THE PHYSICAL CONDITIONS OF A LENSED STAR-FORMING GALAXY AT $z = 1.7$

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Received 2010 October 29; accepted 2011 February 7; published 2011 April 14

ABSTRACT

We report rest-frame optical Keck/NIRSPEC spectroscopy of the bright lensed galaxy RCSGA 032727-132609 at $z = 1.7037$. From precise measurements of the nebular lines, we infer a number of physical properties: redshift, extinction, star formation rate, ionization parameter, electron density, electron temperature, oxygen abundance, and N/O, Ne/O, and Ar/O abundance ratios. The limit on [O iii] 4363 Å tightly constrains the oxygen abundance via the “direct” or $T_e$ method, for the first time in an average-metallicity galaxy at $z \sim 2$. We compare this result to several standard “bright-line” O abundance diagnostics, thereby testing these empirically-calibrated diagnostics in situ. Finally, we explore the positions of lensed and unlensed galaxies in standard diagnostic diagrams, and the diversity of ionization conditions and mass–metallicity ratios at $z = 2$.

Key words: galaxies: abundances – galaxies: evolution – galaxies: high-redshift – gravitational lensing: strong

1. INTRODUCTION

Our knowledge of the universe’s star formation history has advanced remarkably in the past dozen years. First rest-UV photometry (Madau et al. 1996, 1998), then 24 μm Spitzer photometry for $0 < z < 2$ galaxies (Caputi et al. 2007; Le Floc’h et al. 2005) and rest-UV photometry at higher redshift (cf. Ouchi et al. 2005; Bouwens et al. 2010), has shown us that the galaxy MS1512-cB58 (hereafter cB58; Yee et al. 1996) by Pettini et al. (2000) and Teplitz et al. (2000), and can now be possible with current telescopes. Such work was pioneered in the galaxy’s magnification factors of 20–30 make diagnostic spectroscopy highly magnified by gravitational lensing. In such rare cases, the chance to address this question is to study galaxies that are high-redshift galaxies (e.g., Allam et al. 2007; Belokurov et al. 2007; Smail et al. 2007; Rigby et al. 2008; Koester et al. 2010.)

Among these new discoveries is RCSGA 032727-132609, hereafter RCS0327, at $z = 1.7$ (Wuyts et al. 2010), discovered from the second Red Sequence Cluster Survey (RCS2; Gilbank et al. 2011). With an integrated g-band magnitude of 19.15, we believe RCS0327 to be the brightest high-redshift lensed galaxy yet found. Wuyts et al. (2010) present the discovery, spectroscopic confirmation, deep follow-up imaging, spectral energy distribution (SED) modeling, and preliminary lensing analysis. In this paper, using 1.3 hr of integration with NIRSPEC on Keck, we determine with unprecedented precision the physical conditions of star formation in this hopefully typical galaxy at the crucial epoch of $z \sim 2$.

2. METHODS

RCS0327 was observed on 2010 February 4 UT with the NIRSPEC spectrograph (McLean et al. 1998) on the Keck II telescope. The weather was clear, and the seeing was measured as $0.85$ and $0.45$ when the telescope was focused during the night. We used the low-resolution mode and the $0.76 \times 42''$ long slit. We targeted the brightest lensed galaxy RCS0327 at $z = 1.7037$, $m_B = 19.15$, and its redshift was confirmed by deep follow-up imaging, spectral energy distribution (SED) modeling, and preliminary lensing analysis. In this paper, using 1.3 hr of integration with NIRSPEC on Keck, we determine with unprecedented precision the physical conditions of star formation in this hopefully typical galaxy at the crucial epoch of $z \sim 2$.

We reduced the spectra using the nirspec_red Oceanara package written by one of us (G. D. Becker), which uses lamp exposures to flatten the data, the skylines to wavelength calibrate, and optimally fits and subtracts the sky following Kelson (2003). For each frame, we measured the spatial profile of the lensed arc by fitting the brightest emission lines, then used this spatial profile to optimally extract the spectrum.

The arc is extended over $38''$, roughly $10''$ of which was captured by the NIRSPEC slit. In a subsequent paper, we will analyze the spatial variation of physical conditions across the arc. In this paper, we consider the integrated spectrum.

Each extracted spectrum was corrected for telluric absorption and fluxed using the tool xtellar general (Vacca et al. 2003), using the closest-in-time observation of the AOV standard star. The flux level is thus appropriate for the fraction of the galaxy...
inside the slit, not for the whole galaxy. In Section 3.3, we estimate the factor by which our NIRSPEC fluxes should be scaled to represent the whole galaxy.

Using a telluric standard to flux the spectra provides excellent relative fluxing within a given filter, but because observations were taken in three separate filters, there can be offsets between filters due to differential slit losses, due for example to changes in seeing or pointing. In addition, the lines in filter NIRSPEC-6 are observed right at the edge of an atmospheric transmission window, and thus may suffer especially high telluric variability. We address these issues in Section 3.2.

For each filter, we combined the individual flux-calibrated one-dimensional spectra with a weighted average, producing one fluxed spectrum for each of the three filters.

We fit line fluxes as follows. We fit each isolated line with a Gaussian to measure the line flux, using Levenberg–Marquardt fitting code MPFITFUN (Markwardt 2009). We report line fluxes in Table 2.

We assume a cosmology of \( \Omega_m = 0.3, \Omega_{\Lambda} = 0.7, \) and \( H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1} \). Solar abundances are taken from Table 1 of Asplund et al. (2009). The initial mass function (IMF) is Chabrier (2003) unless noted.

### Table 1

| Filter     | t (s) | Wavelength Range (\( \mu \text{m} \)) |
|------------|-------|---------------------------------------|
| NIRSPEC-1  | 1200  | 0.948–1.16                            |
| NIRSPEC-3  | 2400  | 1.14–1.43                             |
| NIRSPEC-6  | 1200  | 1.76–2.19                             |

3. RESULTS

Figure 2 plots the spectra. Several of the nebular emission lines are detected at very high signal-to-noise ratio (S/N); for example, we detect \(~50,000\) net counts in the \( H\beta \) line. Continuum is detected in filters NIRSPEC-1 and NIRSPEC-3 at \( S/N \lesssim 1 \text{ pixel}^{-1} \). Continuum is not confidently detected near the lines of interest in NIRSPEC-6, which is unsurprising given the low atmospheric transmission at those wavelengths.

#### 3.1. Extinction

Based on SED fitting, Wuyts et al. (2010) report low extinction values of \( E(B-V) = 0.03–0.11 \), depending on metallicity and spatial position. Given the potential degeneracies when fitting SEDs between extinction and age and SFR, a spectroscopic measurement of the extinction is desired.

The \( \alpha, \beta, \gamma, \) and \( \delta \) transitions of the Balmer series are detected; \( H\epsilon \) is formally undetected. The correction for stellar absorption, \( \sim 2 \text{ Å} \) (McCull et al. 1985), is negligible at these extremely high equivalent widths: \( E_r = 430 \pm 70 \text{ Å} \) and 100 and 20 Å for \( H\beta \) and \( H\gamma \).

\( H\alpha \) appears in filter NIRSPEC-6, \( H\gamma \) and \( H\beta \) in NIRSPEC-3, and \( H\delta \) and \( H\epsilon \) in NIRSPEC-1. A line is detected at the position of \( H\delta \), but is too strong to be \( H\delta \) alone. We suspect it is a blend of \( H\delta \) with two \( H\epsilon \) lines, as seen in the Orion Nebula (Osterbrock et al. 1992).

