THE MOSDEF SURVEY: OPTICAL ACTIVE GALACTIC NUCLEUS DIAGNOSTICS AT $z \sim 2.3$

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ABSTRACT

We present results from the MOSFIRE Deep Evolution Field (MOSDEF) survey on rest-frame optical active galactic nucleus (AGN) identification and completeness at $z \sim 2.3$. With our sample of 50 galaxies and 10 X-ray and IR-selected AGNs with measured Hα, [O III], Hβ, and N II emission lines, we investigate the location of AGNs in the BPT, MEx (mass-excitation), and CEx (color-excitation) diagrams. We find that the BPT diagram works well to identify AGNs at $z \sim 2.3$ and that the $z \sim 0$ AGN/star-forming galaxy classifications do not need to shift substantially at $z \sim 2.3$ to robustly separate these populations. However, the MEx diagram fails to identify all of the AGN identified in the BPT diagram, and the CEx diagram is substantially contaminated at high redshift. We further show that AGN samples selected using the BPT diagram have selection biases in terms of both host stellar mass and stellar population, in that AGNs in low mass and/or high specific star formation rate galaxies are difficult to identify using the BPT diagram. These selection biases become increasingly severe as high redshift, such that optically selected AGN samples at high redshift will necessarily be incomplete. We also find that the gas in the narrow-line region appears to be more enriched than gas in the host galaxy for at least some MOSDEF AGNs.

Key words: galaxies: active – galaxies: evolution – galaxies: high-redshift – galaxies: Seyfert

1. INTRODUCTION

It is now well established that the population of active galactic nuclei (AGNs), which trace the growth of supermassive black holes (SMBHs) via accretion, has evolved strongly with cosmic time (e.g., Boyle et al. 1993; Ueda et al. 2003; Barger et al. 2005). The overall accretion rate density peaks at a redshift of $z \sim 1–3$ (e.g., Hasinger et al. 2005; Ross et al. 2013; Ueda et al. 2014), similar to the overall star formation rate density (e.g., Boyle & Terlevich 1998; Silverman et al. 2008; Aird et al. 2010), indicating that the growth of galaxies via star formation and the growth of their central SMBHs via accretion are fundamentally linked.

This evolution of the AGN population is primarily driven by a rapid decline in the space density of the most luminous AGN between $z \sim 2$ and the present day, while the space density of lower luminosity AGN evolves more weakly and peaks at somewhat lower redshifts. This evolution is often described as “downsizing” and indicates that the most massive SMBHs likely undergo the bulk of their growth earlier in the history of the universe than their lower mass counterparts (e.g., Ueda et al. 2003; Merloni 2004; Heckman et al. 2004). However, more recently it has also become clear that the overall fraction of galaxies hosting an AGN likely increases at higher redshift (e.g., Xue et al. 2010; Aird et al. 2013; Delvecchio et al. 2014), and thus AGNs are more prevalent at earlier cosmic times. The physical details and extent of the co-evolution of galaxies and SMBHs during this key epoch when the bulk of SMBHs and galaxy growth occurred remains unclear (e.g., Kriek et al. 2007; Hainline et al. 2012; Kocevski et al. 2012; Mullaney et al. 2012; Rosario et al. 2013; Jones et al. 2014).

It has been difficult to make progress on these questions in part because few low- to moderate-luminosity AGNs have measured spectroscopic redshifts at $z \gtrsim 1$, forcing most studies to rely on photometric redshifts (Xue et al. 2010; Brusa et al. 2010; Bongiorno et al. 2012). Furthermore, the lack of rest-frame optical spectra has prohibited many of the detailed studies of the relationship between host galaxy and AGN properties that have been performed at $z < 1$ (e.g., Kauffmann et al. 2003; Kauffmann & Heckman 2009; Hickox et al. 2009; Aird et al. 2012, among many others).

In order to determine the properties of AGN host galaxies at high redshift and to understand the physical drivers of AGN fueling and the co-evolution of galaxies and AGNs, large spectroscopic surveys with well-understood selection effects are needed at $z \sim 1–3$, spanning the cosmic peak of AGN accretion. In particular, rest-frame optical spectra provide a wealth of information about the gas, stellar, and dust properties of galaxies, and while such information is now widely available at low redshift, it has until very recently been difficult to obtain at high redshift, due to the lack of multi-object near-infrared (NIR) spectrographs on 8–10 m class telescopes.

In terms of identifying AGNs within galaxy surveys, deep X-ray data provide unequivocal AGN identification as X-ray emission is a ubiquitous feature and identifies AGNs that may be missed at UV, optical or IR wavelengths due to dust obscuration and/or host galaxy dilution. However, X-rays may fail to identify heavily obscured (Compton-thick) sources or lower accretion rate AGN (e.g., Gilli et al. 2007; Aird et al. 2012). Mid infrared (MIR) emission can also be used to identify AGNs, where high energy radiation from the AGN is reprocessed by hot dust (e.g., Rieke & Lebofsky 1981; Elvis et al. 1994).

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Such MIR AGN selection can potentially also detect Compton-thick AGNs that are missed by X-ray surveys (e.g., Donley et al. 2005; Alonso-Herrero et al. 2006; Polletta et al. 2006; Messias et al. 2012; Mendez et al. 2013). Thus, well-calibrated AGN identifications at different wavelengths are necessary to obtain a more complete AGN census.

At low redshifts, optical diagnostics such as the “BPT diagram” (Baldwin et al. 1981; Veilleux & Osterbrock 1987) have been widely used to identify AGNs via the ratios of the nebular emission lines [O iii] λ5008 to Hβ and [N ii] λ6585 to Hα. This diagnostic can identify AGNs in galaxies where the black hole is growing at a low rate and where the direct line of sight to the AGN is obscured. This diagnostic has been used to identify large numbers of AGNs at $z < 0.2$ and has revolutionized our understanding of the demographics and physics of AGNs at late cosmic times (e.g., Kauffmann et al. 2003; Heckman et al. 2004; Yan et al. 2006).

However, at higher redshifts these emission lines fall outside the wavelength coverage of optical spectrographs. In particular, at $z > 0.45$ the N ii and Hα lines are redshifted to the observed NIR, and at $z > 1$ all four lines required for the BPT diagram are shifted to this wavelength. This has led authors to propose alternative optical AGN diagnostics using the [O iii]/Hβ and either rest-frame galaxy color (Yan et al. 2011) or stellar mass (Juneau et al. 2011). These diagnostics essentially use the known correlation between galaxy stellar mass and metallicity to replace the [N ii]/$H\alpha$ ratio with stellar mass or rest-frame color, which depends on stellar mass. These “color-excitation” (CEx) and “stellar mass-excitation” (MEx) optical diagnostics are calibrated using Sloan Digital Sky Survey (SDSS) sources in the BPT diagram at $z \sim 0.1$. The proposed AGN classification lines in the MEx and CEx diagram have been verified to $z \sim 0.8$ using deep X-ray data (Yan et al. 2011; Juneau et al. 2011). However, these diagnostics have been applied to galaxy samples at $z \sim 1–2$, assuming no evolution in the star-forming galaxy–AGN classifications (Yan et al. 2011; Juneau et al. 2011; Trump et al. 2011, 2013), until recently Newman et al. (2014); Juneau et al. (2014).

The BPT diagram in particular may require calibration at $z > 1$, as we know that galaxies at these redshifts are offset in this space toward the region of the diagram that contains AGNs. This is especially true for the current samples at $z \sim 1–2$, assuming no evolution in the star-forming galaxy–AGN classifications (Yan et al. 2011; Juneau et al. 2011; Trump et al. 2011, 2013), until recently Newman et al. (2014); Juneau et al. (2014).

Using a sample of 36 galaxies and 4 X-ray sources in a flux-limited sample at $z \sim 1.5$, Trump et al. (2013) found that 2/3 of the galaxies in their sample may show evidence for an optically selected AGN based on the $z < 1$ BPT, CEx, and MEx diagnostics, using the $z \sim 0$ classifications. Similarly, Juneau et al. (2013) infer for their $70\mu m$ selected galaxy sample at $0.3 < z < 1.0$ a high AGN fraction (37%) that is twice that of previous similar studies, when they include optically selected AGNs identified using the MEx diagram that are not identified as AGNs in either X-ray or IR emission. While these high fractions may result from evolution in the AGN fraction with redshift, they could also result from not allowing the $z \sim 0$ AGN classification lines to evolve with redshift. Several authors have also suggested that the observed offset of galaxies in the BPT diagram at $z \gtrsim 1$ could be due to contamination from weak AGN activity (Trump et al. 2011; Wright et al. 2010), though this would imply that almost all galaxies at high redshift harbor AGNs, which seems unlikely.

It is clearly important to test AGN classifications in the BPT, MEx, and CEx diagrams at $z > 1$, to ensure that these diagnostic diagrams can be used to robustly identify AGNs, whether they are removed as contaminants from galaxy samples or studied in their own right. Estimates of the incidence of AGN activity at $z > 1$ in particular will be very sensitive to any evolution in the underlying demarcations separating star-forming galaxies and AGNs in these optical diagnostic diagrams. Assuming no evolution could possibly lead to contamination of AGN populations by star-forming galaxies, while assuming more evolution than necessary could underestimate AGN samples.

Kewley et al. (2013a) recently published theoretical predictions for how the classification lines separating star-forming galaxies from AGNs in the BPT diagram should evolve from $z = 0$ to $z = 3$, given different assumptions about interstellar medium (ISM) conditions in high-redshift galaxies, as well as the metallicities of AGN host galaxies. Kewley et al. (2013b) test the evolution in the star-forming galaxy/AGN classification in the BPT diagram using data from the literature to $z \sim 2.5$ and conclude that local calibrations should not be applied at $z > 1.5$. They derive a new redshift-dependent classification, which they test at $z \sim 2.5$ using a sample of 19 gravitationally lensed galaxies. Juneau et al. (2014) also propose that the MEx classification should evolve with redshift and test evolution in both the BPT and MEx diagrams using samples at $z \sim 1.5–2$ from the literature. They find that while samples at $z \sim 1.5$ are large enough to study galaxy and AGN properties, at $z \sim 2$ the current samples are too small and have potentially strong selection biases.

