Evidence for a Hard Ionizing Spectrum from a $z = 6.11$ Stellar Population

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Abstract

We present the Magellan/FIRE detection of highly ionized C IV\,$\lambda$1550 and O III\,$\lambda$1666 in a deep infrared spectrum of the $z = 6.11$ gravitationally lensed low-mass galaxy RXC J2248.7-4431-ID3, which has previously known Ly$\alpha$. No corresponding emission is detected at the expected location of He II\,$\lambda$1640. The upper limit on He II, paired with detection of O III and C IV, constrains possible ionization scenarios. Production of C IV and O III requires ionizing photons of 2.5–3.5 Ryd, but once in that state their multiplet excitation is powered by collisional excitation at lower energies (~0.5 Ryd). As a pure recombination line, He II emission is powered by 4 Ryd ionizing photons. The data therefore require a spectrum with significant power at 3.5 Ryd but a rapid drop toward 4.0 Ryd. This hard spectrum with a steep drop is characteristic of high-metallicity stellar populations, and less consistent with soft AGN excitation, which features more 4 Ryd photons and hence higher He II flux. The conclusions based on metal line detections to helium non-detection are strengthened if the gas metallicity is low. RXJ2248-ID3 adds to the growing handful of reionization-era galaxies with UV emission line ratios distinct from the general $z = 2$–3 population in a way that suggests hard ionizing spectra that do not necessarily originate in AGNs.

Key words: cosmology: observations – galaxies: evolution – galaxies: formation – galaxies: high-redshift

1. Introduction

Over the past year, the first detailed spectroscopic measurements constraining the nature of $z > 6$ star-forming galaxies have emerged (see Stark 2016 for a review), suggesting a different population than is common at $z \approx 2$–3. Deep near-infrared spectroscopy has revealed strong UV metal line emission in galaxies at $z = 6$–8 with equivalent widths 5–10\,$\mu$m larger than are typical at $z \approx 2$ (Stark et al. 2015a, 2015b, 2017), while ALMA observations have begun to deliver detections of [C II] 158\,$\mu$m and [O III] 88\,$\mu$m emission in typical galaxies at $z > 6$ (Willott et al. 2015; Bradač et al. 2016; Inoue et al. 2016; Pentericci et al. 2016). Perhaps the most surprising result is the discovery of nebular C IV\,$\lambda$1548, 1550 in a galaxy at $z = 7.045$ (Stark et al. 2015b), requiring an extremely hard radiation field capable of producing a large number of photons more energetic than 47.9 eV. Only one percent of UV-selected galaxies at $z \approx 3$ show strong nebular C IV emission (Steidel et al. 2002; Reddy et al. 2008; Hainline et al. 2011). While these systems tend to be low-luminosity narrow-line AGNs, more recent studies have shown that nebular C IV is also found in dwarf star-forming galaxies (Christensen et al. 2012; Stark et al. 2014; Vanzella et al. 2016), presumably powered by the harder radiation field from low-metallicity stars. The detection of nebular C IV in one of the first galaxies targeted in the reionization era suggests that galaxies with high ionizing spectra may be more common in the reionization era.

There are two outstanding issues that must be addressed following these preliminary spectroscopic studies. First, it remains unclear how representative the $z = 7.045$ C IV emitter is of star-forming galaxies at $z > 7$. If stellar populations commonly produce hard ionizing spectra at $z > 6$, it would represent a rapid and qualitative change in the galaxy population relative to all lower redshifts, and these galaxies would play a larger role in reionization than has previously been assumed. Second, one must attempt to establish whether the high ionization emission is powered by hot, low-metallicity stars or AGNs. Both can potentially provide high-energy photons, and with a single metal line detection it is difficult to prove the source beyond a reasonable doubt (e.g., Stark et al. 2015b). At lower redshifts, the separation of AGNs and star-forming galaxies is readily carried out using rest-frame optical emission line ratios (e.g., Baldwin et al. 1981). However, utilization of a similar approach at $z > 6$ must await the launch of JWST. Recent efforts have begun to develop rest-UV diagnostics based on different photoionization models to distinguish the sources of ionizing spectra (Feltre et al. 2016). This can be achieved with current ground-based facilities, provided multiple far-UV lines can be detected.