Because they appear in the same filter, the \( H\beta/H\gamma \) and \( H\delta/H\epsilon \) line ratios are free from relative fluxing errors. We measure \( H\beta/H\gamma = 2.39 \pm 0.37 \), which for Case B recombination at \( T = 10^4 \text{ K} \) and \( n_e = 100 \text{ cm}^{-3} \) yields \( E(B-V) = 0.23 \pm 0.23 \).\(^7\) The \( H\delta/H\epsilon \) ratio of \( >1.87 \) does not constrain the extinction given measurement errors. The best spectroscopic measure of extinction therefore comes from the \( H\beta/H\gamma \) ratio, which for \( R = 3.1 \) yields \( A_v = 0.7 \pm 0.7 \).

The high end of this range is inconsistent with the blue color of the arc, as quantified by the SED fitting of Wuyts et al. (2010). Therefore, in the rest of this paper we will report results assuming first \( A_v = 0.0 \) and then \( A_v = 0.7 \). This considerable uncertainty in the extinction will limit how well we can measure spectral diagnostics that span a large range of wavelength, for example in the 23. A more precise measurement of the extinction

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\(^7\) Using the extinction law of Cardelli et al. (1989).
awaits simultaneous observations of Hα and Hβ, or a longer integration on Hγ and Hβ.

3.2. Tweaking the Flux Calibration

As discussed in Section 2, there may be fluxing offsets among the three filters. We address this issue using the Balmer series. Assuming an extinction of $A_v = 0.7$ as measured from the $H\beta/H\gamma$ ratio in NIRSPEC-3, we tweak the relative scalings of the NIRSPEC-1 and NIRSPEC-6 spectra to bring $H\alpha/H\beta$ and $H\delta/H\beta$ to the appropriate ratios for this extinction. This increases the flux in NIRSPEC-1 by a factor of 1.15 relative to NIRSPEC-3 and decreases the flux in NIRSPEC-6 by a factor of 0.61 relative to NIRSPEC-3. These are reasonable corrections given the slit loss variation expected from seeing changes and atmospheric transparency issues in NIRSPEC-6. Fluxes reported in this paper reflect this scaling.

In Table 2, we report the line fluxes in filters NIRSPEC-1, -3, and -6. Line flux ratios within a filter should be precise, limited by the uncertainty in line -fitting. When calculating a line flux ratio for lines spanning different filters, one should include a 10% relative fluxing uncertainty.

3.3. Fraction of the Galaxy Covered

To estimate the fraction of the galaxy covered by the slit, we use the PANIC/Magellan images in J and K_s of Wuyts et al. (2010), which had seeing of FWHM = 0'.57 and 0'.51. We estimate that 37% ± 5% of the total arc light falls into a slit positioned as in Figure 1, neglecting slit losses. We compute slit losses for seeing of 0'.8–0'.9 and pointing errors of 0'.25. We conclude that 32% ± 4% (random) ± 1% (systematic) of the continuum light should have been captured by our NIRSPEC slit.
We now estimate this quantity in an alternate way. We measure the continuum adjacent to the 3737 Å and Hβ lines as 6.1 × 10^{-18} and 6.0 × 10^{-18} erg s^{-1} cm^{-2} Å^{-1} (using a robust average), with measurement errors of 10%–20%. These continuum levels are 21% of the continuum intensity in the SED in Figure 7 of Wuyts et al. (2010), which is the best fit to the u, B, g, r, i, z, J, H, Ks photometry of the whole arc.

These two methods disagree by 38%. We suspect that the continuum method is as fault, as the continuum is not well detected, and small DC offsets might plausibly be introduced in sky subtraction. (Indeed, this uncertainty in the continuum level is why we chose to flux using AOV stars rather than multiplying line equivalent widths by f_j from broadband photometry as in Teplitz et al. 2000.) Therefore, we adopt the first method and will multiply our NIRSPEC fluxes by the reciprocal, 3.12 ± 0.4, to convert to the expected line flux over the whole arc.

3.4. Average Magnification

Wuyts et al. (2010) measure an average magnification of μ = 17.2 ± 1.4 for RCS0327. Our current lensing model, based on ground-based photometry (Wuyts et al. 2010), has insufficient spatial resolution to determine the magnification of each small knot. Thus, at present we cannot quote a reliable magnification for the portion of the arc that falls in our NIRSPEC slit. It is likely that some of the bright knots are much more highly magnified than the arc on average. For the time being we will adopt the average magnification with these caveats. Fortunately, except for the SFR derived from the Balmer lines, none of the results in this paper depend on the magnification within the NIRSPEC slit.

3.5. Redshift

We fit the mean emission line redshift as 1.7037 ± 0.0001 using the NIST linelist,8 excluding [O ii] 3727 because it is a partially resolved doublet. This compares perfectly with the redshift of rest-UV emission lines in our (not yet published) MagE/Magellan spectrum: 1.70369 ± 0.00006. The MagE spectrum also yields a redshift for absorption lines in the interstellar medium (ISM): Si ii 1260, Si ii 1808, and Al ii 1670, recommended to us by C. Tremonti as isolated ISM lines, yield an ISM redshift of 1.702671 ± 0.0003. Thus, the MagE spectra show that the ISM is blueshifted from the nebular lines by 110 ± 30 km s^{-1}. Our measured redshifts are 3σ and 2σ higher than the 1.7009 ± 0.0008 reported by Wuyts et al. (2010) using a combination of the [O ii] 3727 and C ii] 1909 emission lines and the Fe ii and Mg ii absorption lines.

3.6. Velocity Width

We extract arc lamp spectra using the same apertures as the science frames and combine with the same weighted average technique as for the science frames. For each filter, we fit the instrumental line width versus wavelength relation with a linear fit, then interpolate the instrumental line width at the wavelength of each astronomical line of interest. For example, the observed wavelength of Hα, the arc lines have FWHM = 13.6 Å compared to FWHM=15.3 Å observed for Hα; from this, we infer σ = 50 ± 2 km s^{-1}. For Hγ, Hβ, λ4959, and λ5007, we measure σ = 76, 59, 49, 23 km s^{-1}. With Hα, this gives an average nebular line velocity dispersion of σ = 51 km s^{-1} with an error in the mean of 9 km s^{-1}.

As shown in Figure 3, we fit the [O ii] 3726, 3729 doublet with two Gaussians, fixing the line centers using the NIST vacuum wavelengths and redshift from Section 3.5, and forcing the two line widths to be the same, while varying the continuum, line amplitudes, and the line width. This fitting finds that σ = 51 ± 1 km s^{-1} for [O ii].

Because the lensing morphology of RCS0327 is complex, we cannot yet compute a meaningful effective radius, as needed to determine a dynamical mass from the velocity width. Upcoming Hubble Space Telescope (HST) observations should clarify this matter.

3.7. Star Formation Rate

Wuyts et al. (2010) estimated the SFR by fitting the broadband optical and near-IR photometry, finding an SFR constraint of <77 M⊙yr^{-1} for 40% solar metallicity. (For solar metallicity the SFR is lower.)