Here we aim to test how well the $z \sim 0$ BPT, MEx, and CEx optical AGN diagnostics hold at $z \sim 2$, as well as test the new proposed evolution in the classifications separating star-forming galaxies and AGNs in these diagnostics. Such tests require measurements of the success and contamination rate of AGN selection, where AGNs have been unequivocally identified at non-optical wavelengths. To this end we use a statistical sample of NIR spectra from the MOSFIRE Deep Evolution Field (MOSDEF) survey, taken with the newly commissioned MOSFIRE multi-object NIR spectrograph at Keck. We use measurements of the complete set of rest-frame optical emission lines required for the BPT diagram. We identify an unequivocal, a priori AGN sample based on X-ray and/or IR emission and use emission line ratios for galaxies and AGN in the MOSDEF survey to place $z \sim 2.3$ sources in the BPT diagram, as well as the CEx and MEx diagrams. As with all AGN selection methods, our a priori AGN sample is incomplete; however, it provides a reliable sample that is sufficient for the comparisons performed here. This methodology allows us to characterize the evolution of the division between star-forming galaxies and AGNs in these optical diagnostic diagrams and discuss the completeness of optically selected AGNs compared to X-ray and IR-selected AGNs at these redshifts.

The outline of the paper is as follows. Section 2 describes the data used here, including Chandra and Spitzer selection of AGNs as well as our new MOSFIRE spectra. We additionally describe the methods used to measure emission line ratios, stellar masses, and rest-frame colors for our sources. In Section 3 we present our results and the location of MOSDEF galaxies
and AGNs in the BPT, MEx, and CEx diagrams. We discuss our results in Section 4 and conclude in Section 5. Throughout the paper we assume a cosmology with $\Omega_m = 0.3$, $\Omega_{\Lambda} = 0.7$, and $h = 0.7$.

2. DATA

We use spectroscopic data from the on-going MOSDEF survey (Kriek et al. 2015). This survey uses the recently commissioned MOSFIRE spectrograph (McLean et al. 2012) on the 10 m Keck I telescope. MOSFIRE is a multi-object NIR spectrograph that spans the wavelength range 0.97 μm to 2.45 μm and allows for the simultaneous observation of up to 46 individual sources over a 6′ × 3′ field of view (we typically observe $\sim$ 30 galaxies on a mask). The MOSDEF survey is being undertaken in three of the five CANDELS fields—COSMOS, GOODS-N, and EGS—in areas with coverage by the 3D-Hubble Space Telescope (HST) grism survey (Brammer et al. 2012) and when completed will produce moderate-resolution ($0.5$–$2$ keV) rest-frame optical spectra for $\sim$ 1500 galaxies at $1.4 \leq z \leq 3.8$.

The full survey will use 47 Keck nights over the course of 4 yr; here we use data from the first observing season, spanning 2012 December through 2013 May. During this time a total of eight slitmasks were observed, including two slitmasks in the GOODS-S and UDS fields, which are not part of the main survey fields. The resulting sample at $1.4 \leq z \leq 3.8$ includes a total of 207 galaxies and AGNs for which we obtained emission lines. Targets for spectroscopy are selected down to fixed $H$-band (i.e., rest-frame optical) magnitude, using the HST/WFC3 F160W magnitudes provided by the 3D-HST team. We additionally use 3D-HST grism and photometric redshifts to increase the probability that targets will be at $1.37 \leq z \leq 3.8$ (Skelton et al. 2014). The MOSDEF survey targets sources in three specific redshift intervals (1.37 < z < 1.70, 2.09 < z < 2.61, and 2.95 < z < 3.80), such that the brightest rest-frame optical emission lines fall within atmospheric windows. We design slitmasks for a given redshift range, and each slitmask is observed in multiple filters to cover the entire rest-frame optical spectrum, including multiple emission lines from $\sim$ 3500–7000 Å. Here we focus on sources at $2.09 < z < 2.61$, which are observed in the J, H, and K bands. There are a total of 142 galaxies and AGNs in this redshift interval in the MOSDEF data from the first observing season.

Target weights, which define the likelihood that a source will be selected as a spectroscopic target, are based on the HST/WFC3 F160W magnitude, with brighter sources given higher weights. The limiting magnitude for the $2.09 < z < 2.61$ sample is 24.5. Sources identified a priori as AGNs using either X-ray or Infrared Array Camera (IRAC) imaging data (details below) are given a higher targeting weight. Existing spectroscopic and photometric redshift information is also used in determining target weights, such that the MOSDEF sources are likely to fall in the redshift range of interest.

Slitmasks with sources at $2.09 < z < 2.61$ are observed for 2 hr in each of the J, H, and K bands. Our 0′.7 slits result in resolutions of $R = 3300, 3650$, and 3600 in the J, H, and K bands, respectively. Masks were typically observed with an ABA′B′′ dither pattern, and seeing conditions were $\sim$ 0′.5–1′′ for most observations. The data were reduced with a custom IDL data reduction pipeline. Our spectroscopic success rate is extremely high; we detect emission lines for $\sim$ 85% of our targets. Details of the MOSDEF survey, target selection, data reduction, and galaxy sample characteristics are given in Kriek et al. (2015).

2.1. X-Ray AGN Identification

AGNs were identified prior to designing MOSDEF slitmasks using both Chandra and Spitzer imaging in our fields. In the COSMOS, GOODS-N, GOODS-S, and EGS fields we identified X-ray sources based on the deep Chandra X-ray imaging. The depth of the Chandra data used in these fields is 160ks in COSMOS, 2Ms in GOODS-N, 4Ms in GOODS-S, and 800 ks in EGS, corresponding to hard band (2–10 keV) flux limits (over >10% of the area) of 1.8e-15, 2.8e-16, 1.6e-16, and 5.0e-16 erg s$^{-1}$ cm$^{-2}$, respectively. As the UDS currently lacks the deep, high-resolution Chandra data available in the other fields and is not one of the primary MOSDEF fields, we do not consider this field for our study.

The X-ray data from all the fields were reduced using a consistent procedure, as described in Laird et al. (2009; see also Georgakakis et al. 2014; Nandra et al. 2015). Point source detection was performed according to the method of Laird et al. (2009), applying a false probability threshold of $< 4 \times 10^{-6}$ (roughly corresponding to a 3σ detection) for sources in the full (0.5–2 keV), soft (0.5–2 keV), hard (2–7 keV) or ultra-hard (4–7 keV) energy bands. The source catalogs were merged to create a single multiband catalog in each field. We then identified secure multiwavelength counterparts to the X-ray sources using the likelihood ratio method (Ciliegi et al. 2003, 2005; Brusa et al. 2007; Luo et al. 2010), matching to sources detected at IRAC, NIR and optical wavelengths (see Nandra et al. 2015 for full details). These catalogs were then matched to the 3D-HST catalogs used for MOSDEF target selection, matching to the closest 3D-HST source within 1″.

For X-ray sources observed by MOSDEF, we estimate 2–10 keV rest-frame X-ray luminosities for each source based on either the hard-band flux (when the source is detected) or the soft-band flux (otherwise). We assume the X-ray spectrum is a simple power-law including only Galactic absorption with photon index $\Gamma = 1.9$. Our hard band flux detection limits approximately correspond to X-ray luminosity limits of $L_{2–10keV} \approx 1.3–15.1 \times 10^{32}$ erg s$^{-1}$ at $z \sim 2.3$; sources at off-axis positions will have a higher detection limit. We note that at the redshifts probed by MOSDEF ($z > 1.4$) a relatively large absorption column ($N_H \gtrsim 10^{23}$ cm$^{-2}$) is required to significantly suppress the observed flux, even at 0.5–2 keV, so our luminosity estimates should be reasonably accurate, although a more sophisticated X-ray spectral analysis could indicate higher levels of intrinsic absorption and a higher X-ray luminosity.

For all galaxies in the MOSDEF sample that are not associated with an X-ray detection, we estimate upper limits on the X-ray luminosity. We extract the total counts from the X-ray images within a circular region corresponding to the 90% enclosed energy fraction (based on the Chandra PSF) for both the hard and soft bands. We estimate the background rate within the same aperture based on smoothed background maps and calculate the 95% highest posterior density confidence limit on the X-ray flux using the method of Kraft et al. (1991). We convert the upper limits on the hard and soft fluxes to X-ray luminosities using the same method as described above for the directly detected sources.

2.2. IR AGN Identification

As discussed above, deep X-ray surveys provide a highly reliable means of selecting AGNs. However, at high column densities of $N_H \gtrsim 10^{23}$ cm$^{-2}$ X-ray photons are absorbed, such that X-ray surveys can fail to identify the most heavily
absorbed AGNs. Such obscured AGNs may instead be identified by their MIR emission, as high-energy radiation from an AGN is reprocessed by dust and re-radiated at MIR wavelengths.

Several selection techniques have been developed that use the unique colors of AGNs in the MIR to identify infrared-AGNs (IR-AGNs) using data from the IRAC (Fazio et al. 2004) on Spitzer (i.e., Lacy et al. 2004; Stern et al. 2005). Here we select IR-AGN samples using the IRAC color criteria presented by Donley et al. (2012). This color-selection technique was designed to limit contamination by star-forming galaxies at least to $z = 3$ but still be both complete and reliable for the identification of luminous AGNs. This was confirmed using large galaxy samples at intermediate redshift (Mendez et al. 2013), where it was shown that especially for deep IR surveys the Donley et al. (2012) selection criteria provides robust selection of AGNs, free from galaxy contamination. Donley et al. (2012) compare their AGN selection criteria to various higher redshift samples at $z \sim 3$ and come to the same conclusion.

We use IRAC fluxes reported in the 3D-HST catalogs (Skelton et al. 2014). The IRAC 3.6, 4.5 μm images in the main MOSDEF fields (AEGIS, COSMOS, GOODS-N) are from the Spitzer Extended Deep Survey (SEDS; Ashby et al. 2013) v1.2 data release, while the 5.8 and 8 μm images in AEGIS are from Barmby et al. (2008), in COSMOS from the S-COSMOS survey (Sanders et al. 2007), and in GOODS-N from the GOODS Spitzer second data release. Further details of the IRAC data are given in Skelton et al. (2014).

Following Donley et al. (2012), we require that objects are detected in all four IRAC bands, and have colors such that they lie within the following region in IRAC color–color space:

\[
x = \log_{10} \left( \frac{f_{5.8 \mu m}}{f_{3.6 \mu m}} \right), \quad y = \log_{10} \left( \frac{f_{8.0 \mu m}}{f_{4.5 \mu m}} \right) \quad (1)
\]

\[
x \geq 0.08 \quad \text{and} \quad y \geq 0.15 \quad (2)
\]

\[
y \geq (1.21 \times x) - 0.27 \quad (3)
\]

\[
y \leq (1.21 \times x) + 0.27 \quad (4)
\]

\[
f_{4.5 \mu m} > f_{3.6 \mu m} \quad \text{and} \quad f_{5.8 \mu m} > f_{4.5 \mu m}, \quad \text{and} \quad (5)
\]

\[
f_{8.0 \mu m} > f_{5.8 \mu m}. \quad (6)
\]

The AGNs identified using these IRAC colors have some overlap with the X-ray-selected AGNs. Generally, IR-AGN selection identifies more luminous AGNs than X-ray selection (Mendez et al. 2013).