In this paper, we describe the initial results from a spectroscopic campaign using the Magellan Baade Folded-port InfraRed Echellette (FIRE; Simcoe et al. 2013) aimed at addressing the two issues described above. The spectral coverage provided by FIRE makes it particularly efficient at recovering multiple lines in bright $z > 6$ galaxies. Here we describe FIRE observations of a $z = 6.110$ gravitationally lensed galaxy. The FIRE spectrum reveals the presence of the nebular C IV\,$\lambda$1550 emission line, providing another instance of high ionization lines at $z > 6$. We also report the detection of a second feature (O III\,$\lambda$1660, 1666), enabling exploration of the origin of the high ionization emission.

Throughout the paper we adopt standard $\Lambda$CDM cosmology with $\Omega_M = 0.3$, $\Omega_{\Lambda} = 0.7$, $H_0 = 100$ hr km s$^{-1}$ Mpc$^{-1}$, and $h = 0.7$. Magnitudes are quoted in AB magnitudes.
2. Observations

We report on observations of RXC J2248-ID3, one of five images of a $z = 6.11$ gravitationally lensed galaxy behind the cluster RXC J2248.7-4431. The galaxy was first identified by Boone et al. (2013) and Monna et al. (2014) via the Cluster Lensing And Supernova survey with Hubble (Postman et al. 2012). The images are bright ($J_{225} = 24.8-25.9$), owing to their magnification (2.2–8.3×). We calculate the UV continuum slope using deeper imaging from the Hubble Frontier Field initiative (Lotz et al. 2014). The data show that the galaxy is very blue ($\beta = -2.54 \pm 0.16$) and that the UV absolute magnitude is $M_{UV} = -20.1 \pm 0.2$ after magnification correction, indicating a sub-L* luminosity. As in our previous studies (i.e., Stark et al. 2013, 2017), we perform SED fitting using a code developed by Robertson et al. (2010) that combines the findings of Bruzual & Charlot (2003) with nebular line and continuum emission computed assuming case B recombination and empirical metallic line intensities from Anders & Fritze-v. Alvensleben (2003). For a Salpeter stellar IMF and constant star formation, the magnification-corrected data suggest a low stellar mass ($1 \times 10^{9} M_{\odot}$), little reddening ($E(B-V) = 0.01$), and a large sSFR ($50$ Gyr$^{-1}$). Strong Ly$\alpha$ ($W_{Ly\alpha} = 75$ Å) has been identified in RXC J2248-ID3 by VLT/VIMOS (Balestra et al. 2013), VLT/FORS (Boone et al. 2013), and the HST WFC3/IR grism (Schmidt et al. 2016), consistent with expectations for young, metal-poor galaxies (e.g., Cowie et al. 2011; Trahar et al. 2016).

UV metal lines tend to be most prominent in systems with extremely large EW Ly$\alpha$ emission (e.g., Shapley et al. 2003; Stark et al. 2014), making RXC J2248-ID3 an ideal candidate for detecting metal lines at $z > 6$. At the redshift of RXC J2248-ID3, the FIRE spectrum is able to constrain the relative strengths of the Ly$\alpha$, C iv$\lambda\lambda1548, 1550$, He ii$\lambda1640$, and O iii$\lambda\lambda1660, 1666$ lines. Unfortunately, the C iii$\lambda\lambda1907, 1909$ doublet is situated in a region of low atmospheric transmission between the J and H-bands, precluding useful flux constraints.

We observed RXC J2248-ID3 over 2014 July 19–21 using FIRE in echelle mode, providing continuous spectral coverage between 0.82 and 2.51 μm. The particular image we observed is magnified by 5.5×. We adopted a slit width of 0.′6, resulting in a resolving power of $R = 6000$. The orientation of the slit on the galaxy (PA = 60°) is shown in Figure 1. The exposures were carried out using two dither positions separated by 3′0. Observing conditions were excellent, with clear sky and an average seeing of 0′′4. Given the seeing, source size, and slit width, we require a small aperture correction (1.1×) to the observed fluxes. The total on-source integration time over three nights was 9.17 hr.

The FIRE spectrum was reduced using standard routines in the FIREHOSE data reduction pipeline. The pipeline uses lamp and sky flats. Two-dimensional sky models are iteratively calculated following Kelson (2003). The wavelength solutions are provided by fitting OH skylines in the spectra. Flux calibration and telluric corrections to the data are applied using A0V star observations. Finally, the 1D spectra were extracted using a boxcar with aperture of 1′35 (15 pixels), corresponding to the spatial extent of the strongest emission line (Ly$\alpha$) in the FIRE spectrum.