We also estimate the SFR from mid-IR photometry. We measure the main arc and counterimage separately, finding MIPS/Spitzer 24 μm flux densities of 1040 ± 153 μJy and 43 ± 11 μJy, respectively. Scaling by the average magnifications for the main arc and counterimage from the current lensing model (Wuyts et al. 2010) yields de-lensed 24 μm flux densities of 60 ± 10 μJy for the main arc versus 21 ± 6 μJy for the counterimage. The de-lensed 24 μm flux density of the main arc corresponds to an SFR of 106 ± 30 M⊙yr^{-1} using the prescription of Rieke et al. (2009). The equivalent value from the counterarc is 18 ± 8 M⊙yr^{-1}.

The significant difference between the de-lensed flux densities suggests that the source is strongly non-uniform; resolving this requires a more precise lensing model and a robust comparison of the observed! image-plane data (both spectra and photometry) in the source plane. Until HST imaging of this source is available, the best comparison to the spectra presented here is the main arc, as the spectra sample a portion of that image.

Third, we estimate the SFR from the NIRSPEC spectra, using the Hβ line flux within the aperture, assuming the

8 http://www.pa.uky.edu/~peter/atomic/
extinction from Hβ/Hγ, and the SFR(Hα) conversion of Kennicutt (1998), modified for a Chabrier (2003) IMF following Equation (10) of Rieke et al. (2009):

\[
L(H\alpha) = f(H\beta)(H\alpha/H\beta)4\pi d_L^2/u
\]

\[
= (3.2 \pm 0.1) \times 10^{-15}(3.6 \pm 0.8)4\pi d_L^2/u \tag{1}
\]

\[
= (2.25 \pm 0.5) \times 10^{44}/u \text{ erg s}^{-1} \tag{2}
\]

\[
= (5.9 \pm 1.3) \times 10^{10}/uL_\odot \tag{3}
\]

\[
\text{SFR}(H\alpha) = 0.66 \times L(H\alpha) \times 7.9 \times 10^{-42} \text{ erg s}^{-1} \tag{5}
\]

\[
= (1170 \pm 270) M_\odot \text{yr}^{-1}/u. \tag{6}
\]

A rough method of computing the total SFR is to divide by the average magnification from Wuyts et al. (2010) and multiply by the fraction of the light in the image plane captured by the average magnification of the whole arc, rather than it does suggest that the magnification of this part of the arc is significantly higher than other parts of the arc. Thus, the rough method of computing the total SFR is probably wrong because it uses the average magnification of the whole arc, rather than the magnification of each pixel within the NIRSPEC slit.

A simpler method would be to measure the emission line flux over the entire arc, or at least all of the counterarc, which is more compact and thus easier to map. Pending narrowband \textit{HST} imaging of Hβ should provide this coverage for RCS0327.

The three different methods give quite different answers for the SFR. Only the brightest portion of the main arc was observed with NIRSPEC; this portion of the arc is possibly the brightest because of a conflation of a bright region within the source with a region of larger-than-average magnification, from which we would expect the spectral SFR to be larger than that derived from the average main arc 24 μm flux density, as observed. A robust treatment of this comparison awaits a refined lensing model and reconstruction of source in the source plane.

Imaging is also biased toward regions of high surface brightness, and overrepresents certain portions of the galaxy, but it does capture the entire image plane, and thus should deliver accurate quantities such as average magnification, total magnitudes, and colors.

3.8. Ionization Parameter

Figure 1 of Kewley & Dopita (2002) illustrates the λ5007/λ3727 flux ratio as a diagnostic of the ionization parameter. For an O abundance of 20%–40% solar (on the Asplund system), Equation (12) of Kewley & Dopita (2002)\(^9\) yields an ionization parameter of \( \log U = -2.73 \) to \(-2.85 \) for \( A_v = 0.7 \). For \( A_v = 0 \), \( \log U \) is higher by 0.1 dex. The uncertainty due to extinction dominates over the flux uncertainty.

3.9. Electron Density

The two-component fit to the [O iii] doublet in Section 3.6 (Figure 3) found a line flux ratio of \( f(3726/3729) = 0.893 \pm 0.024 \), where this uncertainty is dominated by the uncertainty in deblending the doublet. This ratio is density-dependent (cf. Figure 5.8 of Osterbrock & Ferland, 2006). Using \texttt{stsdas.analysis.temden} in IRAF,\(^10\) our measurement corresponds to a tight measurement of the density: \( n_e = 235^{+28}_{-26} \times 10^4 \text{ cm}^{-3} \) at \( 1.2 \times 10^4 \text{ K} \).

The ratio of the C iii 1907/1909 doublet also constrains the density (Rubin et al., 2004, their Figure 2). Fitting the doublet in our Mage/Magellan spectra (J. R. Rigby et al., 2011, in preparation) in the same way as the 3727 doublet, we measure a flux ratio of \( f(1907/1909) = 2.16 \pm 0.3 \). This ratio is unphysical by \( 1.7\sigma \), as the zero-density limit is \( 1.65 \) for pure C13 and \( 1.51 \) for pure C12 (Rubin et al., 2004). While deeper data should provide a better measurement of this line ratio, the current measurement of the C iii] ratio is consistent with the low density regime of this diagnostic of \( n_e \lesssim 10^{3.5} \text{ cm}^{-3} \).

The doublet ratio of [S ii] 6716, 6731 Å also constrains the electron density (cf. Figure 5.8 of Osterbrock & Ferland, 2006). Unfortunately, the redder line is mostly lost to a skyline. Fitting in the same way as for the 3727 doublet, we measure a doublet ratio of \( 2.4 \pm 0.4 \), which is unphysical by \( 2.4\sigma \) (the zero-density limit is \( 1.43 \)). This unphysical result is likely due to the skyline contamination; we conclude that in this case we cannot use the [S ii] ratio to constrain the electron density.

To summarize, the [O iii] 3727 doublet ratio provides a tight density constraint, which is consistent with the low density regime indicated by the C iii] 1909 doublet. The [S ii] doublet is contaminated by a skyline and provides no density constraint.

3.10. Electron Temperature

The ratio [O iii] (λ5007+λ4959)/λ4363 constrains the electron temperature with almost no \( n_e \) dependence (cf. Izotov et al., 2006; Figure 5.1 of Osterbrock & Ferland, 2006). The ratio in RCS0327 is \( >139 \) for \( A_v = 0.0 \) and \( >121 \) for \( A_v = 0.7 \). Following Izotov et al. (2006), this corresponds to \( T_e \leq 1.14 \times 10^4 \text{ K} \), \( \leq 1.20 \times 10^4 \text{ K} \), and \( \leq 1.26 \times 10^4 \text{ K} \) for \( A_v = 0.0, 0.7 \), and 1.4.

3.11. Oxygen Abundance

We constrain the oxygen abundance via the “direct” or “\( T_e \)” method following Izotov et al. (2006), using the non-detection of [O iii] 4363 Å to constrain \( T_e \). [O iii] 3727 Å and Hβ to constrain (O"/H") and [O ii] 4959, 5007, and Hβ to constrain (O2+ /H+). Since He ii 4686 is not detected, we can ignore the contribution of O++. The result is \( 12 + \log(O/H) > 8.21 \) for \( A_v = 0.0 \) and \( >8.14 \) for \( A_v = 0.7 \); these are 0.48 and 0.55 dex lower than the solar value of 8.69 ± 0.05 (Asplund et al., 2009).

