LUMINOSITY DEPENDENCE AND REDSHIFT EVOLUTION OF STRONG EMISSION-LINE DIAGNOSTICS
IN STAR-FORMING GALAXIES

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ABSTRACT

We examine the redshift evolution of standard strong emission-line diagnostics for Hβ-selected star-forming galaxies using the local SDSS sample and a new z = 0.2–2.3 sample obtained from Hubble Space Telescope WFC3 grism and Keck DEIMOS and MOSFIRE data. We use the SDSS galaxies to show that there is a systematic dependence of the strong emission-line properties on Balmer-line luminosity, which we interpret as showing that both the N/O abundance and the ionization parameter increase with increasing line luminosity. Allowing for the luminosity dependence tightens the diagnostic diagrams and the metallicity calibrations. The combined SDSS and high-redshift samples show that there is no redshift evolution in the line properties once the luminosity correction is applied, i.e., all galaxies with a given L(Hβ) have similar strong emission-line distributions at all the observed redshifts. We argue that the best metal diagnostic for the high-redshift galaxies may be a luminosity-adjusted version of the [NII]6584/Hα metallicity relation.

Key words: cosmology: observations – galaxies: distances and redshifts – galaxies: evolution – galaxies: formation

1. INTRODUCTION

Over the past few years, there has been considerable interest in determining the redshift evolution of rest-frame optical emission-line ratios in star-forming galaxies. Emission-line properties can provide insight into the redshift evolution of stellar populations, gas densities, and metallicities that cannot be obtained from spectral energy distributions alone. The advent of multi-object near-infrared (NIR) spectrographs has advanced the field considerably by making it possible to obtain rest-frame optical spectra for substantial samples of high-redshift (z ~ 1–3) galaxies, which can then be compared with local samples (e.g., Masters et al. 2014; Steidel et al. 2014; Wuyts et al. 2014; Kewley et al. 2015; Shapley et al. 2015; Yabe et al. 2015).

However, one has to be cautious with such comparisons, because high-redshift galaxies have very different properties from the general population of local galaxies. Even local galaxies with masses similar to high-redshift galaxies may be quite dissimilar in their other properties, such as their star formation rates (SFRs), morphologies, and dust content (e.g., Cowie et al. 1996).

Similar concerns apply to the use of locally calibrated strong-line metallicity diagnostics at high redshifts. Such calibrations are based on a variety of local galaxies whose properties are generally quite different from those of high-redshift galaxies. Thus, these calibrations should not be applied uncritically at high redshifts.

It is therefore important to identify appropriate lower-redshift analogs for any high-redshift galaxy comparisons. Moreover, if true analogs can be identified, then they could potentially be studied more easily. However, they would have
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Juneau et al. (2014) emphasized the importance of this effect in interpreting the line properties of high-redshift galaxies. They postulated that much of the apparent redshift evolution of the line properties could in fact be a luminosity selection effect, in which only the high-SFR portion of the BPT star-forming galaxy locus at high redshifts (which is the only portion being sampled) is being compared with the median of the BPT star-forming galaxy locus locally. However, they stressed that the rarity of the high line-luminosity galaxies at low redshift means that they could be substantially different from the high-redshift galaxies of the same luminosity, making it hard to differentiate between selection bias and evolution.

However, as we shall show in the present paper, all of the line ratios have a strong and well-defined dependence on the Balmer-line luminosity, suggesting that the low-redshift, high-luminosity galaxies may in fact be close analogs of the high-redshift galaxies. Correcting for this luminosity dependence considerably tightens all of the various diagnostic diagrams, and including $L(\text{H} \beta)$ as an additional parameter improves the metallicity estimators. This correction also shows that there is no redshift evolution in the line ratios since the higher-redshift objects closely match lower-redshift samples in the same Balmer-line luminosity range.

Throughout, we use the observed $L(\text{H} \beta)$, without an extinction correction, as our variable, which allows for simple corrections to any data set. We use $L(\text{H} \beta)$ rather than $L(\text{H} \alpha)$, which is contaminated by [N\text{II}] in low-resolution spectra. However, since we would expect that the extinction correction smoothly varies with luminosity, we would expect to see the same type of line-ratio dependence on the extinction-corrected values or SFRs. In the low-redshift SDSS data described in Section 2.1, the mean extinction corrections are almost independent of Balmer-line luminosity, and $\log L(\text{H} \alpha) = \log L(\text{H} \beta) + 0.54$. The SFR for a Kroupa (2001) initial mass function (IMF) is given by a mean relation of log SFR $= \log L(\text{H} \beta) - 40.50$, where the SFR is in $M_\odot$ yr$^{-1}$ and $L(\text{H} \beta)$ is in erg s$^{-1}$, based on the SFRs of Brinchmann et al. (2004) as updated in the current data release. (For a modified Salpeter IMF (Kennicutt 1998), the SFR would be a factor of 1.5 higher.) The intermediate-redshift data also show an extinction that is independent of line luminosity and gives a broadly similar correction to $\log L(\text{H} \alpha) = \log L(\text{H} \beta) + 0.58$. The situation at the highest redshifts ($z \sim 2$) is less clear, and there may be a dependence on line luminosity (Reddy et al. 2015), though this effect may be, at least partly, selection bias. However, the average conversion from H$\beta$ to H$\alpha$ is similar, with $\log L(\text{H} \alpha) = \log L(\text{H} \beta) + 0.54$ for the galaxies with detected H$\beta$. Some of the possible complexities in interpreting the line luminosities are described in Stasińska et al. (2015).

In Section 2, we present the SDSS data that we use and our highly complete optical and NIR spectroscopic sample of galaxies with $z = 0$–2.3 in the GOODS-N field. In Section 3, we focus on the BPT diagram from the SDSS data and show that there is a simple dependence of the star-forming galaxy locus on Balmer-line luminosity. In Section 4, we show that the positions of high-redshift galaxies in the BPT and other diagnostic diagrams are similar to those of SDSS galaxies with comparable luminosities. This suggests that we can use these latter objects as surrogates for the high-redshift population. In Section 5, we use the properties of the high-luminosity SDSS galaxies to determine what is causing the changes in the diagnostic diagrams with luminosity. We summarize our results in Section 6.