The HST grism spectra for RXC J2248 come from the GLASS survey (Giroux et al. 2014; Treu et al. 2015). The HST WFC3/IR grisms G102 and G141 have a spectral resolution of 210 and 130 and cover the wavelengths 0.8–1.15 μm and 1.1–1.7 μm. The data were reduced using aXe (Kümmel et al. 2009). MultiDrizzle was used to combine the direct images. Multiple visits at similar roll angles were drizzled together and tweakshifts was used to determine the offset between the visits. Next, SExtractor was run on the direct images to generate the aXe input catalog. Finally, the aXe routines were run to drizzle the 2D spectra and extract the spectra. The 1D spectra were extracted from the 2D spectra using a 0′′38 (3 pixels) aperture. The extracted 1D spectra were then divided by the instrument sensitivity function and pixel size to flux-calibrate the spectra. The first roll angle (97°7) had a significant contaminating continuum; a sliding median with a window of

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Figure 1. (Left) HST WFC3/IR color image of the cluster RXC J2248 showing the position of the galaxy RXC J2248-ID3. (Right) Slit center and position angle of the Magellan/FIRE observations.
of 11.4 × 10^{-18} \text{ erg cm}^{-2} \text{ s}^{-1}. The theoretically expected flux ratio (CIVλ1548/CIVλ1550 = 2) has also been observed in several intermediate-redshift systems (e.g., Caminha et al. 2016; Vanzella et al. 2016) and would instead predict a total flux of 17.1 × 10^{-18} \text{ erg cm}^{-2} \text{ s}^{-1}.

Unlike the resonant C IV line, the nebular Hελλ1640 and O IIIλλ1660, 1666 lines typically trace the systemic redshift (Shapley et al. 2003; Steidel et al. 2010; Stark et al. 2014). Assuming Lyα velocity offsets (ΔV_{Lyα}) between 0 km s^{-1} and 450 km s^{-1}, consistent with previous studies (Takpen et al. 2007; Erb et al. 2010; Stark et al. 2015b, 2017), we predict that O IIIλ1660 will fall between 11794 and 11808 Å and the O IIIλ1666 will lie between 11832 and 11846 Å. We detect a 4.5σ emission feature (FWHM = 58 km s^{-1}) centered at 11837.1 Å (see Figure 2(d)) with total flux (2.7 ± 0.6) × 10^{-18} \text{ erg cm}^{-2} \text{ s}^{-1}. We identify this line as O IIIλ1666, indicating a systemic redshift of z = 6.1045 for RXC J2248-ID3. Following the same procedure described above for C IV, we calculate a rest-frame equivalent width of 4.6 ± 1.6 Å. Using the O IIIλ1666 redshift, we search for emission associated with O IIIλ1660. A faint emission component (S/N = 2.8) is visible at the expected wavelength (Figure 2(d)). The line flux and rest-frame equivalent width are (1.7 ± 0.6) × 10^{-18} \text{ erg cm}^{-2} \text{ s}^{-1} and 2.9 ± 1.4 Å, respectively. Based on the presence of CIV, we may also expect to see nebular Hελλ. While the line is expected to fall in a clean region of the FIRE spectrum at 11655 Å (based on the systemic redshift), there is no evidence of any emission feature at the expected location (Figure 2(c)), implying a 2σ upper limit on the rest-frame equivalent width of 2.8 Å. The non-detection of Hελλ is consistent with the upper limits (<1.4 Å) derived for young metal-poor galaxies at z = 2–3 (e.g., Stark et al. 2014). Similarly, we do not detect the NVλ1238, 1240 line (W_{NV} < 2.3 Å) that is commonly seen in AGN spectra.

The systemic redshift provided by the detection of O IIIλ1660 allows Lyα to be shifted to the galaxy rest-frame. Figure 3(a) shows the resultant Lyα line profile. The peak Lyα flux is redshifted from systemic by a velocity offset of ΔV_{Lyα} = 235 km s^{-1}. The FWHM of the Lyα (131 km s^{-1}) is narrower than many luminous reionization-era galaxies with Lyα detections (e.g., Oesch et al. 2015). The difference with respect to the C IV and O IIIλ1660 is not surprising given the reprocessing of the line profile by the CGM and surrounding IGM. Including RXC J2248-ID3, there are now 11 z > 6 galaxies with Lyα profile and velocity offset measurements (see Figure 3(b)) where either [C II] 158 μm or [O III] 88 μm (Willott et al. 2015; Bradač et al. 2016; Inoue et al. 2016; Pentericci et al. 2016) or UV metal line detections (Stark et al. 2015a, 2017) constrain the systemic redshift. We discuss trends with M_{UV} and implications for the escape of Lyα from reionization-era galaxies in Section 4.