### 2.3. Spectroscopic AGN Sample

In our first observing season we targeted a total of 18 X-ray and/or IR-selected AGNs, and we measured emission lines for 14 of these sources (the other four were likely outside of our observed redshift range). We emphasize that the fraction of the full MOSDEF sample that contains AGNs should not be interpreted as the fraction of all galaxies at these redshifts that contain s, as AGNs were given higher targeting weights when designing slitmasks.

Of the 14 AGNs for which we obtained emission lines, here we present results for AGNs at $2.09 < z < 2.61$ (this excluded one AGN) that had narrow emission lines and for which of the four lines used in the BPT diagram ([O iii], Hβ, [N ii], or Hα), at least either O iii or Hβ and either N ii or Hα were detected at greater than 3σ (this excluded three AGNs). This criterion resulted in a sample of 10 AGNs listed in Table 1. Two of these AGNs were observed twice, on two different slitmasks; here we use the higher spectral S/N observation for each. As shown in Table 1, three of the 10 AGNs are identified as AGNs using IRAC colors, and eight are identified as AGNs using X-ray detections, with one AGN being both IR and X-ray selected. The log $(L_X/\text{erg s}^{-1})$ values of our X-ray AGNs are $\sim$43–44; therefore these are moderate luminosity X-ray AGNs. The mean redshift of the AGN sample is $z = 2.25$.

To measure line ratios, we fit Gaussian emission lines using the MPFIT non-linear least squares fitting function in IDL, where the error spectra are used to determine the errors on the fit. The fits are shown in Figure 1. For the AGNs presented here, we generally fit a single isolated Gaussian to Hβ, [O iii] $\lambda$5008, [O i] $\lambda$6302, two Gaussians simultaneously to [S ii] $\lambda$6718 and [S ii] $\lambda$6733, and three Gaussians simultaneously to [N ii] $\lambda$6550, Hα, [N ii] $\lambda$6585. The deconvolved FWHM values (subtracting in quadrature the instrumental resolution) are $\sim$200–500 km s$^{-1}$.

For the three AGNs with broad Hα emission where N ii is still visible (IDs 4, 8, 10), we fit four Gaussians simultaneously to [N ii] $\lambda$6550, Hα, [N ii] $\lambda$6585, allowing for both a narrow and broad Hα component. The broad Hα components in these three AGNs have FWHM values of $\geq$1500 km s$^{-1}$.

### Table 1

| ID   | Field   | 3D-HST ID | R.A.    | Decl. | $z$ | AGN Identifier | $\log L_X$ (erg s$^{-1}$) |
|------|---------|-----------|---------|-------|----|----------------|-------------------------|
| 1    | GOODS-S | 42556     | 03:32:19.953 | $-27.42:43.152$ | 2.30403 | X-ray | 43.56 |
| 2    | GOODS-S | 41886     | 03:23:43.463 | $-27.42:55.017$ | 2.14214 | X-ray | 43.18 |
| 3    | GOODS-N | 41748     | 03:32:24.196 | $-27.42:57.551$ | 2.30082 | X-ray | 43.30 |
| 4    | COSMOS  | 10769     | 10:00:20.255 | 02:17:25.763 | 2.10321 | X-ray | 44.10 |
| 5    | COSMOS  | 3146      | 10:00:31.820 | 02:12:43.542 | 2.10598 | IR   | $<43.48$ |
| 6    | GOODS-N | 22299     | 12:36:51.815 | 62:15:04.724 | 2.19391 | X-ray | 43.81 |
| 7    | GOODS-N | 14283     | 12:37:02.600 | 62:12:44.017 | 2.42009 | X-ray | 43.22 |
| 8    | GOODS-N | 21290     | 12:37:04.336 | 62:14:46.253 | 2.21490 | IR   | $<42.88$ |
| 9    | GOODS-N | 19082     | 12:37:07.189 | 62:14:08.090 | 2.48688 | X-ray | 43.51 |
| 10   | GOODS-N | 24192     | 12:37:23.188 | 62:15:38.425 | 2.24335 | X-ray/IR | 43.69 |

Notes.

a) ID in 3D-HST v4.1 catalogs.

b) Rest-frame 2–10 keV X-ray luminosities estimated from the counts in the observed 2–7 keV (hard) band.
Figure 1. MOSDEF AGN spectra and fits for the Hβ, [O iii], Hα, [N ii], and [S ii] emission lines. The observed spectra are shown in black, Gaussian fits in red, and error spectra with dotted green lines. The ID of each AGN is given in the upper left of the row. The y axis is scaled in the left panel to show the [O iii] line well and in the right panel to show the Hα line well. Note that the wavelength width is not identical for each column; the third column with fits to Hα and [N ii] has twice the wavelength range as the other columns. As discussed in the text, we do not fit Hα or [N ii] for ID 5, due to the broad Hα emission, and for ID 7 we fit the [O iii] λ5008 line instead of the [O iii] λ5008 line, which is impacted by a night sky line.

For AGN ID 8, we fit both a broad and narrow component to O iii and Hβ, where the emission lines were not well fit by a single narrow component. In the BPT diagram we use the narrow components of each line, which have FWHM values of ~200–400 km s\(^{-1}\), while the broad components have FWHM values of ~1100 km s\(^{-1}\). For AGN ID 6, we fit two Gaussians to each Hβ, [O iii], [O i], and [S ii] line and six Gaussians simultaneously to [N ii] λ6550, Hα, [N ii] λ6585, allowing two Gaussians for each line. The FWHM values of each Gaussian are ~100–500 km s\(^{-1}\). As we discuss further below, since both components are narrow we keep both in our sample here. We do not fit N ii and Hα for AGN 5, where a very broad Hα line renders the N ii line invisible. This AGN is therefore included in diagnostics that use only [O iii]/Hβ but not [N ii]/Hα. The FWHM of [O iii] is 1370 km s\(^{-1}\); we note that given the broad width of this line the [O iii]/Hβ value on optical AGN diagnostics should be treated with caution. For ID 7 we fit the O iii λ4960 line and scale the resulting flux and error by a factor of three to estimate the parameters for the [O iii] λ5008 line, which is impacted by a night sky line.

In performing the Gaussian fits, we allow as much freedom as the data permit. We do not allow for a continuum slope local to the emission line, but we do fit for a flat continuum. We allow some freedom in the wavelength of the line center (up to 0.15%), though we fix the spacing between the S ii and N ii lines. We generally do not tie the widths of the different lines together for a single source, though we do require that the S ii and N ii lines have the same width of Hα. We force the [N ii] λ6550 flux to be one third of the [N ii] λ6585 flux, and we set a minimum width for the velocity dispersion of 1.5 Å in the rest frame for the narrow lines and 3.5 Å for the broader lines. Line ratios and 3σ limits for the AGNs are given in Table 2.

Gaussian fits are also performed for MOSDEF galaxies that are not identified as AGNs a priori using X-ray or IR imaging. To be consistent with the AGN fitting, we do not allow for a continuum slope for the galaxy line fits (though we note that allowing a slope does not change our results). We also include Balmer absorption corrections to both the Hα and Hβ line fluxes, for both galaxies and AGNs, using results from SED fitting (see below). Typically, this correction to Hα and Hβ is only a few percent. Throughout the paper, in each figure we show MOSDEF galaxies that have S/N ≥ 3 for each of the emission lines required for that figure.

As discussed above, AGN ID 6 displays two spectral components for each emission line. The two spectral components for this AGN are not substantially different in width; there is not a broad and narrow component but rather two narrow components, one at the rest wavelength and one bluer. The bluer component is offset by ~115 km s\(^{-1}\) in [N ii], ~120 km s\(^{-1}\) in Hα, ~205 km s\(^{-1}\) in [O iii], and ~203 km s\(^{-1}\) in Hβ, relative to the redder emission line at the rest wavelength. Figure 2 shows HST postage stamps for this source. The F606W emission (left panel; Giavalisco et al. 2004) appears in a ring, with stronger emission on one side of the ring. This ring is filled in with F160W emission (middle panel; Grogin et al. 2011; Koekemoer et al. 2011), such that the color composite (right panel) shows a blue ring around a central red source. These images suggest that this object is undergoing a merger event, with tidal debris or triggered star formation seen in the F606W image. For this source we do not apply Balmer absorption corrections, as it
is not clear how to apply a single correction derived from the SED, where both components are contributing to the light, to the individual redder and bluer spectral components. However, this correction should be negligible.

2.4. Stellar Mass and Rest-frame Color Measurements

Stellar masses for MOSDEF galaxies and AGNs are estimated from SED fits to the 3D-HST multi-wavelength photometry (Skelton et al. 2014) using the FAST SED fitting code of Kriek et al. (2009), with the Conroy et al. (2009) stellar population synthesis models and the Chabrier (2003) initial mass function (IMF). Errors are derived by perturbing the photometry according to the photometric errors and remeasuring the stellar mass. The 16th and 84th percentiles of the resulting distribution are taken to be the lower and upper error bounds on the stellar, respectively. Rest-frame $(U - B)_{B0}$ colors are estimated from the best-fit template in the FAST SED fitting process, using Bessel U and B filter curves. Error bars on the rest-frame $(U - B)_{B0}$ colors are derived from the input photometry and associated error bars, where we perturb each photometric point by a Gaussian random variable with the width set by the photometric error for that point. The standard deviation that results from doing this 500 times is used to derive the error on the $(U - B)_{B0}$ color.

For the AGN, we do not include $u$-band or IRAC photometry when deriving stellar masses and rest-frame colors, to avoid contamination due to the AGN light. We do use these bands in the SED fits to the galaxies. We find that none of our results change if we include the $u$-band and IRAC photometric points for the AGN, though the exact stellar masses and rest-frame colors for some AGNs change slightly (the median difference in stellar mass is 0.05 dex). Stellar masses and $(U - B)_{B0}$ colors for the AGN are given in Table 2.