2. DATA SETS

2.1. SDSS ($z = 0.05$–0.2)

Our local sample is taken from the Sloan Digital Sky Survey Data Release 7 (SDSS DR7; Abazajian et al. 2009), restricted to $z > 0.05$ to minimize aperture effects. We use the line fluxes from the Value Added Catalogs of the Max-Planck Institute for Astronomy (Garching) and Johns Hopkins University (MPA/JHU).\(^4\) Tremonti et al. (2004) and Brinchmann et al. (2004) give details on the methods that were used to develop this catalog. Even in this redshift range we need to correct the fluxes in the fibers to total fluxes in order to compare properly with high-redshift samples. We follow the standard procedure of multiplying the observed flux in the fiber by the ratio of the total continuum flux to the continuum flux in the fiber. This is clearly approximate, since it assumes that the line emission has the same spatial distribution as the continuum, but it represents our best estimate of the correction. The correction is near unity for the galaxies with the highest line luminosities, though it can be significantly larger in the low-luminosity objects, rising to an average correction of approximately a factor of seven for a fiber $\log L(\text{H} \beta) = 39$ erg s$^{-1}$. Because the correction for the high-luminosity objects is small, the comparison with the high-redshift, high-luminosity objects is not significantly affected by including this effect. The spectra have been corrected for underlying stellar absorption. We restrict consideration to sources with signal-to-noise ratio ($S/N > 10$ in H$\beta$ line flux and compute line luminosities and the various diagnostic line ratios, including O3Hb and N2Ha, for this sample. We also consider only galaxies with $z = 0.05$–0.2. We hereafter refer to this as the “full” SDSS sample.

\(^4\) http://www.mpa-garching.mpg.de/SDSS/DR7/
2.2. DEIMOS (z = 0.2–0.95)

We made DEIMOS observations in a number of runs between 2004 and 2015 with the goal of obtaining consistently high-quality optical spectra of all of the 2850 B < 25 galaxies in the uniformly covered portion of the Hubble Space Telescope (HST) GOODS-N field. We have now observed all but six of these galaxies, and we have obtained robust redshifts for 2501 (88%), many of which are published in Cowie et al. (2004) and Barger et al. (2008). We used the 600 l mm\(^{-1}\) grating, giving a resolution of 3.5 Å and a wavelength coverage of 5300 Å, which was also the configuration used in the KTRS observations (Wirth et al. 2004). We have incorporated archival data, particularly from KTRS, but many of these spectra have relatively poor sky subtraction, and we re-observed them, whenever necessary, to obtain higher-quality spectra. We centered the spectra at an average wavelength of 7200 Å whenever necessary, to obtain higher-quality spectra. We continuously re-observed unidentified galaxies or galaxies with poor spectra, giving maximum exposure times of up to 7 hr. We reduced the spectra following sub-exposures, stepping the galaxies along the slit by 1 hr exposure into three sub-exposures, stepping the galaxies along the slit by 1.5 hr in each direction. We continuously re-observed unidentified galaxies or galaxies with poor spectra, giving maximum exposure times of up to 7 hr. We reduced the spectra following the procedures described in Cowie et al. (1996). Our dithering procedure provides extremely high-precision sky subtraction, which is important for measuring accurate equivalent widths.

We measured the line widths, redshifts, amplitudes, and continuum level for the suite of observable lines in the one-dimensional spectra using the MPFIT program of Markwardt (2009). For the weaker lines, we measured only the amplitudes and adopted the line-widths and redshifts from the strongest neighboring line (where available, [O III]5007, H\(\alpha\), and [O I]3727; for the latter, we measured both members of the doublet separately).

Because of the difficulties in making a precise spectro-photometric calibration of the multi-slit DEIMOS data, we used an indirect method to calculate the fluxes. We matched the contributions of the lines plus continuum to the observed HST magnitude for the corresponding broadband filter. We then determined errors for each line by fitting random positions in the spectra in the neighborhood of the line. Finally, we accounted for underlying absorption using fixed corrections of 3 and 2 Å for the equivalent widths of the H\(\beta\) and H\(\alpha\) lines, respectively. These match the average corrections in the SDSS data.

We found 83 galaxies with H\(\beta\) detected at >10\(\sigma\) between z = 0.2–0.5, where we can measure both O3Hb and N2Ha from the DEIMOS spectra. These provide a nearly complete sample above log \(L(H\beta) = 40.0\) erg s\(^{-1}\) (see Figure 1). We found 180 galaxies with H\(\beta\) detected at >10\(\sigma\) between z = 0.5–0.95, where only O3Hb can be measured from the DEIMOS spectra. Here the completeness limit is log \(L(H\beta) = 40.5\) erg s\(^{-1}\). To get N2Ha determinations for these galaxies requires MOSFIRE spectra in the \(Y\) and \(J\) bands (see Section 2.4).

2.3. HST Grism (z \(\geq\) 0.95)

For galaxies at z \(\geq\) 0.95, we measured the Balmer-line luminosities from the HST WFC3 G141 and G102 grism observations covering nearly all of the GOODS-N field (PIs B. Weiner and G. Barro, respectively). While these data have now been incorporated into the 3D–HST sample (Brammer et al. 2012), we used our own extractions that we made from the raw data using the aXe software package supported by STScI. We extracted spectra for 5709 galaxies with AB magnitudes brighter than 24.5 in the F140W band. We formed one-dimensional spectra over the full galaxy areas, as defined by the corresponding continuum image. We show a typical spectrum in Figure 2.

We can make precise line-flux measurements with the grism data, since, in contrast with the ground-based data, there are no issues of slit losses or photometric conditions. However, the resolution is low: R \(\sim\) 130 in the G141 grism over the wavelength range 1.1–1.7 \(\mu\)m and R \(\sim\) 210 in the G102 grism over the wavelength range 0.8–1.5 \(\mu\)m, with the exact value depending on the size and shape of the galaxy. This means that the H\(\alpha\) line is blended with the [N II]6584,6548 blend and the [S II]6717,6734 doublets are unresolved (see Figure 2). However, the lines in the [O III]4959,5007 and H\(\beta\) complex can be fitted to determine the H\(\beta\) fluxes. We did this in the following way: we measured the [O III]5007 and H\(\beta\) fluxes from the one-dimensional spectra using MPFIT. We then forced the [O III]4959 line to a value of 0.326 times the [O III]5007 line and fitted all three lines in the complex simultaneously using a single redshift and line-width. For H\(\alpha\), we measured the combined H\(\alpha\)+[N II] line flux. Once again, we corrected for underlying absorption using fixed corrections of 3 and 2 Å for the equivalent widths of the H\(\beta\) and H\(\alpha\) lines.