\(^9\) Which uses the Anders & Grevesse (1989) abundances; we convert to Asplund et al. (2009).
\(^10\) IRAF is distributed by the National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.
We compare this “direct” lower limit on the oxygen abundance to results from the bright-line diagnostics. We follow the calibrations for each diagnostic, then remove the relative offsets via the conversions of Kewley & Ellison (2008), so that all diagnostics are on the system of the N2 index of Pettini & Pagel (2004). The bright-line results are as follows.

1. The N2 index, log([N II]/Hα) = −1.19 ± 0.07, yields 12 + log(O/H) = 8.20 ± 0.04 by the third-order polynomial calibration of Pettini & Pagel (2004) and 8.22 ± 0.04 by their linear fit. Each of these two calibrations was reported to have a 1σ spread against $T_e$ of 0.18 dex (Pettini & Pagel 2004). Reddening is irrelevant.

2. The N2 index calibration of Denicoló et al. (2002) yields 12 + log(O/H) = 8.20 ± 0.05.

3. The O3N2 index, log((5007/Hβ)/(N II/Hα)) = 1.88 ± 0.07, yields 12 + log(O/H) = 8.16 ± 0.02 by the calibration of Pettini & Pagel (2004), which has a 1σ spread of 0.14 dex. Reddening is irrelevant.

4. The index log([N II] 6584)/[O II] 3727) is −0.99 ± 0.07 for $A_v = 0$ and −1.19 ± 0.07 for $A_v = 0.7$. The calibration of Kewley & Dopita (2002) as modified by Kewley & Ellison (2008) produces a double-valued abundance: 12 + log(O/H) = 8.21, 8.34 ± 0.06 for $A_v = 0$; and 12 + log(O/H) = 8.21, 8.22 ± 0.06 for $A_v = 0.7$.

5. The Ne3O2 index, log([Ne II]3869/[O II]3727) = −0.96 ± 0.07, yields 12 + log(O/H) = 8.19 ± 0.08 via the calibration of Shi et al. (2007). Reddening is irrelevant. This diagnostic does not appear in Kewley & Ellison (2008), so we cannot remove any calibration offsets.

The $R_{23}$ index, log([O III]λ3727 + λ4959 + λ5007)/Hβ, is unfortunately double-valued as well. We measure log $R_{23}$ as 0.94, 0.96, 0.99 for $A_v = 0, 0.7, 1.4$, all with uncertainties of ±0.02 from the propagated flux uncertainty. (This is similar to the value of 0.92 measured for cBS8 by Teplitz et al. 2000.) Such a high $R_{23}$ requires a high ionization parameter ($\log U \geq -2.87$ from Figure 5 of Kewley & Dopita 2002). Several $R_{23}$ calibrations use various means to separate the “lower branch” and “upper branch,” typically [N II]/[O II] or [N II]/Hα (Kewley & Ellison 2008). Unfortunately, for RCS0327 these ratios are on the border between upper and lower branch. Thus, we compute the abundance for each branch.

1. Zaritsky et al. (1994) published an $R_{23}$ calibration for the upper branch only. We use it with caution since RCS0327 is not clearly in either the upper or lower branch. For $A_v = 0$, this calibration yields 12 + log(O/H) = 8.15 ± 0.02. For $A_v = 0.7$, it yields 8.14 ± 0.02.

2. The Pilyugin & Thuan (2005) method yields 12 + log(O/H) = 8.26 ± 0.05 and 8.07 ± 0.08 for the upper and lower branches for $A_v = 0$, and 8.19 and 8.22 (same uncertainties) for $A_v = 0.7$.

3. The Kobulnicky & Kewley (2004) method yields 12 + log(O/H) = 8.19 and 8.16 ± 0.02 for the upper and lower branches and $A_v = 0$, and 8.17 ± 0.02 for both branches at $A_v = 0.7$.

These inferred abundances are plotted in Figure 5.

3.12. Abundances of Other Elements

Following Izotov et al. (2006), we constrain the abundance of N+, Ne2+, Ar2+, and Ar3+ relative to H+. Unlike O, the full suite of ionization states is not observed for these elements, so we must apply ionization correction factors to infer abundances.

1. N: we derive 12 + log(N/H) > 6.53 (>6.42) for $A_v = 0$ (0.7). Thus, N is depleted relative to the solar value by no more than 1.41 dex. The uncertainty from extinction is larger than from flux uncertainties.

2. Ne: we derive 12 + log(Ne/H) > 7.33 ± 0.09, which is 0.60 dex below solar.

3. Ar: we derive 12 + log(Ar/H) > 5.54 ± 0.18, which is 0.86 dex below solar.

Though we have measured lower limits on all abundances, we can tightly constrain the key abundance ratios, which depend only weakly on $T_e$.

1. N/O: for the maximum allowed $T_e$, log(N/O) = −1.70 ± 0.02. If the λ4363 flux is one-third the upper limit, then $T_e$ is 70% of the maximum and log(N/O) = −1.89 ± 0.04. These ratios are 0.84 ± 0.02 to 1.03 ± 0.04 dex below the solar abundance ratio.

2. Ne/O: for the maximum allowed $T_e$, log(Ne/O) = −0.89 ± 0.09 for $A_v = 0$, which is 0.13 dex below the solar ratio. For $A_v = 0.7$, the ratio is log(Ne/O) = −0.72 ± 0.09, which is 0.04 dex above solar. At 70% of the maximum permitted $T_e$, the constraints are from 0.03 dex below to 0.14 dex above solar. Thus, no matter the actual $T_e$, the Ne/O ratio must be solar-like.

3. Ar/O: for the maximum allowed $T_e$, log(Ar/O) = −0.89 ± 0.18, which is 0.13 dex below the solar value. For 70% of the maximum permitted $T_e$, log(Ar/O) = −0.62 ± 0.18, which is 0.14 dex above solar.

Thus, RCS0327 has an abundance pattern in which the O abundance is at least 29% of solar, the Ne/O and Ar/O ratios are solar-like, and the N/O ratio is less than 15% of the solar ratio.

3.13. Joint Constraints on Physical Conditions from Photoionization Models

As a cross-check on these diagnostics, we run spectral synthesis and photoionization models. The UV spectra come from Starburst 99 (v5.1, Web version; Leitherer et al. 1999 and Vázquez & Leitherer 2005), assuming continuous star formation, an upper mass cutoff of 100 $M_\odot$, the default IMF parameters, the Padova asymptotic giant branch models, and with stellar metallicity set at 40% of solar. We feed these UV spectra to the photoionization code Cloudy version c08.00 (Ferland et al. 1998), running a grid of models of given electron density and starburst age, and in each model optimizing the metallicity and ionization parameter, as constrained by the measured line intensities relative to Hβ, assuming a foreground screen extinction of $A_v = 0.7$, the measured uncertainties for lines contiguous with Hβ, and 20% relative fluxing errors for noncontiguous lines. The abundance pattern is “HII” region. Our grid of electron density covers ±1σ of the value measured in Section 3.9.

Cloudy computes an average electron temperature of $T_e = 1.19 \times 10^4$ K, which is consistent with the value inferred in Section 3.10. Cloudy converges on an oxygen abundance in the range 12 + log(O/H) = 8.07−8.13 and an ionization parameter in the range log $U = -2.57$ to $-2.42$. Figure 4 illustrates these constraints. Thus, Cloudy converges on an O abundance that is 0.1 dex lower than via the $T_e$ method, and a log $U$ that is higher by 0.2–0.3 dex than derived from the Kewley & Dopita (2002) method.