For comparison purposes, we also compile line ratios, stellar masses, and rest-frame $(U - B)_{B0}$ colors for galaxies and AGNs in the SDSS. We restrict the SDSS sample to sources with $z < 0.2$ and show only those sources with S/N $> 3$ in all of the relevant emission lines used for a particular diagnostic. Line ratios and stellar masses are taken from the SDSS Data Release 7 (DR7) emission line and stellar mass catalogs developed by the Max-Planck Institute for Astronomy (Garching) and Johns Hopkins University (MPA/JHU). The methodology for measurements of emission-line fluxes is described by Tremonti et al. (2004). Balmer absorption corrections have been applied to these SDSS line fluxes. Stellar masses are based on SED fits, following the methodology of Kauffmann et al. (2003) and Salim et al. (2007), and use the Bruzual & Charlot (2003) stellar population synthesis models and the Chabrier (2003) IMF. Rest-frame $(U - B)_{B0}$ colors are taken from the best-fit SED template using SEDfit outputs from Moustakas et al. (2013). The SED fits use photometry spanning the ultraviolet (GALEX) through the

### Table 2: AGN MOSDEF Derived Parameters

| ID | log ([O iii]/Hβ) | log ([N ii]/Hα) | log ([S ii]/Hα) | log ([O i]/Hα) | log $M_*$ ($M_\odot$) | $(U-B)_{B0}$ | Broad line* |
|----|-----------------|----------------|----------------|--------------|-----------------|-------------|------------|
| 1  | >0.52           | <−0.29         | <−0.08         | <−0.18       | 10.38 ± 0.21    | 0.98 ± 0.03 |            |
| 2  | 0.69 ± 0.14     | −0.07 ± 0.05   | −0.40          | −0.62        | 11.07 ± 0.06    | 0.99 ± 0.02 |            |
| 3  | >0.01           | −0.23 ± 0.06   | −0.32          | −0.64        | 10.96 ± 0.06    | 0.90 ± 0.01 |            |
| 4  | 0.22 ± 0.06     | −0.22 ± 0.01   | −0.62 ± 0.04   |              | 10.82 ± 0.03    | 0.57 ± 0.01 | Hα         |
| 5  | >0.48           |               |                |              | 11.13 ± 0.08    | 0.96 ± 0.03 | Hα         |
| 6b | 0.27 ± 0.32     | −0.22 ± 0.04   | −0.84 ± 0.14   | −0.53        | 10.35* ± 0.49   | 0.70 ± 0.11 |            |
| 6c | 0.04 ± 0.10     | −0.46 ± 0.09   | −0.56 ± 0.10   | −0.40        | 10.35* ± 0.46   | 0.70 ± 0.11 |            |
| 7  | <−0.45          | −0.19 ± 0.05   | −0.43 ± 0.14   | −0.81        | 10.92 ± 0.07    | 0.84 ± 0.05 |            |
| 8  | 1.22 ± 0.13     | −0.40 ± 0.03   | −0.86 ± 0.09   | −1.27 ± 0.16 | 10.66 ± 0.01    | 0.84 ± 0.01 | Hα, [O iii], Hα |
| 9  | >−0.46          | −0.18 ± 0.07   | −0.24          | −0.62        | 11.23 ± 0.25    | 0.97 ± 0.06 |            |
| 10 | 0.72 ± 0.07     | −0.42 ± 0.05   | −0.69          | −1.41        | 10.66 ± 0.06    | 0.72 ± 0.08 | Hα         |

### Notes.

* Where both a narrow and broad Gaussian fit was required.
* Bluer spectral component.
* The stellar mass and color for this AGN are derived for the entire source, not the bluer and redder spectral components separately.
* Redder spectral component.
optical to the MIR (WISE) and use the Conroy et al. (2009) models and the Chabrier (2003) IMF. The differences in how the stellar masses and rest-frame colors are derived in SDSS compared to MOSDEF are small and do not affect any of our conclusions.

3. RESULTS

In this section we present the location of MOSDEF galaxies and AGNs, identified either through X-ray or IR emission, in the various optical AGNs diagnostic figures, including the BPT, MEx, and CEx diagrams. We compare their locations with local SDSS galaxies as well as the various proposed classifications between star-forming galaxies and AGNs in these diagrams.

3.1. BPT Diagram

In Figure 3 we show the [O\textsc{iii}]/\text{H}\beta versus [N\textsc{ii}]/H\alpha BPT diagram (Baldwin et al. 1981; Veilleux & Osterbrock 1987) for our MOSDEF AGNs (red and purple circles) and galaxies (blue triangles). MOSDEF targets that are identified as AGNs from their IRAC colors are marked with a purple circle, while X-ray AGNs are shown with red circles. For the AGNs with two spectral components (ID 6) we plot each component separately; “6b” indicates the bluer component, while “6r” indicates the redder component. It is possible that only one of these components contains an AGN. For clarity, only those MOSDEF galaxies with at least 3σ detections in all four lines used for this diagram are shown here; this results in a sample of 50 MOSDEF galaxies. We note that the Balmer absorption corrections are typically small (~0.01 dex in [N\textsc{ii}]/H\alpha and ~0.06 dex in [O\textsc{iii}]/\text{H}\beta) for galaxies and AGNs and do not affect their location in the BPT diagram substantially.

For comparison we show the distribution of SDSS sources with contours and grayscale; we show all SDSS sources in DR7 that have S/N > 3 for H\beta, [O\textsc{iii}], [N\textsc{ii}], and H\alpha. The dashed dark green line indicates the local empirical division between star-forming galaxies and AGNs from Kauffmann et al. (2003), while the dot–dashed dark green line indicates the local theoretical “maximum” allowed starburst galaxy in Kewley et al. (2001). At z ~ 0 sources above the latter division have line ratios that can only be due to AGNs, in the models of Kewley et al. (2001). Sources in between these two divisions are often referred to as “composite” sources, where there are contributions to the line ratios from both star formation and AGN activity. A more complete local optical AGN sample would therefore include these “composite” sources.

As discussed in the introduction, many authors have found that galaxies at z ~ 1–3 are offset in the BPT diagram when compared with local samples. Similarly, here we find that the MOSDEF galaxies have, on average, slightly higher [O\textsc{iii}]/\text{H}\beta ratios at a given [N\textsc{ii}]/\text{H}\alpha ratio (or equivalently, higher [N\textsc{ii}]/H\alpha at a given [O\textsc{iii}]/\text{H}\beta), compared to SDSS galaxies. We find that the vast majority of MOSDEF galaxies not identified as X-ray or IR AGNs lie below the Kauffmann et al. (2003) division, and only two MOSDEF galaxies lie above the Kewley et al. (2001) line. The latter are identified in Figure 3 with cyan outlines. We also outline in light green the four additional galaxies above the Kauffmann et al. (2003) line. Here we consider these galaxies as potential optical AGN candidates, given their location in the BPT diagram with respect to local AGN classification lines.

We note that of the nine MOSDEF X-ray and IR AGNs (one with two spectral components) shown here, four have limits in [O\textsc{iii}]/\text{H}\beta (three lower limits and one upper limit), one of which also has an upper limit in [N\textsc{ii}]/H\alpha, as indicated with red arrows. Five of the MOSDEF AGNs lie above the Kewley et al. (2001) line (though one is an upper limit in [N\textsc{ii}]/H\alpha and another an upper limit in [O\textsc{iii}]/\text{H}\beta), while AGN ID “6b” is just below the line, with an [O\textsc{iii}]/\text{H}\beta error that extends well above the line. AGN ID 4 is also just below the line, 1.3σ away. There are two additional AGNs (ID 3 and 9) in the “composite” region that have lower limits in [O\textsc{iii}]/\text{H}\beta such that they could potentially be above the Kewley et al. (2001) line. Only AGN ID “6r” clearly falls well below the Kewley et al. (2001) line; it is just below the Kauffmann et al. (2003) line. As discussed above, AGN ID 6 is an X-ray source and contains an AGN, but we do not know whether the AGN is associated with the redder or bluer spectral component (or both). Therefore it could be that the bluer component has an AGN, and indeed the BPT diagram strongly suggests that this is likely. We therefore find that our X-ray and IR AGN are either above or consistent with being above the Kewley et al. (2001) line.

This figure clearly shows that both the [O\textsc{iii}]/\text{H}\beta and [N\textsc{ii}]/H\alpha ratios are necessary to separate AGNs from galaxies at z ~ 2.3, and that of the two line ratios, the [N\textsc{ii}]/H\alpha ratio has much more discriminatory power in that all of the MOSDEF AGN have [N\textsc{ii}]/H\alpha of z ~ 0.5, while they span a wide range of [O\textsc{iii}]/\text{H}\beta values. It appears that at the depth of the MOSDEF survey the [N\textsc{ii}]/H\alpha ratio alone may be sufficient to separate AGNs from galaxies at these redshifts (see also Stasińska et al. 2006).

As to whether divisions between star-forming galaxies and AGNs such as the Kauffmann et al. (2003) and Kewley et al. (2001) lines can be applied at z ~ 2, Figure 3 shows that because galaxies at these redshifts are offset, on average, with respect...
Figure 4. [O \text{iii}]/H\beta vs. [S \text{ii}]/H\alpha (left) and [O \text{iii}]/H\beta vs. [O \text{i}]/H\alpha (right) diagrams for MOSDEF galaxies and AGNs at z = 2.3. As in Figure 3, contours and grayscale show the locations of SDSS sources, while blue triangles show MOSDEF galaxies and red and purple circles MOSDEF AGNs, identified as AGN either through X-ray or IR emission. Arrows indicate 3\sigma limits for some galaxies (right panel) that are not detected in all four lines. Open blue triangles show galaxies that are not included in Figure 3, due to low S/N in [N \text{ii}] and/or H\alpha. The dot-dashed green lines show the z = 0 divisions between star-forming galaxies (below the line) and AGNs (above the line) from Kewley et al. (2001), while the dotted green line in the left panel shows the division between Seyfert AGN and LINERs from Kewley et al. (2006). The two MOSDEF galaxies in Figure 3 that are above the Kewley et al. (2001) line in the BPT diagram are outlined here in cyan, and four additional galaxies above the Kauffmann et al. (2003) line are outlined in light green. In the right panel, most MOSDEF sources have upper limits in [O \text{ii}]/H\alpha, though one AGN and eight galaxies have >3\sigma detections.

to SDSS sources these divisions need to be revised slightly (~0.1–0.2 dex) such that galaxies are not included in AGN samples. We return to this point in Section 4.1 below.