We are interested in using the grism data primarily to find galaxies in the redshift ranges z = 1.38–1.74 and z = 2.03–2.65, where O3Hb and N2Ha can be simultaneously measured from ground-based MOSFIRE data (Section 2.4). For redshifts z \(\geq\) 1.52, the H\(\alpha\) line is no longer observable in the grism data, and we rely on H\(\beta\), which is observable in the G141 grism data through the whole lower-redshift interval and out to z = 2.30 in the upper interval.

Over z = 1.30–1.52, both the H\(\alpha\) and H\(\beta\) lines are in the grism data, so we determine the completeness of the H\(\beta\) selection by seeing at what point we start to miss H\(\alpha\) sources in H\(\beta\). Based on this analysis, we adopt a flux selection of \(f(H\beta) = 5 \times 10^{-15}\) erg cm\(^{-2}\) s\(^{-1}\), which corresponds to a luminosity limit of log \(L(H\beta) = 41\) erg s\(^{-1}\) for z = 1.38–1.74.
and log \( L(\beta) = 41.5 \text{ erg s}^{-1} \) for \( z = 2.03-2.30 \). These selections give samples of 43 and 28 galaxies, respectively.

### 2.4. MOSFIRE

In order to measure the standard diagnostic line ratios, we need higher-resolution data than the \( HST \) grism spectra can provide. We therefore made follow-up observations of the \( H\beta \) luminosity-selected sample using the MOSFIRE NIR spectrograph on the Keck I telescope (McLean et al. 2012). The ground-based NIR windows (and the corresponding MOSFIRE filters) limit the redshift intervals in which the line ratios can be measured. We illustrate this in Figure 3, where for each of the \( N2H\alpha \) and \( O3Hb \) ratios, we show the redshift interval where the ratio can be measured (black for optical from DEIMOS, gold for \( Y \)-band, blue for \( J \)-band, green for \( H \)-band, and purple for \( K \)-band). The gray shading shows where it is possible to measure both ratios via some combination of instruments and bandpasses; this encompasses nearly the full \( z = 0-1 \) interval, as well as the intervals \( z = 1.38-1.74 \) and \( z = 2.03-2.65 \).

We obtained MOSFIRE observations of the \( H\beta \) luminosity-selected galaxies during three two-night runs from 2013 to 2015. We focused on galaxies with redshifts that allowed selection galaxies during three two-night runs from 2013 to 2015. We focused on galaxies with redshifts that allowed us to use a combination of instruments and bandpasses allows both ratios to be measured. (We ignore the tiny region around \( \beta \) where the green and gold bars overlap.)

We obtained MOSFIRE observations of the \( H\beta \) luminosity-selected sample using the MOSFIRE NIR spectrograph on the Keck I telescope (McLean et al. 2012). The ground-based NIR windows (and the corresponding MOSFIRE filters) limit the redshift intervals in which the line ratios can be measured. We illustrate this in Figure 3, where for each of the \( N2H\alpha \) and \( O3Hb \) ratios, we show the redshift interval where the ratio can be measured (black for optical from DEIMOS, gold for \( Y \)-band, blue for \( J \)-band, green for \( H \)-band, and purple for \( K \)-band). The gray shading shows where it is possible to measure both ratios via some combination of instruments and bandpasses; this encompasses nearly the full \( z = 0-1 \) interval, as well as the intervals \( z = 1.38-1.74 \) and \( z = 2.03-2.65 \).

![Figure 3](image.png)

**Figure 3.** Redshift vs. \( K_s \) magnitude for the GOODS-N (black squares). Galaxies with MOSFIRE spectra from which the redshift can be measured are shown with larger red squares. The redshifts at which the \( N2H\alpha \) and \( O3Hb \) ratios (colored bars) can be measured are shown on the left. The colors mark the MOSFIRE filter in which the lines lie (gold—\( Y \), blue—\( J \), green—\( H \), and purple—\( K \)), while black marks where the lines are covered by the DEIMOS spectra. The gray shading shows the redshift ranges in which some combination of instruments and bandpasses allows both ratios to be measured. (We ignore the tiny region around \( z \sim 1.2-1.3 \) where the green and gold bars overlap.)

In contrast to the DEIMOS spectra, the continua in the MOSFIRE spectra are often too weak to measure equivalent widths, so we measured flux ratios directly. Since the flux ratios are only of neighboring lines, we do not need accurate spectrophotometry. To account for underlying absorption, we measured equivalent widths in the grism data and applied fixed corrections of 3 Å and 2 Å for \( H\beta \) and \( H\alpha \), respectively. Where \( H\alpha \) was not covered by the grism data, we computed the \( H\alpha \) equivalent width from \( H\beta \) using the median value of the EW (\( H\alpha \))/EW(\( H\beta \)) ratio determined from the sources where both were measured. Most of the galaxies have corrections which are close to the median values of 0.89 in \([\text{[O}\text{III]}]/\beta \) and 0.98 in \([\text{[N}II]/\beta \). Thus, the use of a single correction value for each
line ratio, as in Steidel et al. (2014; who used 0.85 for \([\text{[O III]}]/\text{H}\beta\) and 1 for \([\text{[N II]}]/\text{H}\alpha\)), provides a good approximation. Removing the absorption correction would raise \(\text{O3Hb}\) by 0.07 in the high-redshift galaxies.

We also work with the two-dimensional spectral images rather than extracting one-dimensional spectra. There are two reasons for following this course, which we illustrate in Figure 4. The first is that the two-dimensional spectral images often show resolved velocity structure. In these cases, extracting a one-dimensional spectrum adds unnecessary noise relative to working directly with the two-dimensional spectral image. The second is the strength of the night-sky lines in the NIR, which can greatly increase the noise. In the upper panel of Figure 4, we see that portions of the \(\text{H}\alpha\) and \([\text{[N II]}]\) lines are severely contaminated in this way. By extracting the fluxes from the two-dimensional spectral images, we can avoid these regions.

For both \(\text{N2Ha}\) and \(\text{O3Hb}\), we are measuring a weaker line ([N II]6584 or H\(\beta\)) relative to a stronger neighboring line (H\(\alpha\) or [O III]5007). We made an optimal extraction from the two-dimensional spectral image by forming an integral of the two-dimensional spectral image of the weaker line weighted by the two-dimensional intensity of the stronger line, excluding any regions covered by the strongest night-sky lines, and dividing by the integral of the two-dimensional spectral image of the stronger line with the same weighting. Once again, we determined the noise levels by randomizing the wavelength positions of the weaker line and measuring the ratio at these positions.