The source of this discrepancy may lie with different assumptions of abundance pattern, filling factor, atomic data, or ionizing.
stellar spectra compared to Kewley & Dopita (2002). Resolving this moderate discrepancy is outside the scope of this paper at this time, but it provides a caution that one must be careful, when comparing derived physical properties of galaxies, to use the same methodology. In this paper, we will adopt the log U derived via the Kewley & Dopita (2002) method, so that we may compare to other lensed galaxies in the literature.

Dust grains were not included in the Cloudy models. As a test, we added dust grains with the same metallicity and abundance pattern as the gas, which changed the inferred metallicity and ionization parameter by only 2% and 1%.

4. DISCUSSION

Since this is the first investigation of the rest-frame optical lines in RCS0327, only the brightest “knots” were targeted, representing only 32% ± 4% (random) ±1% (systematic) of the total light of the arc (Section 3.3). RCS0327 was selected as the brightest and one of the largest lensed sources in a large survey; despite its exceptional appearance, SED and lensing modeling show it to be a fairly typical object (Wuyts et al. 2010). As such, it is likely that the high surface brightness portions of the source galaxy coincide with high magnification and that this coincidence makes RCS0327 such a spectacular example of strong lensing. This supposition would explain the differing SFRs derived from 24 μm imaging of the main arc and counterimage, as noted in Section 3.7. Moreover, because the lensed source straddles the lensing tangential caustic (cf. Figure 6 in Wuyts et al. 2010), the lens model suggests that only some regions of the galaxy are represented in the giant arc, namely the core, and one of two apparent spiral arms, and may be highly magnified. Thus, the giant arc is likely not a fair representation of the source galaxy as a whole.

Since superb spectra can be quickly obtained for these bright knots, it is their physical conditions that we probe in this paper, with a caveat that these may not be “ordinary” regions of this galaxy. Once the arc has been fully mapped in these emission lines, and a high-resolution lensing map has been derived from HST imaging, we should understand how much the physical conditions vary across the source plane and locate the brightest knots in the source plane. It will then be possible to fully contextualize our results in terms of the range of physical conditions across the spatial extent of RCS0327.

For now, we assume that the knots for which we have spectra are representative. Since these are highest-quality rest-frame optical spectra ever obtained for a z = 2 galaxy, and yield precise measurements of the physical conditions, we now consider these measurements in the context of the literature and the conditions under which stars form in the distant universe.

4.1. Extinction

The following $E(B - V)$ extinctions have been measured from Balmer decrements in lensed blue galaxies: 0.27 for cB58 (Teplitz et al. 2000), 0.28 ± 0.04 for the Clone (Hainline et al. 2009), 0.45 ± 0.04 for the Cosmic Horseshoe (Hainline et al. 2009), 0.59 ± 0.08 for J0900 (Bian et al. 2010), and 0.67 ± 0.21 for the 8 o’clock arc (Finkelstein et al. 2009). Our measurement of $E(B - V) = 0.23 ± 0.23$ for RCS0327 is consistent with the lower part of this range, but the uncertainty is large, stemming mostly from the flux uncertainty in H$\alpha$. A spectrograph that obtains H$\alpha$ and H$\beta$ simultaneously, for example FIRE on Magellan or LUCIFER on the Large Binocular Telescope (LBT) would provide a very precise measurement of the Balmer decrement in this galaxy, allowing a detailed comparison of the relative extinctions suffered by the gas and the stars.

4.2. The Reliability of O Abundance Diagnostics at z = 2

For RCS0327, the non-detection of [O iii] 4363 Å sets a strict constraint on the oxygen abundance via the “direct” $T_e$ method: it must be no more than 0.55 dex (0.48 dex) below the solar value for $A_v = 0.7$ ($A_v = 0$) or 28% and 33% as percentages of solar. Neon provides a cross-check on this abundance measurement. Since both Ne and O are alpha-group elements, their ratio should be solar-like, and indeed our measured ratio is solar with an uncertainty of ±0.14 dex. We believe this to be the first time the Ne/O ratio has been measured at $z \approx 2$.

We now accept the $T_e$ method’s oxygen abundance measurement and assess the reliability of the “bright-line” diagnostics. These diagnostics are empirically calibrated at $z = 0$ against the $T_e$ method or calibrated with photoionization models. As such, they implicitly assume densities and ionization parameters typical of nearby galaxies, which may not be appropriate for high-redshift galaxies, for reasons of luminosity bias and evolution in the galaxy population. In addition, these diagnostics have significant relative offsets (up to 0.7 dex) at $z = 0$ whose origins are not understood and which must be empirically calibrated away using Sloan Digital Sky Survey (SDSS) galaxies (Kewley & Ellison 2008); it is not clear that for rapidly star-forming $z = 2$ galaxies these offsets will be the same.

Thus, it is important to test these bright-line diagnostics in situ at $z = 2$. Figure 5 compares the O abundances inferred in Section 3.11 for the bright-line diagnostics in RCS0327. For ease of comparison, we plot $A_v = 0$ and $A_v = 0.7$ separately. We divide the calibrations into five categories: [N ii]/[O ii], Ne3O2, N2, O3N2, and R23 methods.

The [N ii]/[O ii] diagnostic (Kewley & Dopita 2002) is consistent with the $T_e$ method, in part because its double-valued results and the large uncertainty covers 0.3 dex of parameter space. Because this index has a large extinction correction, we cannot adequately test it until the extinction of RCS0327 is more precisely measured.
The Ne3O2 diagnostic is consistent with the $T_e$ method, especially for $A_V > 0$.

The N2 calibrations of Pettini & Pagel (2004) and Denicoló et al. (2002) are consistent with the lower limit from the $T_e$ method, especially for $A_V > 0$. This test is especially important, since this diagnostic is the one used to measure the evolution in the mass–metallicity relation from $z = 0$ to $z = 2$ (Erb et al. 2006) and $z = 3$ (Mannucci et al. 2009; Maiolino et al. 2008; Richard et al. 2011).

The O3N2 diagnostic (Pettini & Pagel 2004) yields an abundance that is $2.5\sigma$ below the $T_e$ lower limit for $A_V = 0$ and is thus inconsistent with the $T_e$ limit. However, moderate extinction ($A_V = 0.7$) makes the results consistent. The O3N2 result is lower than the abundances from the N2 and [N II]/[O III] indices.

The R23 index has a large extinction correction. As such, it is difficult to assess the performance of this diagnostic given the current uncertainty in the extinction of RCS0327. For $A_V = 0$, only the upper branch of Pilyugin & Thuan (2005) is consistent with the $T_e$ result; for $A_V = 0.7$ the Pilyugin & Thuan (2005) method is also consistent. The Zaritsky et al. (1994) method produces an inconsistent result, but this is unsurprising since it is only valid for high metallicity.

This is the first test in situ at $z = 2$ of the bright-line abundance diagnostics for a star-forming galaxy of typical metallicity. To summarize, the R23 and [N II]/[O III] methods are not inconsistent with the $T_e$ method so long as the extinction exceeds zero; the definitive test must await a more precise extinction measurement, since both diagnostics have large reddening corrections. The Ne3O2 diagnostic is consistent with the $T_e$ method, though the error bars are larger than for N2 and O3N2, since [Ne III] is not a terribly bright line. The N2 and O3N2 methods are most constraining given the current extinction measurement: of these, the N2 results are entirely consistent with the $T_e$ method, and the O3N2 diagnostic is consistent only given significant but plausible extinction.