3.2. [S \text{ii}]/H\alpha and [O \text{i}]/H\alpha BPT Diagrams

In Figure 4 we show the other two BPT-like diagrams that are commonly used at low redshift to separate star-forming galaxies and AGNs (Veilleux & Osterbrock 1987). On the left is the [O \text{iii}]/H\beta versus [S \text{ii}]/H\alpha diagram, and on the right is the [O \text{iii}]/H\beta versus [O \text{i}]/H\alpha diagram. The left panel includes 56 MOSDEF galaxies, where we include all galaxies with S/N > 3 in each of the four lines used for this figure. Open blue triangles show galaxies that have S/N > 3 in the sum of the [S \text{ii}] lines but S/N < 3 in the [N \text{ii}] \lambda 6585 line, such that they are not shown in Figure 3. Ten of these twelve galaxies have S/N > 3 in the [N \text{ii}] \lambda 6585 line, with values of log [N \text{ii}]/H\alpha < -0.8 such that they would not be classified as AGNs in the BPT diagram. The two MOSDEF galaxies in the BPT diagram in Figure 3 that are above the Kewley et al. (2001) line are shown here with cyan outline, and the four additional galaxies above the Kauffmann et al. (2003) line are shown with light green outlines, as in Figure 3. We note that MOSDEF galaxies do not have, on average, higher [O \text{iii}]/H\beta at a given [S \text{ii}]/H\alpha ratio, unlike at a given [N \text{ii}]/H\alpha ratio, as seen above (see also Shapley et al. 2014).

In the [S \text{ii}]/H\alpha diagram the MOSDEF AGNs lie throughout the entire range of the MOSDEF galaxies in both [S \text{ii}]/H\alpha and [O \text{iii}]/H\beta. Five of the AGNs have upper limits in [S \text{ii}]/H\alpha. Five of the MOSDEF AGNs (along with many MOSDEF galaxies) lie above the local “maximal” starburst line from Kewley et al. (2001), and the other four AGNs (one with two spectral components) lie below it. Those AGNs that are below the Kewley et al. (2001) line in this diagram are also those that are in the “composite” region in Figure 3. This is consistent with studies that have shown that at low redshift, “composite” sources often lie below the Kewley et al. (2001) line in the [S \text{ii}]/H\alpha diagram (e.g., Stern & Laor 2013). There is one MOSDEF AGN (ID 1) in the LINER region of this diagram, though given that it has limits in both line ratios such that it could fall in the Seyfert region. We therefore do not classify any of our X-ray/IR AGNs as LINERs. Given the high overlap between the MOSDEF galaxies and AGNs in this figure, it appears that that [S \text{ii}]/H\alpha versus [O \text{iii}]/H\beta diagram does not have as much discriminatory power at z ~ 2 to identify AGNs. We note that of the four “composite” sources outlined in light green, three lie near or above the Kewley et al. (2001) line, such that they would be classified as AGNs, though there are an additional nine MOSDEF galaxies above this line that are below the Kauffmann et al. (2003) line in the BPT diagram. It therefore appears that the Kewley et al. (2001) classification in the [O \text{iii}]/H\beta versus [S \text{ii}]/H\alpha diagram is not as useful in reliably identifying AGNs at z ~ 2 compared to the classification in the BPT diagram.

The right panel of Figure 4 shows the [O \text{ii}]/H\beta versus [O \text{i}]/H\alpha diagram, where here we show all MOSDEF galaxies with >3\sigma detections in [O \text{ii}]/H\beta, regardless of whether they have a detection in [O \text{i}]. This results in a sample of 71 galaxies. For most MOSDEF galaxies and AGNs we have only upper limits in [O \text{i}]. There are eight galaxies and one AGN for which we have >3\sigma detections in O\text{i} and H\alpha, shown here with error bars (all of these sources are shown in Figure 3). The one detected AGN is above the Kewley et al. (2001) division, as are all but one of the MOSDEF galaxies that are detected. It is difficult to draw conclusions from this figure, given how many sources are not detected, but having seven sources that were not identified as AGNs from either X-ray or IR emission above the Kewley et al. (2001) line might indicate that at z ~ 2 galaxies and AGNs do not separate as cleanly in this space as they do at z ~ 0.
3.3. MEx Diagram

In Figure 5 we show the MEx diagram of Juneau et al. (2011), where here we show all MOSDEF galaxies that have >3σ detections in both O III and Hβ; this results in a sample of 87 galaxies. The 37 additional galaxies shown here that are not shown in Figure 3 due to having S/N < 3 in the N II and/or Hα lines are plotted with open blue triangles. The vast majority of them are likely not AGNs, given that >90% of the galaxies in Figure 3 are not identified as AGNs, and these additional galaxies do not have strong N II lines. For AGN ID 6, here we plot only the bluer spectral component, as this component in the BPT diagram is in the AGN region, while the redder spectral component is below the Kauffmann et al. (2003) line. For this source we only have a stellar mass for the entire object, not a mass associated with each spectral component; the stellar mass is therefore overestimated.

In the MEx diagram the dot–dashed green lines show the divisions suggested in this space between star-forming galaxies, composite galaxies, and AGNs in SDSS from Juneau et al. (2014). It is immediately clear that these divisions are not appropriate for our sources at z ∼ 2.3. Juneau et al. (2014) predict a shift in these divisions to higher stellar mass for high redshift surveys. They use a functional form describing the evolution of $L_{Hα}$ (the break in the Hα luminosity function), to essentially track the evolution in the global SFR density. This is then combined with the Hα and O III line luminosity detection limits in a given high redshift survey, to select galaxies in SDSS that have similar line luminosities relative to $L_{Hα}$ (at $z ∼ 0$) as galaxies in the high redshift survey (relative to $L_{Hα}$ at the redshift of the survey). Then they use the separation of star-forming galaxies and AGNs from this “similarly selected” sample in SDSS to determine how much the MEx dividing lines should shift to higher mass, for a given high redshift survey. Essentially, they predict that for high redshift spectroscopic surveys, especially those that are not particularly deep, the MEx divisions between star-forming galaxies and AGNs should shift to higher stellar mass because galaxies and AGNs with higher line luminosities populate the “upper” region of the MEx diagram, such that the division between star-forming galaxies and AGN shifts to higher masses (see their Figure 3).

The MOSDEF survey is fairly sensitive; in our $z ∼ 2.3$ sample we detect at 3σ Hα fluxes down to $∼ 8 \times 10^{-18}$ erg s$^{-1}$ cm$^{-2}$. The resulting line luminosity detection limit for both Hα and O III is $∼ 10^{31.5}$ erg s$^{-1}$. Given the redshift of the sample and the prescriptions in Juneau et al. (2014), the MEx divisions should therefore shift to higher stellar mass by $\Delta \log(M_*/M_\odot) = 0.25$ for our sample. However, as seen by the dotted green lines in the left panel of Figure 5, shifting the divisions by this amount is clearly insufficient to cleanly separate star-forming galaxies and AGNs in our sample; there are many galaxies in the red shaded region, which highlights the upper part of the AGN region (above the higher of the two green dotted lines). Instead we find that a substantially higher shift of $\Delta \log(M_*/M_\odot) = 0.75$ is needed (Figure 5, right panel), so as not to contaminate the AGN region of this diagnostic figure with star-forming galaxies.

We note that Newman et al. (2014) also found that a similarly large shift in the MEx diagram is needed to separate star-forming galaxies and AGNs in their $z ∼ 2$ galaxy sample (see also Henry et al. 2013; Price et al. 2014). Such a large shift is needed to match the stellar masses of local and $z ∼ 2$ galaxies with the same metallicity (Steidel et al. 2014; Sanders et al. 2014), as galaxies at a given stellar mass have higher [O III]/Hβ at higher redshift, due to having lower metallicity. Therefore, the shift required appears to depend more upon the evolution in the mass-metallicity relation of galaxies and therefore the redshift, rather than the depth, of a given survey.

With our proposed shift of $\Delta \log(M_*/M_\odot) = 0.75$ we find that five of our ten X-ray and IR-selected AGNs are in the AGN-only region of this diagram, two are in the AGN/star-forming region
(between the two dotted lines), and another two (ID 1 and 6b) could be within this region given their stellar mass errors (and the lower limit on [O III]/Hβ for ID 1). ID 9 has a lower limit in [O III]/Hβ, such that it could be in this region as well. Therefore all of our X-ray/IR AGNs are consistent with being identified as AGNs in this diagram.

Using the more extreme classification in the right panel of Figure 5, there is one MOSDEF galaxy clearly in the red shaded region (above the upper dotted green line) of the diagram, with log $M_*$ = 11.04. This source has log ([O III]/Hβ) = 0.491 and log ([N II]/Hα) = −0.80; in the BPT diagram it is in the star-forming sequence, 1.3σ from the Kauffmann et al. (2003) line. The X-ray upper limits for this source are log ($L_X/\text{erg s}^{-1}$) = 42.9 in the hard band and log ($L_X/\text{erg s}^{-1}$) = 42.2 in the soft band. While the X-ray data are not deep enough to rule out an AGN, the [N II]/Hα ratio is more consistent with star formation, not AGN activity. This appears to be a particularly massive galaxy that is not an AGN, even though the MEx classification would identify it as such. There is another MOSDEF galaxy in the AGN region, with log $M_*$ = 9.65; within the errors on [O III]/Hβ it could be below the AGN classification line, however the high [O III]/Hβ ratio could also indicate the presence of an AGN.

We further note that one of the “composite” MOSDEF galaxies with a high [N II]/Hα, which is outlined in light green, is in the AGN/star-forming galaxy region of this diagram, and it may well be an AGN. The other four “composite” galaxies above the Kauffmann et al. (2003) line, however, are well below the AGN classification lines and are in the middle of the MOSDEF galaxy sample, as are the two galaxies outlined in cyan that are above the Kewley et al. (2001) line.

There are several additional MOSDEF galaxies in the “composite” AGN region of this figure (between the two dotted lines), using our proposed stellar mass shift. All of these galaxies fall below the Kauffmann et al. (2003) line in the BPT diagram. They are therefore likely star-forming galaxies without any AGN contribution to their line ratios and are contaminants in the MEx diagram. However, given that the region between the two classification lines in the MEx diagram is defined to contain ∼50% star-forming galaxies and 50% AGNs, some contamination from star-forming galaxies is allowed. Overall, the MEx diagram appears to be fairly complete for our X-ray and IR-selected AGNs, using the larger shift in stellar mass found here.

### 3.4. CEx Diagram

In Figure 6 we show the CEx diagram of Yan et al. (2011), which is similar to the MEx diagram but uses rest-frame $(U − B)_0$ color instead of stellar mass as a proxy for [N II]/Hα in order to effectively separate AGNs from star-forming galaxies. We do not plot AGN ID 6 in this diagram, as we do not have colors estimated for each of the two spectral components separately, only a composite color for the entire galaxy.