### 3. LOCAL RELATIONS FROM THE SDSS DATA

We start by re-examining the dependence of the BPT star-forming galaxy locus (the left wing of the BPT diagram) on Balmer-line luminosity and redshift using the SDSS sample. In Figure 5(a), we show the BPT diagram for the full SDSS sample in intervals of log \(L(\text{H}\beta)\) (colors). We show the median values of \(\text{O3Hb}\) in 0.2 dex bins of \(\text{N2Ha}\) (squares). The sizes of the squares represent the number of sources in each bin, ranging from 10–100 (smallest), 100–1000, 1000–10,000, to 10,000–100,000 (largest). In the star-forming galaxy locus (the left wing of the BPT diagram; \(\text{N2Ha} < -0.5\)), the normalization of \(\text{O3Hb}\) relative to \(\text{N2Ha}\) rises with \(L(\text{H}\beta)\). In (b) and (c), respectively, we show the effects of introducing an offset in \(\text{N2Ha}\) using Equations (1) and (2) and in \(\text{O3Hb}\) using Equation (3) to normalize to \(L(\text{H}\beta) = 40.5\) erg s\(^{-1}\). Either offset approximately aligns the BPT star-forming galaxy locus.

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**Figure 5.** (a) BPT diagram for the full SDSS sample in intervals of log \(L(\text{H}\beta)\) (colors). We show the median values of \(\text{O3Hb}\) in 0.2 dex bins of \(\text{N2Ha}\) (squares). The sizes of the squares represent the number of sources in each bin, ranging from 10–100 (smallest), 100–1000, 1000–10,000, to 10,000–100,000 (largest). In the star-forming galaxy locus (the left wing of the BPT diagram; \(\text{N2Ha} < -0.5\)), the normalization of \(\text{O3Hb}\) relative to \(\text{N2Ha}\) rises with \(L(\text{H}\beta)\). In (b) and (c), respectively, we show the effects of introducing an offset in \(\text{N2Ha}\) using Equations (1) and (2) and in \(\text{O3Hb}\) using Equation (3) to normalize to \(L(\text{H}\beta) = 40.5\) erg s\(^{-1}\). Either offset approximately aligns the BPT star-forming galaxy locus.
We immediately see the known result that at higher \( L(\text{H}\beta) \) luminosities, O3Hb is high at a given N2Ha and N2Ha is high at a given O3Hb (Brinchmann et al. 2008; Juneau et al. 2014; Salim et al. 2014). More profoundly, however, we see that the shape of the star-forming galaxy locus remains roughly invariant with \( \log(\text{H}\beta) \). It is only the normalization of O3Hb relative to N2Ha that is changing as a function of \( \log(\text{H}\beta) \).

Motivated by Figure 5(a), we fitted the dependence of O3Hb on N2Ha and \( L(\text{H}\beta) \) for the star-forming galaxy locus (N2Ha \(<0.5\)) using the MPFIT2DFUN two-dimensional fitting routine from Markwardt (2009). We adopted a third-order fit for the dependence on N2Ha and a linear fit for the dependence on \( L(\text{H}\beta) \). Including the luminosity dependence by shifting N2Ha, we find

\[
x = N2Ha - 0.09(\log L(\text{H}\beta) - 40.5),
\]

and

\[
O3Hb = -1.85 - 4.02x - 2.18x^2 - 0.42x^3.
\]

Alternatively, we can include the luminosity dependence by shifting O3Hb, giving

\[
O3Hb = -1.85 - 4.02(N2Ha) - 2.18(N2Ha)^2 - 0.42(N2Ha)^3 + 0.09(\log L(\text{H}\beta) - 40.5).
\]

In Figures 5(b) and (c), we show the effects of applying the above luminosity offsets in N2Ha and O3Hb, respectively, to the SDSS data to normalize to \( L(\text{H}\beta) = 40.5 \text{ erg s}^{-1} \). Either offset aligns the star-forming galaxy loci across the luminosity range and, based solely on the BPT diagram, variation in either variable or a combination of both could produce the measured offsets.
We find that the formal errors on the coefficients are extremely small. However, when we vary the fitting ranges for both redshift and N2Ha, and when we adjust the \( L(\text{H} \beta) \) S/N away from the adopted value of 10 (see Section 2.1), we find larger systematic errors. In particular, the log \( L(\text{H} \beta) \) coefficient in both sets of equations can range from 0.08 to 0.10, depending on these choices.

The luminosity offset is not simply a shift in the medians, as we illustrate in Figure 6, where we plot the BPT diagram for the individual SDSS points in log \( L(\text{H} \beta) \) intervals of (a) 41.25–41.75 and (b) 40.25–40.75 erg s\(^{-1}\), each separated into two redshift intervals (black for \( z = 0.1–0.2 \) and red for \( z = 0.05–0.1 \)).

There is essentially no difference between the source distributions for the two redshift intervals in either panel. There is, however, an increase in N2Ha relative to O3Hb for the higher-luminosity points in (a). This can clearly be seen by plotting the fit to the star-forming galaxy locus of the full SDSS sample at the median log \( L(\text{H} \beta) = 40.5 \) erg s\(^{-1}\) (green solid curve), along with the luminosity-offset loci (green dashed curve) determined by evaluating Equations (1) and (2), which vary N2Ha, at log \( L(\text{H} \beta) \) of (a) 41.5 erg s\(^{-1}\) and (b) 40.5 erg s\(^{-1}\). As expected, the higher-luminosity points in (a) lie uniformly above the green solid curve but generally along the green dashed curve, while the lower-luminosity points in (b) are consistent with the green solid curve, which is nearly identical to the green dashed curve. The agreement may be more clearly seen in panel (c) where we show the medians in each luminosity and redshift interval compared with the fits.

4. COMPARISON WITH HIGHER-REDSHIFT SAMPLES

Having established the dependence of the BPT star-forming galaxy locus on Balmer-line luminosity (but not redshift) for the SDSS local sample, we turn our attention to the higher-redshift samples. As we did in Figure 6, we start in Figure 7 by plotting the SDSS data in two well-separated log \( L(\text{H} \beta) \) intervals, this time using 39.0–40.0 erg s\(^{-1}\) (black dots) and 41.5–42.5 erg s\(^{-1}\) (light green squares). The green curve is again the fit to the star-forming galaxy locus of the full SDSS sample at the median log \( L(\text{H} \beta) = 40.5 \) erg s\(^{-1}\). Compared to this curve, the lower-luminosity points lie uniformly low, while the higher-luminosity points lie uniformly high.

