim 2.5 \times 10^9 M_\odot \), respectively, for the same \( z = 2.35 \) DLA, and Bouché et al. (2013) found \( M_{\text{dyn}} \sim 2 \times 10^{10} M_\odot \) for a \( z \sim 2.3 \) DLA. These estimates for DLA galaxies, including DLA2233+131 presented here, are generally consistent with the dynamical mass of star-forming galaxies at high redshift, estimated to be \( 3 \times 10^9 M_\odot \leq M_{\text{dyn}} \leq 25 \times 10^9 M_\odot \), by Law et al. (2009). The dynamical mass of DLA2233+131 falls into the low end of this range.

At a lower-redshift range, \( 0 \leq z \leq 1 \), DLAs have similar dynamical mass ranges, spanning \( 7.9 \times 10^9 M_\odot \) to \( 7.9 \times 10^{10} M_\odot \) (Chengalur & Kanekar 2002; Péroux et al. 2016, 2011).

4.5. Gas Mass Estimates

We estimate the gas mass of the galaxy using the Kennicutt–Schmidt relation (Kennicutt 1998). We first estimate the SFR surface density by dividing SFR by the area over which we detect [O iii] λ5007 emission. We can then use Equation (4)
and convert the gas mass surface density to a total gas mass by multiplying it by the area of the emission region. For the estimates of SFRs for DLA2233+131 detailed in section Section 3.4, we find, $3.8 \times 10^4 M_\odot \leq M_{\text{gas}} \leq 4.9 \times 10^5 M_\odot$. This estimate is lower than the average gas mass for $z \sim 2$ star-forming galaxies, measured by Erb et al. (2006) as $\langle M_{\text{gas}} \rangle = (2.1 \pm 0.1) \times 10^{10} M_\odot$. It is the same order of magnitude as measurements of gas mass by Jorgenson & Wolfe (2014) and Krogager et al. (2013) for the same $z \sim 2.3$ DLA of $M_{\text{gas}} = 4.2 \times 10^9 M_\odot$ and $1 \times 10^9 M_\odot$, respectively.

We estimate the gas fraction of DLA2233+131, $f_{\text{gas}} = \frac{M_{\text{gas}}}{M_{\text{gas}} + M_{\text{dyn}}}$ (4)

to be $f_{\text{gas}} \sim 0.6$, also similar to those found in Jorgenson & Wolfe (2014) and Krogager et al. (2013).

4.6. Morphology and Kinematics

4.6.1. Artificial Slit Analysis

We use the emission maps shown in Figures 4 and 5 to search for signs of kinematic structure. The [O III]λ5007 emission is more extended and has approximately circular morphology, while the Hβ/λ4861 emission is less extended and slightly elongated in shape, albeit at a lower S/N. While the circular morphology is consistent with a face-on disk, the red and blueshifted clumps could indicate disk rotation viewed edge-on. One apparent kinematic axis presents itself. To assess quantitatively whether a rotational signature appears in these maps, we lay down an artificial slit along this kinematic axis, shown in Figure 7. The slit width is $0''15$, matching the LOSAO-corrected seeing, and we sample $0''07$ regions to extract velocity and velocity dispersion.

Moving along the slit from the peak of the emission at velocity $v = 0 \text{ km s}^{-1}$ (indicated by the centroid of the contours), to the upper left is a redshifted clump at $v \sim 25 \text{ km s}^{-1}$. To the lower right is a blueshifted clump at $v \sim -40 \text{ km s}^{-1}$. While these features are reminiscent of a rotating disk viewed edge-on, we observe $\Delta v_{\text{rot}} \sim 65 \text{ km s}^{-1}$, which is small compared with $v_{\text{rot}}$ for a rotating disk galaxy. Additionally, the observed velocity dispersion is not consistent with this interpretation. In an edge-on rotating disk model, one would expect to see the velocity dispersion peak at the center of emission. As can be seen in Figure 7, the velocity dispersion (red diamonds) remains high across the emission region. Even if the velocity dispersion were consistent with a rotating disk, an analysis along a single kinematic axis would be inconclusive at best.

4.6.2. Kinematic Summary and Analysis

In Table 3 and Figure 6 we summarize the emission-line measurements of DLA2233+131, including all previous measurements from the literature and those of the current work.