The dividing line proposed for this diagnostic by Yan et al. (2011) (dot–dashed dark green line) is calibrated using SDSS data and the location of BPT-identified AGNs, but Yan et al. (2011) show that to $z = 0.4$ it works well, when compared to X-ray selected AGNs. They claim that the CEx diagram and their proposed division between AGNs and star-forming galaxies can be used to $z ∼ 1$, and that while galaxies at $z ∼ 1$ are bluer in $(U − B)_0$ than galaxies at $z ∼ 0$ by $0.14$ mag, this difference is small and therefore not applied in their application of the CEx diagram to $z ∼ 1$. Trump et al. (2013) propose that for galaxies at $z ∼ 1.5$ the CEx classification line should shift by 0.2 mag to bluer colors, where X-ray AGNs were used to determine the shift at $z ∼ 1.5$. The dotted green line in Figure 6 shows this shifted line.

While the locus of MOSDEF galaxies on this figure, relative to the location of the bulk of SDSS galaxies, shows that indeed galaxies are bluer on average at $z ∼ 2$ than locally, there is no clean division between MOSDEF X-ray/IR AGNs and galaxies in this space. While many of the reddest MOSDEF sources at $z ∼ 2.3$ are AGNs, there are also AGNs with bluer colors. There are also many galaxies above the proposed AGN classification line. Using the revised Trump et al. (2013) division results in even more contamination by star-forming galaxies than the original Yan et al. (2011) division (see Section 4.4 below).

Cimatti et al. (2013) also find that at $1.7 < z < 3$ there are many X-ray AGNs in the blue cloud (21% of X-ray AGNs are in the blue cloud in their sample), and that at $1 < z < 1.7$ the fraction of AGNs on the red sequence rises. The reason the CEx diagram works at lower redshift is that at late cosmic times the most massive galaxies are generally red and quiescent. The red color of a galaxy can be used as a proxy for high stellar mass. However, at $z ∼ 2$ massive galaxies show a large diversity in galaxy properties and colors (Kriek et al. 2008; Brammer et al. 2011; Barro et al. 2013; Ilbert et al. 2013; Muzzin et al. 2013). As seen in Figure 8 in Muzzin et al. (2013), for galaxies with log ($M_*/M_\odot$) > 11, below $z ∼ 1.7$ there are more quiescent galaxies, while above $z ∼ 1.7$ there are more star-forming galaxies. From the results presented here we conclude that the CEx diagram cannot be reliably used at $z ∼ 2.3$ for AGN/star-forming galaxy classification.

### 4. DISCUSSION

In this paper we test the widely used optical locally calibrated AGN diagnostcs at $z > 2$ using a statistical sample of ∼50 galaxies and 10 X-ray and/or IR-selected AGNs from the MOSDEF survey. We find that the BPT diagram remains a useful diagnostic for separating star-forming galaxies and X-ray and IR-selected AGNs at $z ∼ 2$. Below we discuss what
classification line(s) should be used at this redshift to identify AGNs; we compare the Kauffmann et al. (2003) and Kewley et al. (2001) classification lines at \( z \sim 0 \) with the updated Kewley et al. (2013b) line at high redshift and discuss the use of these classifications at \( z \sim 2 \). We also discuss the completeness of AGN samples selected using the BPT diagram at low and high redshift, as well as the completeness of the MEx diagnostic. We also discuss the metallicities of \( z \sim 2 \) AGNs and whether “contamination” by weak AGNs may be causing a shift in the \( z \sim 2 \) galaxy population in the BPT diagram.

4.1. Classifying Star-forming Galaxies and AGNs in the BPT Diagram at \( z \sim 2 \)

We find that using the \( z \sim 0 \) demarcations to classify optical AGNs in our MOSDEF sample leads to only two additional sources being classified as “pure” AGNs, i.e., above the Kewley et al. (2001) line, and four sources classified as “composite,” in between the Kauffmann et al. (2003) and Kewley et al. (2001) lines. As the hard band X-ray upper limits on most MOSDEF galaxies is only \( \log (L_{X}/\text{erg s}^{-1}) \sim 43 \), and given that IR AGN selection tends to identify only luminous AGNs (Mendez et al. 2013), it is plausible that at least some, if not all, of these sources are AGNs.

As we have shown, however, at \( z \sim 2 \) galaxies lie somewhat above the main locus of star-forming galaxies in SDSS (see also e.g., Yabe et al. 2012; Masters et al. 2014; Steidel et al. 2014; Newman et al. 2014; Shapley et al. 2014). Due to this “offset” of galaxies in the BPT at high redshift, it is likely that the demarcations used to separate star-forming galaxies from AGNs in SDSS at \( z \sim 0 \) need to be shifted somewhat at high redshift.

However, there is somewhat less of an “offset” in the BPT diagram if high redshift galaxies are compared with SDSS galaxies with a similar line luminosity limit (Juneau et al. 2014). In Figure 7 we show the BPT diagram with MOSDEF galaxies and AGNs as above in Figure 3, but here we show only SDSS sources with H\( \alpha \) and O\( \text{iii} \) luminosities greater than the MOSDEF limit of \( \sim 10^{41.5}\text{erg s}^{-1} \). There is less of an offset for MOSDEF galaxies in this figure, compared to Figure 3, though at a given [N\( \text{ii} \)]/H\( \alpha \) the MOSDEF galaxies have a slightly higher log ([O\( \text{iii} \)]/H\( \beta \)) by \( \sim 0.1 \) dex. Shapley et al. (2014) fit the MOSDEF galaxy locus in the BPT diagram, and when compared to the fit by Kewley et al. (2013a) for all SDSS sources, at [N\( \text{ii} \)]/H\( \alpha \) = \( -1.0 \) the [O\( \text{iii} \)]/H\( \beta \) values in the MOSDEF fit are high by 0.12 dex. The sample of Steidel et al. (2014) is more offset, but as discussed in Shapley et al. (2014) et al. this is due to differences in the sample selection.

Kewley et al. (2013b) propose a new redshift-dependent semi-empirical demarcation between pure star-forming galaxies and those with contributions from an AGN, using their theoretical models. Sources above this line should be “composite” sources. In Figure 7 we show the proposed Kewley et al. (2013b) line indicated with a dark green dotted line for the median redshift of our sample, \( z = 2.3 \). The \( z \sim 0 \) classification of Kewley et al. (2001) is shown with a dot–dashed dark green line. At \( z = 2.3 \) there is not a substantial difference between these classifications, though the redshift-dependent line does allow galaxies at high redshift to have somewhat higher [O\( \text{iii} \)]/H\( \beta \) ratios (log ([O\( \text{iii} \)]/H\( \beta \)) for galaxies is <0.1 dex higher at low [N\( \text{ii} \)]/H\( \alpha \) in the updated demarcation). The lines have different physical motivations, however, in that “composite” sources at \( z \sim 0 \) should be below the Kewley et al. (2001) line and at \( z \sim 2.3 \) should be above the Kewley et al. (2013b) line.

We find that five of the nine MOSDEF X-ray and IR-selected AGNs are above the Kewley et al. (2013b) line, and of the four AGNs below these lines, two are lower limits in [O\( \text{iii} \)]/H\( \beta \) such that they could be higher and another is above the line within the error bars. AGN ID “6r” is a spectral component that may not correspond to an AGN. Using either the Kewley et al. (2001) or Kewley et al. (2013b) lines to identify AGNs, the two MOSDEF galaxies outlined in cyan would be classified as optical AGNs. While the Kewley et al. (2013b) classification appears to reliably identify AGNs at \( z \sim 2 \), it is not clear that it includes “composite” sources at \( z \sim 2 \), as using either the Kewley et al. (2001) or Kewley et al. (2013b) lines limits AGN samples by preferentially excluding AGNs with star-forming host galaxies (see next section below).

At low redshift, using the Kauffmann et al. (2003) classification line results in a more complete AGN sample and allows one to determine whether the line ratios from a source are purely from star formation or have some contribution from AGN activity. If indeed ISM conditions at high redshift differ from those in nearby galaxies (discussed in Section 4.4 below), then the Kauffmann et al. (2003) line would need to evolve with redshift, but not as substantially as the proposed Kewley et al. (2013b) line. From Figure 7 it appears that the “composite” classification needs to shift by \( \sim 0.1–0.2 \) dex at \( z \sim 2 \) so as not to be contaminated by star-forming galaxies. Using the proposed AGN classification line of Stasinska et al. (2006), which is below the Kauffmann et al. (2003) line, one would classify 18 MOSDEF galaxies as AGNs; clearly at \( z \sim 2 \) this classification suffers from contamination by star-forming galaxies and should not be used.

Recently, Meléndez et al. (2014) use photoionization models that include from both starburst galaxies and AGNs to predict a curve in the BPT diagram showing where sources have a minimal contribution from an AGN. This line can therefore be used to separate star-forming galaxies from AGNs, and it provides a new theoretical alternative classification scheme to
the empirical Kauffmann et al. (2003) line. In Figure 7 we show the Meléndez et al. (2014) prediction as a dot–dot–dashed orange line. We show the predicted line that does not include dust; including dust shifts the line ~0.1 dex higher. All of the MOSDEF X-ray/IR AGN are above this line, and using this classification scheme there are four additional optical AGNs. Two of these sources are also above the Kewley et al. (2013b) line and two are composite sources above the Kauffmann et al. (2003) line. The two composite sources have relatively high \([\text{[N} \text{II}] / \text{H} \alpha\) and are closer in the BPT diagram to the X-ray/IR AGNs and further from the bulk of the MOSDEF galaxies than the other two composite sources that are not identified as AGNs using this new line. With the initial MOSDEF data set we therefore find that this new classification scheme appears to work well at \(z \sim 2\).