Next, we plot our high-redshift galaxies, including every source with a well-measured (>3σ) O3Hb (purple circles). To increase the sample size, we also plot the high-redshift galaxies from Steidel et al. (2014, orange squares) and Shapley et al. (2015, orange circles). We show galaxies with only upper limits on N2Ha at their 2σ limits (leftward pointing arrows)

All three high-redshift galaxy samples overlap substantially with one another and are broadly consistent, though our luminosity-selected sample extends to somewhat lower values of N2Ha, while the mass-selected sample of Shapley et al. (2015) is slightly higher in N2Ha. The Steidel et al. (2014) sample lies in between. Note that some of the sources are likely AGNs, given their locations on the diagram.

The most striking observation from Figure 7 is how similar the high-redshift data are to the higher-luminosity SDSS data for the star-forming galaxy locus. This emphasizes how critical it is to choose appropriate counterparts when comparing high-redshift samples with low-redshift ones.

The similarity of the high-redshift data to the higher-luminosity SDSS data is not unique to the BPT diagram. In Figure 8, we show two alternative diagnostic diagrams that are frequently used, (a) [N ii]6584/[O iii]3726,3729 (N2O2) versus O3Hb and (b) [N ii]6584/[S ii]6717,6731 (N2S2) versus O3Hb. In both cases, the denominator is the sum of the fluxes from both members of the doublet. For N2O2, we include an extinction correction because of the wide wavelength separation of the lines. We plot the SDSS data in the same two well-separated log \( L(\text{H} \beta) \) intervals as in Figure 7.

We fitted the dependence of N2S2 on O3Hb and \( L(\text{H} \beta) \) and the dependence of N2O2 on O3Hb and \( L(\text{H} \beta) \) for the SDSS star-forming galaxy locus (N2Ha < −0.5) using the
Figure 9. O32 vs. R23 for the full SDSS sample on the star-forming galaxy locus of the BPT diagram (N2Ha < −0.5) in two intervals of log $L$(Hβ) (black dots—39.0–40.0 erg s$^{-1}$; light green squares—40.5–41.5 erg s$^{-1}$). The orange circles show the high-redshift galaxies from Shapley et al. (2015), which closely match the positions in the diagram of the higher-luminosity SDSS galaxies. Extinction corrections are included in both ratios for all of the samples.

MPFIT2DFUN two-dimensional fitting routine from Markwardt (2009). This time we adopted a linear dependence for both O3Hb and $L$(Hγ), obtaining

$$N2O2 = -0.71 - 0.75(O3Hb) + 0.16\log(L(H\beta) - 40.5)$$

and

$$N2S2 = -0.20 - 0.40(O3Hb) + 0.17\log(L(H\beta) - 40.5).$$

In Figure 8, we show these linear fits at the median log $L$(Hβ) = 40.5 erg s$^{-1}$ (green line). In both diagnostic diagrams, compared to this line, the lower-luminosity points lie uniformly low, while the higher-luminosity points lie uniformly high. Because of the weakness of the [S ii]6717,6731 lines and the difficulty of both cross-calibrating the [O ii] 3726,3729 and [N ii]6584 lines and applying appropriate extinction corrections, we compare the SDSS data only to the deeper high-redshift galaxy sample of Shapley et al. (2015, orange circles), who carefully treated the relative calibrations of the [O ii]3726,3729 and [N ii]6584 lines. Again, the positions of the high-redshift galaxies in the diagrams closely match the positions of the higher-luminosity SDSS galaxies. The luminosities of the high-redshift galaxies in Figure 8 lie between log $L$(Hβ) = 41.1 and 42.6 with 85% lying in the 41.5 to 42.5 range (Reddy et al. 2015) where we show the SDSS galaxies.

Finally, we consider the [O ii]5007,4861/[O ii]3727 versus ([O ii]3727+[O ii]5007,4861)/Hβ (O32 versus R23) diagram, which is a well-known probe of both metallicity and ionization parameter (Kewley & Dopita 2002). (Note that [O ii]3727 is the sum of the fluxes in the [O ii] doublet.) In Figure 9, we again show the higher-luminosity SDSS sample (light green squares) and the lower-luminosity SDSS sample (black points), together with the Shapley et al. (2015) high-redshift data (orange circles). We include extinction corrections in computing all of these ratios. The positions of the high-redshift galaxies in the diagram are fully consistent with the positions of the higher-luminosity SDSS galaxies, within the R23 errors (i.e., the high-redshift galaxies are more scattered due to the larger errors).

Now that we have established the similarity of the high-redshift data to the higher-luminosity SDSS data for all the diagnostic diagrams, we return to the BPT diagram to examine
in closer detail the redshift evolution of our $L(H\beta)$-selected galaxy sample. In Figure 10, we show the galaxies that satisfy the luminosity limits at which our samples are complete (see Section 2.3) for (a) two high-redshift and (b) two low-redshift intervals. In (a), we show the galaxies with $\log L(H\beta) > 41.0$ erg s$^{-1}$ and $z = 1.38$–1.74 as black circles and the galaxies with $\log L(H\beta) > 41.3$ erg s$^{-1}$ and $z = 2.03$–2.30 as yellow circles. The median luminosities are $\log L(H\beta) = 41.9$ erg s$^{-1}$ for both samples. We made these measurements solely from the MOSFIRE data. In (b), we show galaxies with $\log L(H\beta) > 40.5$ erg s$^{-1}$ and either $z = 0.2$–0.5 (black circles) or $z = 0.5$–1 (red circles). Here the median luminosities are $\log L(H\beta) = 40.9$ erg s$^{-1}$ and 41.5 erg s$^{-1}$, respectively. We made the $z = 0.2$–0.5 measurements solely from the DEIMOS data, while we made the $z = 0.5$–1.0 measurements from both the DEIMOS (O3Hb) and MOSFIRE (N2Ha) data. We have included 1σ error bars on all the data points based on randomized measurements in the spectra. The error bars are generally very small for O3Hb in the DEIMOS data but much larger in the MOSFIRE data. Note that some of the data points lie off the locus of star-forming galaxies, in the regime consistent with being powered by AGNs.