We note when discussing these results that a direct comparison between Lyα emission and nebular lines like [O III]λ5007 is not immediately instructive, because the Lyα line is affected by resonant scattering, which affects the shape of the emission-line profiles. Rather, we discuss these previous studies to provide a comprehensive overview of this DLA.

Other studies of DLA2233+131 have also been inconclusive with respect to kinematics. Djorgovski et al. (1996) observed DLA2233+131 in Lyα emission via single-slit spectroscopy. The emission was measured $2''3$ from the quasar at position angle $159^\circ$, which is consistent with the observations presented here. The authors measured the peak of Lyα emission at $z = 3.1530 \pm 0.003$, which corresponds to rest frame $\Delta v = 208 \text{ km s}^{-1}$ relative to the centroid of the absorption system at $z = 3.14927$. While the Djorgovski et al. (1996) measurement of $\Delta v$ is consistent with $v_{\text{rot}}$ for a normal disk galaxy, it is insufficient evidence to conclude that the rotating disk interpretation is correct.

Similarly, Christensen et al. (2004) explored the possibility of disk rotation in DLA2233+131 with an analysis of composite spectra representing large regions of the $3 \times 5''$ field of view. Upon breaking the field of view into four subregions and measuring the shifts between the emission
peaks in the east–west and north–south regions of the field, the authors find shifts of 2.5 Å (∼150 km s⁻¹) and 5 Å (∼300 km s⁻¹), respectively. While these velocities may be consistent with $v_{rot}$ for a disk galaxy, more conclusive evidence is needed to support the rotating disk interpretation. Christensen et al. (2004) instead speculate that DLA2233+131 has multiple emission regions based on the observed double-peaked Lyα emission. The possible clumpy nature of DLAs is discussed further in Augustin et al. (2018).

To date, no observations of DLA2233+131 including those presented here, have yielded evidence that is conclusively in favor of an edge-on rotating disk.

5. Summary

We present Keck/OSIRIS IFU observations of DLA2233+131, a $z = 3.153$ sub-DLA, or super Lyman limit galaxy. With the use of LGSAO, we are able to marginally resolve extended [O iii]λ5007 emission from DLA2233+131 with S/N = 13.2. Furthermore, we detect and report unresolved [O iii]λ4959 and Hβλ4861 emission with S/N = 1.8 and 3.1, respectively. We find a dynamical mass $M_{dyn} = (0.24–4.24) \times 10^{9} M_\odot$ and estimate a SFR using both [O iii] and Hβ emission, finding SFR $\sim 6.5 – 9.4 M_\odot$ yr⁻¹.

With these marginally spatially resolved observations, we are able to map the [O iii]λ5007 and Hβλ4861 emission to search for kinematic signatures that may help to determine the nature of the host galaxy. While DLA2233+131 does display small clumps of red and blueshifted emission, which initially seem indicative of possible edge-on disk rotation, a careful analysis shows them to be inconsistent with the interpretation of an edge-on rotating disk. These observations demonstrate, along with those of Jorgenson & Wolfe (2014), the use of Keck/OSIRIS + LGSAO for spatially resolving faint DLA emission, particularly the potential for performing a detailed kinematic analysis that is clearly necessary for understanding the true nature of these enigmatic galaxies.

The authors thank the anonymous referee for comments that have significantly improved the manuscript. R.A.J. gratefully acknowledges support from the NSF Astronomy and Astrophysics Postdoctoral Fellowship under award AST-1102683. R.A.J. and H.C. acknowledge support from NSF-REU grant AST-1358980, as well as the generous support of the Nantucket Maria Mitchell Association. The authors gratefully acknowledge the support of the Theodore Dunham, Jr. Grant of the Fund for Astrophysical Research. The data presented herein were obtained at the W. M. Keck Observatory, which is operated as a scientific partnership among the California Institute of Technology, the University of California and the National Aeronautics and Space Administration. The Observatory was made possible by the generous financial support of the W. M. Keck Foundation. The authors recognize and acknowledge the very significant cultural role and reverence that the summit of Maunakea has always had within the indigenous
Hawaiian community. We are most fortunate to have the opportunity to conduct observations from this mountain.