For now we consider all six sources above the Kauffmann et al. (2003) line as potential optical AGN candidates. Information on these sources is given in Table 3. (The additional three sources listed in Table 3 are discussed below in Section 4.5.) The hard band X-ray upper limits are all \(\sim 10^{43} \text{erg s}^{-1}\) and do not rule out the presence of an AGN. Of the two optical AGN candidates above the Kewley et al. (2013a) line (IDs 11597 and 3182), one source (ID 11597) also has a high \([\text{S} \text{II}] / \text{H} \alpha\) ratio and is separated from the star-forming galaxies in the left panel of Figure 4. It is therefore likely to be an AGN. We note that while both candidates above the Kewley et al. (2013a) line have high \([\text{O} \text{III}] / \text{H} \beta\) and \([\text{N} \text{II}] / \text{H} \alpha\) ratios, neither is in the AGN region of the MEX diagram as both have stellar masses \((M_\star / M_\odot) < 10\). Of the four composite sources, ID 13085 has high \([\text{N} \text{II}] / \text{H} \alpha\) (> 0.35) and also satisfies the Donley et al. (2012) IR AGN color selection criteria (while it does not strictly satisfy the criteria of \(f_{50.0} > f_{50.1}\), it does within the 1.1 \(\sigma\) error). A second source (ID 1740) has a similar \([\text{N} \text{II}] / \text{H} \alpha\) as the two sources above the Kewley et al. (2013a) line and is above the Meléndez et al. (2014) line. The other two sources (IDs 22457 and 28846), however, do not separate from the star-forming galaxies in any of the optical diagnostics; these do not appear to be AGNs in the BPT diagram. We therefore conclude that at least two or three of the six optical AGN candidates are very likely to be AGNs, based on multiple optical diagnostics. The complete MOSDEF sample will be useful to re-examine the Kauffmann et al. (2003) and Meléndez et al. (2014) lines and their applicability at \(z \sim 2\) and will allow us to further determine optical AGN demographics at \(z \sim 2\).

### 4.2. Completeness of the BPT Diagram for AGN Identification

In this section we discuss the completeness of optical AGN identification using the BPT diagram, both at low and high redshift. It should first be mentioned that when creating optically selected AGN samples using the BPT diagram, “composite” sources should be included when one is interested in having a more complete AGN sample. While some of the line emission in these sources is from star formation, the line ratios indicate that ionization from AGNs is also present, such that samples that exclude these sources will be incomplete. In the SDSS, 35% of SDSS sources that have all four lines required for the BPT diagram detected are classified as AGNs when including “composite” sources. This fraction decreases to 13% when using only sources above the Kewley et al. (2001) line, which are defined such that there is no contribution to the line ratios from star formation. This relatively high fraction, especially when including composite sources, indicates that, at least in SDSS, AGNs can be identified down to low Eddington ratios using the BPT diagram (Aird et al. 2012; Kelly & Shen 2013).

Alternatively, the BPT diagram can be used to identify AGNs that one wishes to exclude as “contaminants” in samples of star-forming galaxies. We find that the BPT diagram can be used in such a manner at \(z \sim 2\), as moderate-luminosity (log \((L_X / \text{erg s}^{-1}) > 43\)) X-ray and IR AGNs do separate fairly cleanly in the BPT diagram from star-forming galaxies at these redshifts. However, using the BPT diagram in this way (even including “composite” sources using the local Kauffmann et al. (2003) line) will not identify all AGNs, as the BPT diagram has biases and is incomplete in terms of AGN selection, as is any AGN selection technique.

Identifying complete AGN samples requires multi-wavelength data and AGN selection across a range of wavebands. Optical AGN selection, using the BPT diagram, should in theory be somewhat complementary to selections at other wavelengths, as it should identify both lower luminosity and/or more obscured

### Table 3

| Field   | ID\(a\) | R.A.       | Decl.     | \(z\) | \(\log L_X^{\text{bol}} / \text{(erg s}^{-1})\) | \(\log ([\text{O} \text{III}] / \text{H} \beta)\) | \(\log ([\text{N} \text{II}] / \text{H} \alpha)\) | \(\log ([\text{S} \text{II}] / \text{H} \alpha)\) | \(\log (M_\star / M_\odot)\) | \((U - B)_{0}\) |
|---------|---------|------------|-----------|---|----------------|----------------|----------------|----------------|----------------|----------------|
| COSMOS  | 1740\(b\) | 10:00:14.161 | 02:11:51.627 | 2.29986 | \(< 43.44\) | \(0.45 \pm 0.08\) | \(< -0.45 \pm 0.05\) | \(< -0.56 \pm 0.10\) | 9.92 \(\pm 0.08\) | 0.68 |
| COSMOS  | 2876\(c\) | 10:00:14.301 | 02:12:26.264 | 2.29807 | \(< 43.68\) | \(0.57 \pm 0.08\) | \(< -0.41 \pm 0.12\) | \(< -0.52 \pm 0.14\) | 9.76 \(\pm 0.08\) | 0.55 |
| COSMOS  | 2575 | 10:00:14.795 | 02:12:19.395 | 2.31585 | \(< 43.44\) | \(< -0.29 \pm 0.10\) | \(< -0.31\) | 10.94 \(\pm 0.06\) | 1.11 |
| COSMOS  | 3182 | 10:00:18.241 | 02:12:42.586 | 2.10206 | \(< 43.40\) | \(< -0.22 \pm 0.03\) | \(< -0.63 \pm 0.08\) | 11.40 \(\pm 0.07\) | 1.36 |
| COSMOS  | 11597\(d\) | 10:00:21.720 | 02:17:50.358 | 2.52736 | \(< 43.62\) | \(0.66 \pm 0.05\) | \(< -0.45 \pm 0.10\) | \(< -0.28 \pm 0.13\) | 9.82 \(\pm 0.09\) | 0.66 |
| GOODS-N | 26458 | 12:36:57.389 | 02:16:18.160 | 2.48636 | \(< 43.04\) | \(< -0.34 \pm 0.09\) | \(< -0.31\) | 10.32 \(\pm 0.04\) | 0.68 |
| GOODS-N | 22457\(e\) | 12:37:10.679 | 02:15:07.182 | 2.46938 | \(< 42.70\) | \(0.48 \pm 0.07\) | \(< -0.65 \pm 0.11\) | \(< -0.54 \pm 0.14\) | 9.85 \(\pm 0.04\) | 0.61 |
| GOODS-N | 28846\(f\) | 12:37:13.096 | 02:17:03.225 | 2.47198 | \(< 43.13\) | \(0.68 \pm 0.04\) | \(< -0.78 \pm 0.10\) | \(< -0.60 \pm 0.13\) | 9.27 \(\pm 0.12\) | 0.33 |
| GOODS-N | 13085\(g\) | 12:37:20.054 | 02:12:22.854 | 2.46015 | \(< 43.19\) | \(0.10 \pm 0.09\) | \(< -0.34 \pm 0.03\) | \(< -0.65 \pm 0.10\) | 10.84 \(\pm 0.10\) | 0.78 |

Notes.

\(\text{a}\) ID in 3D-HST v4.1 catalogs.

\(\text{b}\) In the 2–10 keV hard band.

\(\text{c}\) Above the Kewley et al. (2013a) AGN classification line.

\(\text{d}\) Above the Kauffmann et al. (2003) AGN classification line.

\(\text{e}\) Above the Meléndez et al. (2014) AGN classification line.
AGNs. It should also be useful if there is little or only shallow X-ray data of the sources of interest. Additionally, as X-ray imaging is subject to substantial vignetting, resulting in a non-uniform depth across a field, optical AGN identification could be useful to ensure a more uniform selection as a function of depth and could identify AGNs that are missed when the X-ray data is “off-axis.”

However, optical AGN identification has selection effects that must be taken into account. One may expect a bias against identifying AGNs in galaxies with high specific star formation rates, as the line ratios in such galaxies may be dominated by star formation. In the BPT diagram AGNs will likely be more easily identified if they reside in galaxies with less star formation, where Hα and Hβ are low. There is therefore a selection bias toward identifying AGNs in galaxies with older stellar populations. Additionally, the presence of dust can preferentially extinguish O iii produced by the AGNs, such that the BPT diagram is biased against identifying AGNs in very dusty galaxies (Goulding & Alexander 2009).

These selection biases are shown in Figure 8, where we show in black contours the SFRs and stellar masses of all SDSS DR7 sources, while in red contours (left panel) we show the distribution for those sources identified as AGNs in the BPT diagram, using the Kewley et al. (2001) line (see also Salim et al. 2007). The middle panel shows the distribution of “composite” sources (orange contours) identified using the Kauffmann et al. (2003) line, and the right panel shows the distribution of star formation rates for AGNs and all sources with 10.5 < log (M_*/M_☉) < 11. The Kewley et al. (2001) selection clearly preferentially identifies AGNs in quiescent galaxies. While almost no AGNs are identified in sources with high specific star formation rate (sSFR = SFR / M_∗), as shown by the dotted line in the left panel, there are also relatively few star-forming hosts for these AGNs, as shown in the right panel. The Kauffmann et al. (2003) selection preferentially identifies AGNs in star-forming hosts, though even among the star-forming hosts the median star formation rate is lower for the identified AGN hosts than for the full galaxy population.

While this figure alone does not fully indicate whether these differences in galaxy properties are intrinsic to AGN hosts or are due to selection effects, when these results are compared with the literature it is clear that there are strong selection effects at play. A number of recent studies have indicated that X-ray selected AGNs at intermediate and high redshift are in fact preferentially hosted by star-forming galaxies. Rovilos et al. (2012) used Herschel data to show that X-ray selected AGNs in the CDFs (spanning z ≈ 0.5–4) are mostly hosted by galaxies with similar (or higher) SFRs as typical star-forming galaxies at the same redshift. Rosario et al. (2013) and Harrison et al. (2012) both measured average SFRs of X-ray selected AGNs in the COSMOS, GOOD-S and GOODS-N fields by stacking Herschel data and found that the average SFRs were consistent with normal star-forming galaxies at the same redshift. Furthermore, Mullaney et al. (2012) and Santini et al. (2012) showed that X-ray AGNs have high detection rates in the far-IR, which indicates that the majority are hosted by normal star-forming galaxies. Most recently, Azadi et al. (2014) showed that the probability of a galaxy hosting an X-ray selected AGNs above a given Eddington ratio is higher for star-forming galaxies than quiescent galaxies and generally increases with sSFR (they also showed that the Eddington ratio distribution does not change with stellar mass or SFR at 0.2 < z < 1.2). Taken together, these results have shown that AGNs commonly reside in star-forming galaxies with relatively high SFRs, while we show above that the BPT diagram, even when including composite sources, has a bias against identifying AGNs in such galaxies.