In both panels, we show the fit to the star-forming galaxy locus of the full SDSS sample (N2Ha $< -0.5$) at the median $\log L(H\beta) = 40.0$ (green solid curve), along with the luminosity-offset locus determined by evaluating Equations (1) and (2), which vary N2Ha (green dotted), at median $\log L(H\beta)$ values of (a) 41.9 erg s$^{-1}$ and (b) 41.5 erg s$^{-1}$ (using the median for the $z = 0.5$–1 interval for (b)). As already expected from Figure 7, we see that we can smoothly represent our high-redshift data with increasing luminosity based on the luminosity offset calculated from the SDSS data. Put simply, galaxies of a given $L(H\beta)$ have the same strong emission-line properties, regardless of redshift.

5. LUMINOSITY-ADJUSTED METALLICITY RELATIONS FOR THE SDSS GALAXIES

A major goal of this paper is to explore what underlying properties in the galaxies might be causing the observed offsets with $\log L(H\beta)$ in the diagnostic diagrams. We do this by examining the various line ratios individually. For reference, the recent compilation of Asplund et al. (2009) gives solar abundances of $12 + \log(O/H)= 8.69$, $12 + \log(N/H)= 7.83$ and $12 + \log(S/H)= 7.12$. The models of Kewley & Dopita (2002) discussed below use the values from Anders & Grevesse (1989): $12 + \log(O/H)= 8.93$, $12 + \log(N/H)= 8.05$ and $12 + \log(S/H)= 7.21$, together with dust depletions of O and N of $-0.22$ dex.

There are several well-known mechanisms that can produce offsets in the diagnostic diagrams, including changes in the ionization parameter ($i.e.$, $q$, the ratio of the ionizing photon flux to the hydrogen number density), relative abundance variations (including the effects of dust depletion), particularly in the N to O ratio, and changes in the hardness of the ionizing spectrum. If the underlying mechanism(s) are similar in the SDSS and high-redshift samples, then we can parameterize the dependence of the metallicity relations on $\log L(H\beta)$ using the SDSS sample and generate luminosity-adjusted metallicity relations that may be applicable to the high-redshift samples. However, regardless of whether these relations really apply at high redshift, the addition of the second parameter ($i.e.$, line luminosity) tightens the relations and improves the low-redshift metallicity estimates.

As we shall discuss further below, the N2O2 parameter is insensitive to the ionization and therefore is primarily a measure of the relative N/O abundance (e.g., Pérez-Montero & Contini 2009). The high N2O2 ratio in the high-redshift galaxies has been interpreted as showing that N/O is overabundant in these objects (Masters et al. 2014; Steidel et al. 2014; Shapley et al. 2015). Pérez-Montero & Contini (2009) give an empirical calibration based on local galaxies of

$$\log(N/O) = 0.93(N2O2) - 0.20$$

which, when combined with Equation (4), gives a relationship for the median track at a given $L(H\beta)$ of

$$\log(N/O) = -0.86 - 0.70(O3Hb) + 0.15(\log L(H\beta) - 40.5).$$

For O3Hb $= 0.00$, $\log(N/O)$ would range from −1.08 at $L(H\beta) = 39$ to −0.64 at $L(H\beta) = 42$, compared to the adopted solar value of −0.86, while at O3Hb $= 0.50$ the range would be −1.43 to −0.98. However, the uncertainties in the absolute values should be born in mind. More robustly, we can see from Equation (7) that at a fixed value of O3Hb, high-luminosity objects ($\log L(H\beta) = 42$) would have a N/O abundance which is a factor of 1.7 times higher than the average local galaxy ($\log L(H\beta) = 40.5$); this is the same effect that is seen in the high-redshift samples.

Absent any other effects, the increase in N/O with increasing $\log L(H\beta)$ will produce an increase of N2Ha at a fixed O3Hb, resulting in a shift in the BPT diagram in the sense that is seen in Figure 5. However, the dependence on $\log L(H\beta)$ is too strong, with a slope of 0.15 in Equation (7) compared with 0.09 in the evolution of the BPT diagram (Equations (1)–(3)). This suggests that there must be a countervailing trend that reduces N2Ha for a given O3Hb and reduces the evolution in the BPT diagram.

We investigate this issue by comparing the strong emission-line ratios with direct O abundances, which we calculate using the relations defined in Izotov et al. (2006). We use only SDSS galaxies on the star-forming galaxy locus of the BPT diagram (N2Ha $< -0.5$) where the [OIII]4363 line is strongly detected (>10σ). Unfortunately, this strong detection requirement will result in a bias toward lower metallicity (where the [OIII]4363 line is stronger) and higher Balmer-line luminosity, which means we will have a relatively limited dynamic range for determining dependences of $\log L(H\beta)$.

5.1. N2O2 and N2S2

We first consider the changes in N2O2 and N2S2. Both these ratios are extremely weakly dependent on $q$. At low O abundances relative to solar, these line ratios are also almost independent of metallicity (see, e.g., Figures 3 and 4 of Kewley & Dopita 2002).

In Figure 11, we show $12 + \log(O/H)$ versus (a) N2O2 and (b) N2S2. We use colored circles to denote three intervals of $\log L(H\beta)$ (black—40.5–41.0 erg s$^{-1}$; green—41.0–41.5 erg s$^{-1}$, and purple—41.5–42.0 erg s$^{-1}$). Over the range $12 + \log(O/H) < 8.4$, we assume that N2O2 is independent of $12 + \log(O/H)$, and over the range $12 + \log(O/H) < 8.3$, we use a linear fit to the extremely weak dependence of N2S2 on $12 + \log(O/H)$ from Kewley & Dopita (2002; orange dashed lines). We use these slopes to
compute the offsets to the medians of the colored symbols (colored lines), but we do not find the offsets between the luminosity samples to be sensitive to the adopted slopes.

We find that the different luminosity samples can be brought into consistency using offsets that are linear functions of log $L(H\beta)$. In Figure 11(c), we show $12 + \log(O/H)$ versus $N2O2 - 0.29(\log L(H\beta) - 41)$, and in Figure 11(d), we show $12 + \log(O/H)$ versus $N2S2 - 0.26(\log L(H\beta) - 41)$. We have checked that the offsets are not sensitive to the choice of the N2Ha limit used to define the star-forming galaxy locus in the BPT diagram, nor to the use of a luminosity-adjusted N2Ha limit (Equations (1) and (2)). We also checked that the offsets...
are not sensitive to the choice of S/N in the [O iii]4363 line
detection; we obtained a similar result using a 5σ threshold
instead of a 10σ threshold.