The only other published $T_e$ measurement at $z = 2$ of which we are aware is in Lens22.3, a low-mass, low-metallicity galaxy behind A1689 (Yuan & Kewley 2009). For Lens22.3, the $T_e$ method yields $12 + \log(O/H) = 7.5 \pm 0.1$ for zero extinction and $7.3 \pm 0.1$ for high extinction. We apply the Pettini & Pagel (2004) N2 and O3N2 calibrations to the published line fluxes of Yuan & Kewley (2009) (N ii is not detected). From N2 < $-2.30$ comes an abundance of $12 + \log(O/H) < 7.47$ (7.59) using the third-order (linear) N2 calibration. The O3N2 index, log O3N2 > 3.11, yields $12 + \log(O/H) < 7.73$ on the original Pettini & Pagel (2004) scale, which is outside the range that can be converted to the N2 frame (Kewley & Ellison 2008). These N2 and O3N2 measurements are consistent with the $T_e$ result. However, all these diagnostics are highly inconsistent with the R23 result of $12 + \log(O/H) = 8.0$–8.3 (Yuan & Kewley 2009).

Yuan & Kewley (2009) noted the discrepancy between the R23 and $T_e$ results and attributed the fault to the $T_e$ method. Given the consistency between the N2, O3N2, and $T_e$ methods, we suggest that it may instead be R23 that is failing in Lens22.3.

4.3. The Reliability of O Abundance Diagnostics in Other $z = 2$ Lensed Galaxies

Only in RCS0327 and Lens22.3 are the spectra sufficient to measure abundances via the $T_e$ method. However, the bright-line diagnostics have been used for a number of galaxies. A re-analysis of the mass–metallicity relation at $z \geq 2$ is outside the scope of this paper. However, it is appropriate at this juncture to re-examine the N2 and O3N2 diagnostics in light of the results above. In Figure 6, we plot the mass–metallicity relation at $z = 2$, using literature results for lensed and unlensed galaxies, and our results for RCS0327. For fair comparison, we convert stellar masses to the Chabrier (2003) IMF, take line fluxes from the literature, and apply the N2 and O3N2 calibrations of Pettini & Pagel (2004), brought to the N2 system via the conversion$^{11}$ of Kewley & Ellison (2008).

We plot four lensed galaxies in Figure 6: cB58 (Teplitz et al. 2000), J0900+2234 (Bian et al. 2010), the 8 o’clock arc (Finkelstein et al. 2009), and RCS0327 (this work). These four galaxies span a range of 400 in stellar mass, extending below the mass range probed by stacked samples (Erb et al. 2006). In all four cases, the O3N2-derived abundances are systematically lower than those derived from N2, strikingly so in the case of the 8 o’clock arc. (Recall that the relative offset between these indices, as measured in SDSS at $z = 0$, has already been removed.) These offsets were noted for each galaxy in their respective papers, but were dismissed as less than the calibration dispersion of the diagnostics. The Clone and Horseshoe lack stellar mass measurements to plot them on Figure 6, but comparison of their N2- and O3N2-derived abundances shows the same trend: the O3N2 index is low by 0.16 and 0.07 dex.

$^{11}$ This conversion is modest ($< 0.05$ change in $12 + \log(O/H)$) at these metallicities.
Teplitz et al. (2000) and Siana et al. (2008); the 8 o’clock arc from Finkelstein et al. (2009) of unlensed $z_e = 2$ LBGs from Erb et al. (2006; hollow squares), as well as four lensed galaxies at $z = 2$: J0900+2234 from Bian et al. (2010); cB58 from Teplitz et al. (2000) and Siana et al. (2008); the 8 o’clock arc from Finkelstein et al. (2009); and RCS0327 from this work (filled points). For consistency, when authors fit stellar masses using a Salpeter IMF, we have converted to a Chabrier IMF.

This behavior is not surprising when we consider that O3N2 has 5007/αHβ in the numerator, and that what makes $z_e = 2$ galaxies stand out in the BPT diagram of Baldwin et al. (1981) is their high 5007/αHβ compared to SDSS galaxies. Thus, we suggest that high ionization conditions in $z_e = 2$ galaxies cause the O3N2 diagnostic to function poorly at these redshifts.

4.4. Lensed Galaxies and the $z_e = 2$ Mass–Metallicity Relation

RCS0327 has a stellar mass of $M_\star = 10.0 \pm 0.1 M_\odot$ (Wuyts et al. 2010); both the main arc and the counterarc give consistent results. This is $0.94 \pm 0.14$ dex lower than the Schechter function parameter $M_{\star, 26}$ at $z = 2.0$ (Marchesini et al. 2009) and lower than most of the Lyman break galaxies in Erb et al. (2006). The low-measured velocity dispersion qualitatively supports a low mass. In the mass–metallicity plane, RCS0327 lies significantly, $0.17\pm0.04$ dex, below the $z_e = 2$ relation of Erb et al. (2006). This offset is too large to be measurement error, and so we attribute it instead to a real abundance difference: RCS0327 is metal-poor by about 50% for its stellar mass and redshift, compared to Erb et al. (2006).

J0900+2234 shows this effect to an even greater degree (Bian et al. 2010), since it has almost the same N2-derived oxygen abundance and a slightly higher stellar mass.

On the high-mass end, the N2-derived oxygen abundance of the 8 o’clock arc is quite consistent with the high–mass side of Erb et al. (2006), perhaps $0.05–0.08$ dex low. By contrast, at the very low mass end, cB58 lies far off the relation, having a very low stellar mass but a high oxygen abundance, more typical of the mass–metallicity relation at $z = 0$ than at $z = 2–3$. Thus, even from a modest sample of four lensed galaxies, we are already beginning to probe the intrinsic spread in the mass–metallicity relation at $z = 2$.

4.5. Abundance Pattern

In Section 3.12, we constrained the N/O ratio as $\log(N/O) \leq -1.70$. For plausible values of $T_e$, the ratio can be lower by 0.2 dex. These abundances are startlingly close to the values measured for cB58: $\log(N/O) = -1.76 \pm 0.2$ dex (Pettini et al. 2002) and $12 + \log(O/H) = 8.26$ (Teplitz et al. 2000). Even though RCS0327’s stellar mass is 18 times larger than cB58’s, and its redshift is lower, star formation in these two galaxies has produced very similar ratios of N, O, and H. UV spectroscopy for RCS0327, as in Pettini et al. (2002) for cB58, should allow element-by-element comparison of abundance ratios.

For now, we concentrate on the N/O ratio. RCS0327 lies near the intersection of the primary and secondary N production lines. In other words, it lies right on the trend for secondary N production and is somewhat below the primary plateau of $\log(N/O) \sim -1.5$. As such, its N/O ratio is at the low end of what has been measured for Hα regions in spiral galaxies of comparable O abundance and is typical of dwarf galaxies (van Zee et al. 1998). Analytic models such as Henry et al. (2000) combine both N production mechanisms to produce smooth curves of N/O versus O. RCS0327 lies on these curves near the “knee,” where the N/O ratio rapidly transitions from being independent of the oxygen abundance (“primary” production) to being highly dependent on the O abundance (“secondary” production). Comparing RCS0327 and cB58 to the numerical models of Henry et al. (2000; their Figure 3(b)) suggests that both galaxies have relatively high star formation efficiencies. With a sample of two galaxies, it is premature to draw conclusions about how galaxies build up their nitrogen, but the strict N/O and O measurements we have made bode well for the future, if such work can be repeated for a larger sample.