**ORCID iDs**

Holly M. Christenson @ https://orcid.org/0000-0002-0421-065X

Regina A. Jorgenson @ https://orcid.org/0000-0003-2973-0472

**References**

Augustin, R., Péroux, C., Möller, P., et al. 2018, MNRAS, 478, 3120

Blanton, M. R., Bershady, M. A., Abolfathi, B., et al. 2017, AJ, 154, 28

Bouché, N., Murphy, M. T., Kacprzak, G. G., et al. 2013, Sci, 341, 50

Bunker, A. J., Warren, S. J., Clements, D. L., Williger, G. M., & Hewett, P. C. 1999, MNRAS, 309, 875

Chengalur, J. N., & Kanekar, N. 2002, A&A, 388, 383

Christensen, L., Noterdaeme, P., Petitjean, P., Ledoux, C., & Fynbo, J. P. U. 2009, A&A, 505, 1007

Christensen, L., Sánchez, S. F., Jahnke, K., et al. 2004, A&A, 417, 487

Christensen, L., Wisotzki, L., Roth, M. M., et al. 2007, A&A, 468, 587

Djorgovski, S. G., Pahre, M. A., Bechtold, J., & Elston, R. 1996, Natur, 382, 234

Erb, D. K., Steidel, C. C., Shapley, A. E., et al. 2006, ApJ, 646, 107

Fynbo, J. P. U., Laursen, P., Ledoux, C., et al. 2010, MNRAS, 408, 2128

Genzel, R., Tacconi, L. J., Eisenhauer, F., et al. 2006, Natur, 442, 786

Hinshaw, G., Larson, D., Komatsu, E., et al. 2013, ApJS, 208, 19

Jorgenson, R. A., & Wolfe, A. M. 2014, ApJ, 785, 16

Kennicutt, R. C., Jr. 1992, ApJ, 388, 310

Kennicutt, R. C., Jr. 1998, ApJ, 498, 541

Kewley, L. J., & Dopita, M. A. 2002, ApJS, 142, 35

Krogager, J.-K., Fynbo, J. P. U., Ledoux, C., et al. 2013, MNRAS, 433, 3091

Krogager, J.-K., Möller, P., Fynbo, J. P. U., & Noterdaeme, P. 2017, MNRAS, 469, 2959

Kulkarni, V. P., Hill, J. M., Schneider, G., et al. 2000, ApJ, 536, 36

Kulkarni, V. P., Woodgate, B. E., York, D. G., et al. 2006, ApJ, 636, 30

Larkin, J., Barczys, M., Krabbe, A., et al. 2006, NewAR, 50, 362

Law, D. R., Steidel, C. C., Erb, D. K., et al. 2007, ApJ, 669, 929

Law, D. R., Steidel, C. C., Erb, D. K., et al. 2009, ApJ, 697, 2057

Lowenthal, J. D., Hogan, C. J., Green, R. F., et al. 1995, ApJ, 451, 484

Lu, L., Sargent, W. L. W., & Barlow, T. A. 1997, arXiv:astro-ph/9711298

Møller, P., Warren, S. J., Fall, S. M., Fynbo, J. U., & Jakobsen, P. 2002, ApJ, 574, 51

Péroux, C., Bouché, N., Kulkarni, V. P., York, D. G., & Vladilo, G. 2011, MNRAS, 410, 2251

Péroux, C., Bouché, N., Kulkarni, V. P., York, D. G., & Vladilo, G. 2012, MNRAS, 419, 3060

Péroux, C., Quiret, S., Rahmani, H., et al. 2016, MNRAS, 457, 903

Rafelski, M., Wolfe, A. M., Prochaska, J. X., Neeleman, M., & Mendez, A. J. 2012, ApJ, 755, 89

Sargent, W. L. W., Steidel, C. C., & Boksenberg, A. 1989, ApJS, 69, 703

Savage, B. D., & Sembach, K. R. 1991, ApJ, 379, 245

Srianand, R., Hussain, T., Noterdaeme, P., et al. 2016, MNRAS, 460, 634

Steidel, C. C., Pettini, M., & Hamilton, D. 1995, AJ, 110, 2519

Suzuki, T. L., Kodama, T., Tadaki, K.-I., et al. 2015, ApJ, 806, 208

Warren, S. J., Möller, P., Fall, S. M., & Jakobsen, P. 2001, MNRAS, 326, 759

Weatherley, S. J., Warren, S. J., Möller, P., et al. 2005, MNRAS, 358, 985

Wolfe, A. M., Gawiser, E., & Prochaska, J. X. 2005, ARA&A, 43, 861

Wolfe, A. M., Turnshek, D. A., Smith, H. E., & Cohen, R. D. 1986, ApJS, 61, 249