As we have discussed above, the offsets in the N2O2 and
N2S2 ratios must be understood as arising from changes in the
gas-phase abundance ratios of N relative to O and N relative to
S, with the higher-luminosity sources being progressively more
abundant in N relative to O, and the O and S abundances not
changing relative to each other. Since changes in the dust
depletion would result in S (which does not deplete onto dust)
changing relative to O, it is likely that the changes are in the
overall abundances (i.e., gas plus dust) rather than only in the
gas-phase abundances.

More specifically, we can interpret Figures 11(c) and (d) as
implying that the average relations between log(N/O) and log
(N/S) and log L(H β) for these luminous galaxies are

\[ \log(N/O) = -0.74 + 0.29(\log L(H β) - 41), \]

and

\[ \log(N/S) = 0.64 + 0.26(\log L(H β) - 41). \]

The normalizations in these equations are chosen to match the
observed means shown in Figure 11 to the Kewley & Dopita
(2002) models shown by the orange dashed lines.

Relative to the local solar value of log(N/O) = −0.86,
Equation (8) would imply that the high-L(H β) galaxies (and
hence the high-redshift galaxies) are, on average, over-
abundant in N relative to O by a factor of 2.2 at
log L(H β) = 41.6 erg s^{-1}.

The above L(H β) dependences derived from the direct O
abundance measurements are slightly steeper than the L(H β)
dependences of Equations (4), (5), and (7) for N2O2 and N2S2
versus O3Hb. This does not appear to come from variations of
O3Hb with luminosity, since, for the observed range of O3Hb,
we see no dependence of O3Hb on L(H β) for the galaxies with
direct [O iii]4363 measurements. We illustrate this in
Figure 12(a), where we show 12 + log(O/H) versus O3Hb
for the same three intervals of log L(H β) used in Figure 11.
The lack of dependence on log L(H β) is a consequence of the
low metallicities and high ionization parameters in the sample
with direct O measurements, which result in low values of
[O iii]/[O ii] and values of [O iii]5007/H β that are insensitive
to the ionization parameter and metallicity.

Instead, the L(H β) dependences derived from the direct O
abundance measurements reflect the bias of galaxies with such
measurements toward a more limited range in L(H β). When
we limit the N2O2 and N2S2 versus O3Hb fits to the same
L(H β) range, we find similarly steep relations.

To summarize, our results show that it is the increases in the
overall abundance ratios of N/O and N/S that are producing the
offsets seen in the N2O2 and N2S2 diagnostic diagrams of
Figure 8 for the higher-luminosity SDSS sample. The high-
redshift samples are similar in over-abundance to the low-
redshift samples with the same high L(H β).

5.2. N2Ha

We now examine the change in N2Ha and its role in the
observed evolution of the BPT diagram. To do so, we start by
considering the Pettini & Pagel (2004) N2Ha calibrator
(hereafter, Pettini–Pagel relation), which has been widely used
in high-redshift galaxies, though with some concerns (e.g., Erb et al. 2006; Liu et al. 2008; Newman
et al. 2014; Sanders et al. 2015). While empirically the relation
between direct O abundance measurements and N2Ha is good
at low metallicities (Pettini & Pagel 2004; Maiolino et al.
2008), the relation has always been treated with some
suspicion because it is strongly dependent on both the
ionization parameter and the abundance ratio of N/O.

Not surprisingly, there is also a dependence of the Pettini–
Pagel relation on L(H β). In Figure 12(b), we show
12 + log(O/H) versus N2Ha for three intervals of log L(H β)
used in Figure 11. Adopting the slope of 0.57 used by Pettini &
Pagel (2004) for their calibration, we match the medians of the
colored symbols between −2 and −1.3 (colored lines). We see
that the higher-L(H β) galaxies have a higher N2Ha for a given
direct O abundance. We remove this luminosity dependence in
Figure 12(c) by plotting log L(H β) versus N2Ha −0.14(log L(H β) − 41). This gives a luminosity-adjusted relation of

\[ 12 + \log(O/H) = 8.90 + 0.57(N2Ha) \\
- 0.14(\log L(H β) - 41). \]

The luminosity correction is large enough to have a significant
effect on metal measurements in high-redshift galaxies, which
generally will be over-estimated by about 0.1 dex using the
uncorrected relation.

The N2Ha dependence on L(H β) is a combination of two
effects: the N/O ratio increasing with luminosity, and the
ionization parameter increasing with luminosity. These drive
the relation between 12 + log(O/H) and N2Ha in opposite
directions, with increasing N/O raising N2Ha for a given O
abundance, while increasing q reduces it.

To disentangle the two effects, we first consider how q
depends on L(H β). We calculate q using the Kewley & Dopita
(2002) [O iii]/[O ii]− q relation, the parameterization for which
is given in Equation (13) of Kobulnicky & Kewley (2004). In
The color of the symbols shows the approximate agreement throughout much of the abundance measurements. As we show in Figure 13, there is quite a tight relation between $q$ and $\log L(H\beta)$. We approximate this with

$$\log q = 7.51 + 0.21(\log L(H\beta) - 41),$$

which we show as the solid line. The galaxies with direct O abundance measurements (red dots) lie primarily in the high-$L(H\beta)$ regime. This is partly a consequence of higher-luminosity galaxies having higher ionization parameters, and partly a consequence of the selection bias introduced by the higher line S/N in these spectra, since the brighter the galaxy, the more likely it will satisfy the S/N criterion for measuring [O iii]4363. It is reasonable to ask whether using the strong-line-based O abundances introduces any biases in Equation (11). We have therefore repeated the fit using only the strong-line-based O abundances, but we find essentially the same result.

The range in $\log q$ is relatively modest, from 7.2 at low $L(H\beta)$ to 7.9 at high $L(H\beta)$, or roughly a multiplicative factor of 4 in $q$. As we noted in Cowie & Barger (2008), it is for this reason that even ionization-sensitive diagnostics, such as N2Ha, can be reasonably good metallicity estimators. However, the close dependence of $q$ on $\log L(H\beta)$ indicates that the metallicity calibration relations can be improved by including $L(H\beta)$ as a second parameter.