4.6. Ionization Parameter

Ionization parameters have been reported for a few other lensed galaxies, derived from the 5007/3727 diagnostic. Unfortunately, this diagnostic has a strong dependence on O abundance, so this must be input to the diagnostic. We use the 5007/3727 line fluxes reported by Hainline et al. (2009) for the Horsehoe and the Clone and assume 40% solar metallicity (Asplund system), as inferred for both from the N2 index. Converting to Anders & Grevesse (1989) abundances and using the calibration of Kewley & Dopita (2002), this corresponds to an ionization parameter of $\log U = -2.8$ for the Horsehoe and $-2.7$ for the Clone, without correcting for extinction. This is consistent within 0.1 dex with the values reported by Hainline et al. (2009). Teplitz et al. (2000) did not calculate an ionization parameter for cB58, so we take their line fluxes and the O abundance from Pettini et al. (2002) and find $\log U = -2.85$ for cB58 without...
correcting for extinction. Extinction dominates the uncertainty on this measurement and acts to lower the ionization parameter.

These ionization parameter measurements are entirely consistent with the value measured for RCS0327 of \(-2.73 \pm 2.85\) (for \(A_v = 0.7; 0.1\) dex higher for \(A_v = 0\)). Thus, we conclude that the four lensed galaxies examined to date with this diagnostic all have very similar ionization parameters of about \(\log U \sim -2.7\).

We now compare to local galaxies. The sample of Kewley et al. (2001) would be ideal for comparison, since these are IR-luminous galaxies at \(z \sim 0\), but unfortunately their spectroscopy did not extend blueward to 3727 Å. Instead, we turn to two papers which measured ionization parameters for 65 SINGS galaxies (Moustakas et al. 2010), 412 star-forming galaxies, and 120,000 galaxies from the SDSS (Moustakas et al. 2006), using the same methodology of calculating \(\log U\) as we do. The SINGS galaxies have a median and mode \(U\) of \(-3.0\). The SDSS and 412 star-forming galaxies (Figure 12 of Moustakas et al. 2006) have a narrow range of \(-3.2 < \log U < -2.9\). The prototypical starburst galaxy M82 has \(\log U = -2.9 \pm 0.07\).

Thus, the four lensed galaxies with measured ionization parameters all have the same measured value, within the uncertainties. This value, \(-2.7\) to \(-2.8\), is roughly twice as high as the median for samples of lower-luminosity nearby galaxies and is 30%–60% higher than for M82. Thus, the ionization parameters of these four \(z \sim 2\) star-forming galaxies are somewhat higher than local galaxies of much lower luminosity.

### 4.7. Electron Density

In Section 3.9, we derived an electron density of \(n_e = 252^{+30}_{-28} \text{ cm}^{-3} \) at \(1.2 \times 10^4 \text{ K}\) from the [O III] 3726, 3729 doublet ratio. This is currently the most precise such measurement at such high redshift. We now compare to density constraints from the literature for other lensed galaxies.

Hainline et al. (2009) measured the [S II] \(\lambda 6717, \lambda 6732\) flux ratio in two lensed galaxies. For the Clone, the result is \(0.9 \pm 0.1\) by extracting the fluxes in each of two apertures and summing, versus \(0.75 \pm 0.25\) by extracting all at once. For the Horsehoe, the result from the summed aperture is \(1.0 \pm 0.35\). Using IRAF’s temden at \(T_e = 10^4 \text{ K}\), these ratios indicate densities of \(900^{+500}_{-300} \text{ cm}^{-3}\) and \(1700^{+200}_{-100} \text{ cm}^{-3}\) for the Clone and \(600^{+400}_{-200} \text{ cm}^{-3}\) for the Horseshoe. Bian et al. (2010) measured an [S II] flux ratio of 0.86 \pm 0.2 for the sum of both apertures in J0900, which yields a density of \(1100^{+700}_{-500} \text{ cm}^{-3}\). In the rest-UV, Quider et al. (2009) measure a C III] flux ratio of \(f(1906)/f(1908) = 1.1 \pm 0.2\) for the Horseshoe, corresponding to a density range of \(5000–25000 \text{ cm}^{-3}\), which is inconsistent with the density range measured by Hainline et al. (2009).

Thus, these literature measurements of electron density are in the range \(600–5000 \text{ cm}^{-3}\), albeit with large uncertainties. The low precision of these measurements indicates a clear need for deeper spectra to better measure electron density. Nevertheless, the current measurements for the Clone, Horseshoe, and J0900 favor high electron densities, much higher than the precise value we measure for RCS0327. Thus, at present it is not clear what is a typical electron density for a star-forming galaxy at these epochs. Additional high-quality measurements are urgently needed.

### 4.8. Location in the BPT Diagram

The “BPT” diagnostic diagram of Baldwin et al. (1981) is commonly used to characterize the ionization conditions in galaxies. For RCS0327, we measure line ratios of \(\log \left( \frac{\text{[N II]}}{\text{H}α} \right) = -1.18 \pm 0.07\) and \(\log \left( \frac{5007/\text{H}β} {\text{H}α} \right) = 0.69 \pm 0.02\) for \(A_v = 0\) and 0.13 less than that for \(A_v = 0.7\). In Figure 7, we plot RCS0327 on the BPT diagram; its high \(\text{O III}/\text{H}β\) and extremely low \(\text{N II}/\text{H}α\) place it in the upper left quadrant, close to the maximal starburst line.

This is an exceptional position compared to the \(z = 0\) SDSS, which has only five galaxies in that region of the BPT diagram. However, \(z = 0\) IR-luminous galaxies do occupy that space: Kewley et al. (2001) have nine galaxies with \(\text{N II}/\text{H}α < -1\). Since extreme star formation is rare in the local universe, these luminous star-forming galaxies may be a better basis for comparison than SDSS.

It has previously been noted that \(z > 1\) galaxies tend to be offset toward higher \(5007/\text{H}β\) ratios in the BPT diagram (Shapley et al. 2005; Erb et al. 2006; Kriek et al. 2007). Brinchmann et al. (2008) proposed that this is caused by an elevated ionization parameter at higher redshift and enumerated the following possible underlying causes: a top-heavy IMF, higher electron densities, a higher volume filling factor, or a higher escape fraction of UV photons.

Figure 7 shows that of the lensed galaxies, J0900 and the Clone show an offset similar to that of the Erb et al. (2006) stacked galaxies, while the 8 o’clock arc is considerably higher, as discussed by Finkelstein et al. (2009). By contrast, RCS0327 and CB58 are not as offset—they lie between the Erb et al. (2006) points and the \(z = 0\) IR-luminous galaxies.\(^{14}\)

RCS0327 has an electron density \(n_e = 235^{+28}_{-26} \text{ cm}^{-3}\) that is lower than the best-fitting densities for the Clone, Horseshoe, and J0900, though those other measurements have very large uncertainties. Its measured ionization parameter \(2.9 \pm 0.17\) for \(A_v = 0.7\) is entirely consistent with measurements of the same diagnostic in the Horseshoe, Clone, and CB58. Thus, in two ways RCS0327 contradicts the picture of Brinchmann et al. (2008) for BPT behavior at \(z = 2\): first, though its ionization

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\(^{14}\) The Horseshoe is not plotted because \(\text{H}β\) was contaminated by a skyline (Hainline et al. 2009). CB58 was not plotted because [S II] was not observed.
parameter is the same as the other $z = 2$ galaxies, it is not as offset in the BPT diagram; second, the electron density is not very high, as has been suggested to explain offsets in the BPT diagram.