The WFC3/IR grism spectrum of RXC J2248-ID3 is shown along the bottom panel of Figure 2. Lyα is clearly detected, as was previously reported in Schmidt et al. (2016). The spectrum also reveals the detection of nebular C IV (unresolved) in both roll angles. The mean integrated fluxes ([14.0 ± 3.8] × 10^{-18} \text{ erg cm}^{-2} \text{ s}^{-1}) and equivalent width (24.5 ± 7.1 Å) of the two roll angles thus reflects both CIVλ1548 and CIVλ1550. The grism spectra covers He II, O IIIλ1660, and C IIIλ1907, but no detections are apparent. The C IV to C IIIλ1666 ratio (>3.9 at 2σ) is slightly larger than the range (0.4–1.6) spanned by metal-poor C IV emitters at moderate redshifts (Stark et al. 2014; Vanzella et al. 2016) but is consistent with flux ratios expected for galaxies powered by low-
metallicity stars (Feltre et al. 2016). The total C IV flux is consistent with the flux range \((11.4-17.1) \times 10^{-18}\text{erg cm}^{-2}\text{s}^{-1}\) predicted from the detection of the single C IV\(\lambda1550\) component predicted from the detection of the single C IV\(\lambda1550\) component.

Since the FIRE constraints on the O III], C IV, and He II fluxes are made under the same atmospheric conditions and are subject to the same aperture corrections, we will limit our

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**Figure 2.** (Top) Magellan/FIRE spectrum \((R = 6000)\) of the \(z = 6.11\) galaxy RXC J2248-ID3. Each panel shows the 2D spectrum (with white corresponding to positive flux) on top of the 1D spectrum. The error in the 1D spectrum is shown in red. (Bottom) HST WFC3/IR G102 spectra \((R = 210)\) of RXC J2248-ID3 at two different roll angles (black corresponds to positive flux), with the middle panel showing the spectrum following contamination subtraction.
investigation to line ratios calculated from FIRE. In the empirically motivated case where $C\text{IV}\lambda 1548/C\text{IV}\lambda 1550 = 1$, we would expect $\log(\text{He}\Pi/C\text{IV}) < -0.87$ and $\log(O\text{III}/C\text{IV}) = -0.39$. The grism measurement places an upper bound on the total C\text{IV} flux (owing to slit losses), suggesting $\log(\text{He}\Pi/C\text{IV}) < -0.96$ and $\log(O\text{III}/C\text{IV}) = -0.51$. We will consider both options in the following section.

4. Discussion and Summary

The discovery of nebular C\text{IV} emission in RXC J2248-ID3 provides the second example of high ionization lines associated with an intrinsically faint lensed reionization-era galaxy. Yet the origin of the UV emission features remains poorly understood. The presence of multiple lines in the spectrum RXC J2248-ID3 provides a unique opportunity to examine the powering mechanism of the high ionization emission. Production of nebular C\text{IV} and O\text{III} emission requires ionizing photons in the range 2.5–3.5 Ryd, but once in that state their multiplet emission is powered by collisional excitation at lower energies (∼0.5 Ryd). As a pure recombination line, He\Pi\lambda 1640 emission is powered by 4 Ryd ionizing photons. Photons with 4 Ryd are also capable of triply ionizing oxygen, thereby decreasing the strength of O\text{III} emission.

The presence of strong O\text{III} and C\text{IV} emission indicates that RXC J2248-ID3 must have an ionizing spectrum with significant power at 2.5–3.5 Ryd. But a rapid drop toward 4.0 Ryd is required to maintain strong O\text{III} emission and explain the non-detection of an He\II line. Such a spectral break is inconsistent with a shallow AGN power-law spectrum. The left panel of Figure 4 demonstrates this empirically. RXC J2248-ID3 and other metal-poor C\text{IV} emitters (Stark et al. 2014, 2015b; Berg et al. 2016; Vanzella et al. 2016) have larger O\text{III}/C\text{IV} flux ratios than both $z ∼ 2–3$ UV-selected AGNs (Hainline et al. 2011) and the majority of type II $z ∼ 2–4$ quasars from Alexandroff et al. (2013). This follows naturally if the metal-poor galaxies have spectra that are deficient in the 4 Ryd photons that power He\II and triply ionize oxygen.