To determine the effects of the dependence of N2Ha on $q$, we make use of the Kewley & Dopita (2002, their Figure 7) model calculations, which we show in Figure 14(a) for the range of $\log q$ of interest ($\sim 7.3$–8.2). For this limited range, we can bring the N2Ha values into consistency by applying a simple offset of $0.68(\log q - 7.5)$. We illustrate this in Figure 14(b), where we apply this offset to the models. Below $12 + \log(O/H) = 9$, the results are well fit by a linear relation (black line),

$$12 + \log(O/H) = 9.29 + 0.82 \log(N2Ha) + 0.68(\log q - 7.5).$$  \hspace{1cm} (12)

Combining Equations (11) and (12) gives

$$12 + \log(O/H) = 9.35 + 0.82 \log(N2Ha) + 0.14(\log L(H\beta) - 41).$$  \hspace{1cm} (13)

This has the opposite sign in the dependence on $L(H\beta)$ from the relation derived from the observational data (Equation (10)). However, when we allow for the variation in N/O abundance with $L(H\beta)$ described by Equation (8), the dependence reverses sign, and Equation (13) becomes

$$12 + \log(O/H) = 9.20 + 0.82 \log(N2Ha) - 0.10(\log L(H\beta) - 41),$$  \hspace{1cm} (14)

which is fully consistent with the observational dependence on $L(H\beta)$. Equation (14) has a slightly steeper dependence on N2Ha than the Pettini–Pagel relation of Equation (10), but it is in close numerical agreement over most of the fitted range.

The ionization dependence also explains why the evolution in the BPT diagram is weaker than that which would be produced by the evolution in the N/O ratio with $\log L(H\beta)$ (Equation (8)). The increase in $q$ reduces the [N ii]6584/[O iii] 5007 ratio and offsets the rise in N2Ha for a given O3Hb produced by the increase in N/O. For $12 + \log(O/H)$ in the range 8.5–9 and $\log q$ in the range 7.2–7.8, Figure 8 of Kewley & Dopita (2002) shows [N ii]6584/[O iii]5007 changing as $-1.2 \log q$. Combining with Equation (11) translates this to [N ii]6584/[O iii]5007 changing as $-0.25 \log L(H\beta)$. Combining the ionization reduction with the N/O increase gives N2Ha increasing as $0.04 \log L(H\beta)$ for a given O3Hb. While this is weaker than the measured value of $0.09 \log L(H\beta)$ in Equation (1), it is well within the uncertainties in the

Figure 14. N2Ha vs. $12 + \log(O/H)$ as a function of the ionization parameter, $q$. (a) Model calculations of Kewley & Dopita (2002) taken from their Figure 7. The color of the symbols shows the $\log q$ parameter ranging from 8.18 (green), 7.90 (gold), 7.60 (blue), to 7.30 (red). (b) Same points from (a) after applying a correction of $-0.66(\log q - 7.5)$ to N2Ha. This brings the points into approximate agreement throughout much of the $12 + \log(O/H)$ range. Below $12 + \log(O/H) = 9$, the points in (a) are well fit by the linear relation of Equation (12), which is shown for $\log q = 7.5$ as the black line in (b).
calculations. It therefore appears that the offsets in the BPT diagram can be understood as being caused by changes in the N/O abundances, which are partially offset by the changes in the ionization parameter.

5.3. O32 and R23

The small variation in R23 seen in Figure 9 means that R23 is not a useful metallicity diagnostic for either the high-redshift sample or the higher-luminosity SDSS sample. However, the O32 ratio may be a useful metallicity indicator. Shapley et al. (2015) argued, using the composite spectra for SDSS galaxies from Andrews & Martini (2013), that there is a strong dependence of galaxy metallicity on position in the O32 versus R23 diagram, with low-metallicity galaxies lying at high O32 and high-metallicity galaxies lying at low O32. They therefore suggested that O32 might be the best approach to measuring the metallicities of high-redshift galaxies.

However, O32 is hard to measure because of the wide wavelength range between the lines, and the necessity for extinction corrections, which require measurements of both Hα and Hβ. Fortunately, we can avoid the use of O32, because it is quite tightly correlated with N2Ha for galaxies in the star-forming galaxy locus of the BPT diagram (N2Ha < -0.5). We illustrate this in Figure 15, where we plot luminosity-adjusted N2Ha versus O32 for galaxies in the full SDSS sample that satisfy this constraint. The luminosity adjustment in N2Ha tightens the correlation and reduces the dispersion by \sim 20\%. The red bars show the 68\% confidence range in each N2Ha interval, and the red line shows a fit of the form

\[
\log N2Ha = -1.11 - 0.93 \log O32 - 0.14 (\log L(H\beta) - 40). \tag{15}
\]

Thus, over the full spread in O32, we can use the much more easily measured N2Ha as a proxy for O32. A luminosity-adjusted N2Ha is therefore a promising method for measuring the metallicities of high-redshift galaxies.

6. SUMMARY

We confirm that all the standard strong emission-line diagnostics for high-redshift galaxies are shifted relative to the average for SDSS galaxies. However, the major result of this paper is that these diagnostics are not shifted relative to SDSS galaxies at similar values of \( L(H\beta) \). That is, all galaxies with a given \( L(H\beta) \) show invariant emission-line properties at all redshifts.

This remarkable result suggests that we can use the easier to study SDSS galaxies as proxies for high-redshift galaxies of the same luminosity. Through such analyses, we showed that the increase of N2Ha, for fixed O3Hb, seen in the BPT diagram as a function of increasing line luminosity is primarily driven by higher N/O abundances in higher-line-luminosity galaxies. However, this effect is partially offset by an increase in the ionization parameter with increasing line luminosity, which decreases \([\text{[Nii]}]6584\) relative to \([\text{[Oiii]}]5007\). Changes in N2O2 and N2S2, which increase with log \( L(H\beta) \), are driven solely by the increase in N/O with increasing luminosity.

Finally, we argue that we can determine the metallicities of galaxies using a luminosity-adjusted N2Ha parameter, for which we provide the equation (Equation (10)). Such a luminosity-adjusted N2Ha parameter is much easier to measure than O32, which also appears to be a useful diagnostic for higher-line-luminosity galaxies.

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Figure 15. N2Ha − 0.17 log(\( L(H\beta)/40 \)) vs. O32 (black dots) for the full SDSS sample on the star-forming galaxy locus of the BPT diagram (N2Ha < −0.5). The red bars show the 68% confidence range in each N2Ha interval, while the red line shows the linear fit of Equation (15).