Of the IR-luminous sample of Kewley et al. (2001) with $\text{N}_\text{II}/\text{H}$ < $-1$, the median electron density is $\sim 100$ cm$^{-3}$. This is another case in which offsets in the BPT diagram do not appear to be caused by high density.

At present, too few $z = 2$ galaxies have the high-quality spectroscopy necessary to fully map their behavior in the BPT diagram, and link offsets back to evolution in physical conditions. This will presumably change as new lensed galaxies are pursued, and as new multi-object near-IR spectrographs push down the luminosity function of the non-lensed galaxy population. That said, RCS0327 demonstrates that offsets in the BPT diagram are not driven by higher ionization parameters and densities, as has been suggested. It also demonstrates that star-forming $z = 2$ galaxies may have quite similar ionization parameters and densities to $z = 0$ galaxies.

Last in our discussion of the BPT diagram, we note that RCS0327’s extreme location places it as far as possible from the $z = 0$ active galactic nucleus (AGN) locus. Thus, it is unlikely that the nebular emission of this galaxy is dominated by an AGN, though we have not ruled out a low-luminosity AGN (cf. Greene & Ho 2007). Upcoming observations with the Chandra X-ray Observatory should test this.

5. CONCLUSIONS

The spectra published here total 1.3 hr of integration time, divided into 20, 20, and 40 minute integrations over three spectral regions. These spectra demonstrate the power of gravitational lensing to explore the physical conditions of star formation at the epoch when most of the universe’s stars formed.

For the second time in any galaxy at $z \sim 2$, and for the first time in an average-metallicity galaxy, we tightly constrain the O abundance using the “direct” $T_e$ method, thanks to the very constraining non-detection of $[\text{O} \text{III}] \lambda 4363$. We use this constraint to test the bright-line diagnostics of oxygen abundance, which are the easiest to measure, but are empirically calibrated at $z = 0$ and thus incorporate assumptions about density and ionization parameter that may well be wrong at $z \sim 2$.

We find that the O abundance inferred from the N2 index (the ratio of $[\text{N} \text{II}]/\text{H}$) agrees closely with the $T_e$ method and has a small uncertainty. Ne3O2 also performs well, albeit with a larger uncertainty since $[\text{Ne} \text{III}]$ is not a bright line. N2O3 and R23 depend so strongly on the extinction that we cannot definitively assess their performance in RCS0327, though they appear to work for the current best estimate of the extinction, $A_V = 0.7$. This is especially interesting because R23 fails in Lens22.3 (Yuan & Kewley 2009), the only published example of an $[\text{O} \text{III}] \lambda 4363$ detection at $z \sim 2$.

The O3N2 diagnostic is on the border of disagreeing with $T_e$ in RCS0327, depending on extinction. Comparing to the N2 index, O3N2 predicts systematically lower abundances in five $z \sim 2$ lensed galaxies, dramatically so at near-solar metallicity. We suggest that O3N2 does not work in $z = 2$ galaxies, perhaps due to different physical conditions compared to $z = 0$ where this diagnostic is calibrated.

After all, O3N2 is effectively a location in the BPT diagram, and it has been shown, via small samples of lensed galaxies and stacked samples of unlensed galaxies, that $z = 2$ galaxies are off-set in the BPT diagram, with higher $5007/\text{H}$, than the cloud of SDSS galaxies at $z = 0$. Indeed, RCS0327 is offset in the BPT diagram compared to the SDSS and Kewley et al. (2001) galaxies, as offset as cB58 is, but not as offset as other $z = 2$ galaxies.

This is particularly interesting given that the measured ionization parameter for RCS0327 is the same as has been measured in the Horseshoe, the Clone, and cB58: $\log U \sim -2.7$ to $-2.8$, which is 30%--60% higher than in M82.

We also tightly constrain the electron density: $n_e = 252^{+30}_{-28}$ cm$^{-3}$ at $1.2 \times 10^4$ K, which is not terribly high compared to local galaxies. Thus, we conclude that it is premature to conclude that $z \sim 2$ star-forming galaxies have extremely high densities and ionization parameters, since the best-measured example, RCS0327, does not.

We measure the relative abundances of N, Ne, and Ar compared to O. The Ne/O and Ar/O ratios are solar with uncertainties of ±0.14 dex, which is reassuring since all these elements are alpha-process and should enrich in lockstep. We believe this to be the first time the Ne/O ratio has been measured at $z \sim 2$. The N/O ratio is 1 dex below the solar value, indicating that secondary N production has not yet begun in earnest. The O abundance and N/O ratio are startlingly similar to those of cB58; it is not clear whether this agreement is merely coincidental or indicates characteristic values for star-forming galaxies at this epoch.

6. FUTURE DIRECTIONS

This is by no means the last word on RCS0327 or on diagnostic spectroscopy of lensed galaxies. The following observations should significantly increase what can be learned about the physical conditions of RCS0327. First, a direct measurement of $[\text{O} \text{III}] \lambda 4363$, or an even stricter upper limit, should provide a more stringent test of the bright-line O abundance diagnostics. This comparison, and a host of other constraints, is limited by the current uncertainty in the measured extinction. This would be improved by a deeper integration of $\text{H}$/$\text{H}$ or a simultaneous measurement of $\text{H}/\text{H}$. Thus far, we have considered only the spatially integrated spectrum across the brightest portion of the arc. It will be fascinating to spatially map the physical conditions across this portion, and the fainter sections of the arc, to see how widely these physical parameters vary across the galaxy. Of course, such work requires a better lensing model, which will be enabled by pending HST observations.

Finally, we humbly remember that a single galaxy can be a maverick and that only by repeating this work in a representative sample of lensed galaxies will the physical conditions of star formation at this epoch be confidently characterized. Larger samples will also fill in the BPT and mass–metallicity relations to characterize the scatter in these relations and explore the reasons for the scatter.

We thank the IRTF Spex team for making public their telluric correction routine and their tool to find telluric standard stars, at http://irtfweb.ifa.hawaii.edu/~spex/. We thank Kevin Schawinski for code to generate the SDSS contours in Figure 7, which is adapted from Schawinski et al. (2010); we thank Fuyan Bian for code to generate Figure 6, which is adapted from Bian et al. (2010). We thank Andrew Marble for use of his implementation of MPFITFUN (Markwardt 2009) to fit multiple Gaussians. J.R.R. gratefully acknowledges the financial support and intellectual freedom of a Carnegie Fellowship.
Data presented herein were obtained at the W.M. Keck Observatory from telescope time allocated to the National Aeronautics and Space Administration through the agency’s scientific partnership with the California Institute of Technology and the University of California. The Observatory was made possible by the generous financial support of the W.M. Keck Foundation. We acknowledge the very significant cultural role and reverence that the summit of Mauna Kea has always had within the indigenous Hawaiian community. We are most fortunate to have the opportunity to conduct observations from this mountain.

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