The origin of the line emission can be clarified further by comparison to photoionization models. The right panel of Figure 4 shows the line ratios of RXC J2248-ID3 in the context of the AGN and stellar models from Feltre et al. (2016). RXC J2248-ID3 has $\log(O\text{III}/\text{He}\Pi) > 0.47$, which is inconsistent with line ratios expected for AGNs ($\log(O\text{III}/\text{He}\Pi = -3$ to $-0.5$), but can be easily explained by stellar models. In particular, a hard spectrum with a steep drop above 4 Ryd is characteristic of low-metallicity stellar populations. The precise metallicity required is dependent on the input stellar spectrum and may vary somewhat for single star models (like those considered in Feltre et al. 2016) and those that include binary evolution.

The presence of C\text{IV} in two of the first few $z > 6$ galaxies with deep spectra suggests that hard ionizing spectra may be more common in the reionization era. However, when considering whether the C\text{IV} emission in RXC J2248-ID3 is typical, it is important to remember that the galaxy was selected to probe the low-mass regime where metallicities may indeed be systematically lower. The existence of Ly\alpha may further bias this selection toward low-metallicity (and low dust content) as well. Indeed, existing data at $z > 1.5$ suggest that nebular C\text{IV} emitters tend to be characterized by low stellar mass ($2 \times 10^8$–$4 \times 10^8 M_\odot$) and large equivalent width Ly\alpha emission, as would be expected if the stellar populations capable of powering high ionization lines are only found among young, low-metallicity stellar populations. The nature of massive stellar populations at low metallicity remains poorly understood. Theoretical work on massive star binary evolution (e.g., Eldridge & Stanway 2009; de Mink et al. 2014) indicates that the lifetimes and high-energy ionizing output of massive stars at low metallicity may be vastly different (and higher) than classically assumed, potentially explaining the large luminosities now being detected in high ionization nebular lines.

Large samples of galaxies with intercombination metal line detections at high spectral resolutions can constrain $z > 6$ Ly\alpha velocity offsets, a critical input for efforts to infer the IGM...
ionization state from Lyα emitters. Our measurement of $\Delta v = 235$ km s$^{-1}$ in a sub-L* object ($M_{UV} = -20.1$) at $z = 6.11$ falls between existing measurements of high-luminosity objects with large Lyα offsets and low-luminosity objects with small offsets at $z > 6$. In a partially neutral IGM, a large velocity offset will allow line radiation to redshift further into the damping wing by the time it encounters intergalactic hydrogen, thereby reducing IGM attenuation relative to systems with smaller offsets (Dijkstra & Wyithe 2010). This $M_{UV}-\Delta v$ relationship (Figure 3(b)) will thus help create a luminosity-dependent Lyα fraction, consistent with emerging measurements (Stark et al. 2017). This issue should be further clarified through increasing samples expected in the near future.

To summarize, the detections of CIV and OIII in $z > 6$ galaxy possibly hint at a markedly different underlying stellar population in typical galaxies at $z > 6$ relative to those studied at lower redshift. The detection of high ionization UV objects in RXC J2248-ID3 likely suggests that they are more common in the reionization era than previously expected. Taken together, this implies that extrapolations from lower redshifts may be missing a significant and qualitative change in the nature of photon production in the epoch of reionization.

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References
Alexandroff, R., Strauss, M. A., Greene, J. E., et al. 2013, MNRAS, 435, 3306
Anders, P., & Fritze-v. Alvensleben, U. 2003, A&A, 401, 1063
Baldwin, J. A., Phillips, M. M., & Terlevich, R. 1981, PASP, 93, 5
Balestra, I., Vanzella, E., Rosati, P., et al. 2013, A&A, 559, L9
Berg, D. A., Skillman, E. D., Henry, R. B. C., Erb, D. K., & Carigi, L. 2016, ApJ, 827, 126
Boone, F., Clément, B., Richard, J., et al. 2013, A&A, 559, L1
Bradač, M., Garcia-Appadoo, D., Huang, K.-H., et al. 2016, ApJL, in press (arXiv:1610.02099)
Bruzual, G., & Charlot, S. 2003, MNRAS, 344, 1000
Caminha, G. B., Karman, W., Rosati, P., et al. 2016, A&A, 595, A100
Choudhury, T. R., Puchwein, E., Haehnelt, M. G., & Bolton, J. S. 2015, MNRAS, 452, 261
Christensen, L., Richard, J., Hjorth, J., et al. 2012, MNRAS, 427, 1953
Cowie, L. L., Hu, E. M., & Songaila, A. 2011, ApJL, 735, L3B
de Mink, S. E., Siana, H., Langer, N., Izzard, R. G., & Schneider, F. R. N. 2014, ApJ, 782, 7
Dijkstra, M., & Wyithe, J. S. B. 2010, MNRAS, 408, 352
Eldridge, J. J., & Stanway, E. R. 2009, MNRAS, 400, 1019
Erb, D. K., Pettini, M., Shapley, A. E., et al. 2010, ApJ, 719, 1168
Erb, D. K., Steidel, C. C., Trainor, R. F., et al. 2014, ApJ, 795, 33
Feltre, A., Charlot, S., & Gutkin, J. 2016, MNRAS, 456, 3354
Hainline, K. N., Shapley, A. E., Greene, J. E., & Steidel, C. C. 2011, ApJ, 733, 31
Inoue, A. K., Tamura, Y., Matsuo, H., et al. 2016, Sci, 352, 1559
Kelson, D. D. 2003, PASP, 115, 688
Kämmler, M., Walsh, J. R., Pizzolat, N., Kuntschner, H., & Pasquali, A. 2009, PASP, 121, 59
Lotz, J., Mountain, M., Grogin, N. A., et al. 2014, BAAS, 223, 254.01
Monna, A., Seitz, S., Greisel, N., et al. 2014, MNRAS, 438, 1417
Oesch, P. A., van Dokkum, P. G., Illingworth, G. D., et al. 2015, ApJL, 804, L30
Pentericci, L., Carniani, S., Castellano, M., et al. 2016, ApJL, 829, L11
Postman, M., Coe, D., Benitez, N., et al. 2012, ApJS, 199, 25
Reddy, N. A., Steidel, C. C., Pettini, M., et al. 2008, ApJS, 175, 48
Robertson, B. E., Ellis, R. S., Dunlop, J. S., McLure, R. J., & Stark, D. P. 2010, Natur, 468, 49
Schmidt, K. B., Treu, T., Bradač, M., et al. 2016, ApJ, 818, 38
Schmidt, K. B., Treu, T., Brammer, G. B., et al. 2014, ApJL, 782, L36
Shapley, A. E., Steidel, C. C., Pettini, M., & Adelberger, K. L. 2003, ApJ, 585, 65
Simcoe, R. A., Burgasser, A. J., Schechter, P. L., et al. 2013, PASP, 125, 270
Stark, D. P. 2016, ARA&A, 54, 761
Stark, D. P., Ellis, R. S., Charlot, S., et al. 2017, MNRAS, 464, 469
Stark, D. P., Richard, J., Charlot, S., et al. 2015a, MNRAS, 450, 1846
Stark, D. P., Richard, J., Siana, B., et al. 2014, MNRAS, 445, 3200
Stark, D. P., Schenker, M. A., Ellis, R., et al. 2013, ApJL, 763, 129

Figure 4. (Left) Comparison of UV line ratios associated with metal-poor CIV emitters and narrow-line AGNs at $z \sim 2-4$. The filled red circle shows the line ratios of RXC J2248-ID3 if we adopt the empirically motivated line ratio (CIVλ1548/CIVλ1550 = 1); the open red circle corresponds to an upper bound on the total CIVλ1548, 1550 flux adopted using the WFC3/IR grism measurement. The metal-poor star-forming systems are mostly separated from the AGN samples, suggesting they are subject to a softer radiation field. (Right) Comparison to photoionization models of Feltre et al. (2016). Gray (green) points correspond to flux ratios predicted from the AGN(stellar) photoionization models in Feltre et al. (2016). The red (blue) dashed line represents 1σ (3σ) lower limits on the line ratios, demonstrating that the data are better explained by a stellar radiation field.
Stark, D. P., Walth, G., Charlot, S., et al. 2015b, MNRAS, 454, 1393
Steidel, C. C., Erb, D. K., Shapley, A. E., et al. 2010, ApJ, 717, 289
Steidel, C. C., Hunt, M. P., Shapley, A. E., et al. 2002, ApJ, 576, 653
Tapken, C., Appenzeller, I., Noll, S., et al. 2007, A&A, 467, 63

Trainor, R. F., Strom, A. L., Steidel, C. C., & Rudie, G. C. 2016, ApJ, 832, 171
Treu, T., Schmidt, K. B., Brammer, G. B., et al. 2015, ApJ, 812, 114
Vanzella, E., De Barros, S., Cupani, G., et al. 2016, ApJL, 821, L27
Willott, C. J., Carilli, C. L., Wagg, J., & Wang, R. 2015, ApJ, 807, 180