Figure 8 also clearly shows a strong selection effect with stellar mass. This is a known selection effect whereby AGNs are more easily detected in massive host galaxies, which have more massive black holes that can therefore been seen down to lower Eddington ratios (Aird et al. 2012). This stellar mass bias exists at all redshifts for flux-limited samples, regardless of the waveband used to identify AGNs (e.g., Hainline et al. 2009). In the BPT diagram, AGNs are most likely to be identified in massive galaxies, which on average have higher metallicities (i.e., Tremonti et al. 2004) and therefore higher [NII]/Hα ratios. The presence of an AGN boosts the [NII]/Hα ratio further, such that AGNs fail to the right in the BPT diagram. It is therefore quite difficult to detect AGNs in low mass (and low metallicity) host galaxies using the BPT diagram (Groves et al. 2006; Stasińska et al. 2006). In fact, Aird et al. (2013) suggest that AGNs do exist in low mass galaxies, but a flux-limited AGN sample will necessarily be dominated by massive host galaxies.
galaxies (where it is easier to identify an AGN down to a lower Eddington ratio compared to lower mass galaxies), such that low mass AGN hosts will be fairly rare in flux-limited samples.

The issue of completeness of the BPT diagram for AGN selection becomes much worse at high redshift, where there are fewer quiescent galaxies than at $z \sim 0$ (e.g., Ilbert et al. 2013; Muzzin et al. 2013). Additionally, SFRs at a given stellar mass are generally higher at high redshift (e.g., Pannella et al. 2009; Elbaz et al. 2011; Karim et al. 2011; Whitaker et al. 2012), such that it will likely be harder to identify AGNs in the BPT diagram at high redshift, as the line fluxes will have more contribution from star formation. While the global AGN accretion rate is also higher at high redshift, and generally traces the variation in the global SFR well, in order to identify AGNs in the BPT diagram the host galaxy must have a low sSFR. As only AGNs in galaxies with relatively low sSFR and high stellar mass can be identified using the BPT diagram, at high redshift this will be a more severe incompleteness than at low redshift, due to the relative dearth of massive galaxies with older stellar populations, when compared to low redshift. Indeed, in MOSDEF the X-ray and IR AGN's have lower sSFR (as derived from SED fits) than the bulk of the galaxy sample (see also Kriek et al. 2007).

The result is that the BPT diagram works well in SDSS, due to the selection effect of identifying AGNs in massive galaxies, which at low redshift are often quiescent. This allows the AGN to contribute substantially to the line ratios in the BPT diagram, such that the detected AGNs clearly separate in this space. At high redshift, however, massive galaxies are not as likely to be quiescent and SFRs are higher, such that it is harder for AGNs to cleanly separate in the BPT diagram.

Indeed, we find here that there is substantial overlap between X-ray/IR AGN and candidate optical AGN identification at $z \sim 2$, in that in the BPT diagram the X-ray/IR AGN all lie above the Kauffmann et al. (2003) and Meléndez et al. (2014) lines. It appears that optical selection, using the BPT diagram, provides a $\approx 50\%$ more complete AGN sample than X-ray and IR selection.

4.3. Completeness of the MEx Diagram for AGN Identification

While reliance on the MEx diagram is becoming less necessary at $1 < z < 3$, given the new multi-object NIR spectrographs that can observe [O iii]/Hβ and [N ii]/Hα at these redshifts, this diagnostic is currently used. Can the MEx diagram be used at these redshifts to reliably identify AGNs?

Juneau et al. (2014) argue that it can, as long as the line luminosity limits and redshift of the sample are taken into account. They show that in SDSS while the demarcations between star-forming galaxies and AGNs in the BPT diagram do not change as the line luminosity limit of a sample is decreased, shallower surveys will miss galaxies or AGNs with lower [O iii]/Hβ, such that the lower part of the BPT diagram will not be occupied. This results in a shift in the AGN classification lines in the MEx diagram to higher stellar mass.

One way to understand this shift is that flux-limited surveys at any wavelength are biased toward identifying AGNs with high host stellar masses (Aird et al. 2012), as more massive galaxies host more massive SMBHs, which can be identified to a lower Eddington ratio (at a given flux limit) than SMBHs in lower mass galaxies. Therefore shallower surveys will mainly find AGNs in more massive galaxies. In less massive galaxies, only the (rare) AGNs with high Eddington ratio will be detected. The detected AGN's population will therefore be dominated by those with higher stellar mass host galaxies, and thus the AGNs classification lines are shifted to higher stellar mass as the line luminosity limits increase.

Juneau et al. (2014) include an additional shift due to evolution in $L^*$ of both Hα and [O ii]. This reflects that a given luminosity limit does not probe as far down the luminosity function at low redshift as it does at high redshift, given that $L^*$ is lower at low redshift. To select galaxies to the same relative depth on the luminosity function, one therefore has to reduce the luminosity limit at low redshift, which reduces the stellar mass shift in the MEx diagram at high redshift.

We find here that for our MOSDEF sample, the shift to higher stellar mass proposed by Juneau et al. (2014) is insufficient to cleanly separate known AGNs from the rest of the sample. Additionally, Domínguez et al. (2013) show that galaxies at $0.75 < z < 1.5$ with high $L_{H\alpha}$ do not also have high [O ii]/Hβ, as in SDSS. We find that a stellar mass shift that takes into account the evolution in the mass–metallicity relation of galaxies (in that at a given stellar mass galaxies have lower metallicity and higher [O ii]/Hβ at high redshift) is required to cleanly separate star-forming galaxies and AGNs in the MEx diagram at $z \sim 2.3$. The need for a shift in the MEx diagram with redshift may be evolution in the mass–metallicity relation, rather than the evolution of $L^*$, and the depth of a survey.

We find that the MEx diagram at $z \sim 2$ is fairly complete in terms of identifying X-ray/IR-selected AGNs, but it does not identify most of the candidate BPT “composite” sources, i.e., those sources that might be AGNs based on their location in the BPT diagram. As shown above, it may additionally suffer from contamination by star-forming galaxies in the “composite” region of the MEx diagram, though this is alleviated somewhat by the probabilistic AGN classification of Juneau et al. (2014). Given this, we propose that the full BPT diagram should be used to identify optical AGN samples at $z \sim 2$.

4.4. Comparison of Completeness and Contamination of Optical AGN Diagnostics

In this section we compare the various optical AGN diagnostics presented in this paper and discuss the completeness and potential contamination of each. Table 4 lists the three optical diagnostics, along with the various proposed classification lines in each diagnostic, along with the number of AGNs defined a priori by X-ray and/or IR emission that can be used for each diagnostic, the number of those AGNs that are positively identified as optical AGNs (for AGN ID 6, we count it as identified if at least one of the two spectral components is identified), the corresponding number of X-ray/IR AGNs that are missed (i.e., not positively identified as AGNs), and the number of MOSDEF sources that are not X-ray/IR AGNs (i.e., galaxies) that are identified as optical AGNs using that diagnostic. The latter are potential contaminants, as they could be star-forming galaxies and not AGNs. Finally, the last column indicates the number of those potential contaminants that are likely to be AGNs, given their location in the BPT diagram. Here a source has to clearly be in the AGN wing of the BPT diagram and have a high [N ii]/Hα ratio ($\log > -0.4$) and/or be above the Kewley et al. (2013b) line to be a likely optical AGN. It is possible that additional potential contaminants are AGNs, but we cannot know without BPT classifications for all of the sources (i.e., those with $S/N < 3$ in [N ii]/Hα) and/or deeper X-ray data.

Our initial MOSDEF sample is small, and thus the errors on the completeness and contamination presented here are large. We will revisit these issues with the full data set, however with
our current sample we find that of the three BPT classification lines presented, the Méndez et al. (2014) line is both the most complete—identifying all nine of the a priori X-ray/IR AGNs and four additional sources that are very likely to be AGNs—and the least contaminated (in that all of the four potential contaminants are very likely to be AGNs). While the Kewley et al. (2013b) line is not likely to be contaminated, it is not as complete, only identifying five of the nine a priori AGNs, along with two further likely optical AGNs. The Kauffmann et al. (2003) line does identify all nine of the a priori AGNs but is likely somewhat contaminated (as two of the six additional sources identified with this diagnostic are likely to be star-forming galaxies without significant AGN contributions).

As presented earlier, the classification lines in the MEX diagram from Juneau et al. (2014) lead to substantial contamination; we therefore propose a larger shift in these lines to minimize this contamination. However, this reflects in a lower fraction of X-ray/IR AGNs being positively identified, and there is still some contamination, as the four additional galaxies that are classified as AGNs are not classified as AGNs in the BPT diagram. Since the MEX classification lines were originally defined by BPT classifications such that only those sources that are AGNs in the BPT diagram can be AGNs in the MEX diagram, it appears that even with the shifted classification lines proposed here, there is still some contamination. Finally, the CEX classifications are highly contaminated, using either the original line proposed by Yan et al. (2011) or the revised line of Trump et al. (2013).

### 4.5. Metallicities of $z \sim 2$ AGNs

Kewley et al. (2013a) present predictions for the locations of galaxies and AGNs in the BPT diagram at high redshift, depending on the physical conditions in the ISM of galaxies and the metallicity of gas near the AGN. They present two predictions for the locations of star-forming galaxies: one is identical to the location of star-forming galaxies at $z \sim 0$, if the ISM conditions in high-redshift galaxies match those found locally. The other scenario shows the positions of galaxies that have “extreme” ISM conditions, which could be due to a larger ionization parameter and a more dense ISM, and/or a harder ionizing radiation field. They also have two predictions for the locations of AGNs in the BPT diagram: one scenario the gas near the AGN is enriched to a higher metallicity than is found generally in the host galaxy (“metal-rich” AGNs) and in the other scenario the gas near the AGN has the same metallicity as the gas in the host galaxy, on larger scales (“metal-poor” AGNs).

In Figures 9 and 10 we compare the locations of MOSDEF galaxies and AGNs at $z \sim 2.3$ with these predictions. Figure 9 corresponds to their scenarios 1 and 2, where “local” ISM conditions prevail at high redshift, with the left panel showing the location of metal-rich AGNs and the right panel showing the location of metal-poor AGNs. Figure 10 corresponds to their scenarios 3 and 4, where “extreme” ISM conditions prevail at high redshift, and again the left panel shows metal-rich AGNs and the right panel metal-poor AGNs.

We find that at $z \sim 2$ local ISM conditions do not appear to match the local star-forming sequence perfectly, in that in Figure 9 the MOSDEF galaxies have a higher $[O \text{ii}] / H\beta$ and/or $[N \text{ii}] / H\alpha$ than predicted (see also Shapley et al. 2014). But the difference is not large. Figure 10 clearly shows that the “extreme” ISM conditions presented in Kewley et al. (2013a) are too extreme, as most MOSDEF galaxies lie well below the star-forming sequence. Overall, the data may prefer a somewhat intermediate ISM, though the local ISM conditions appear to work reasonably well.

In terms of the location of MOSDEF AGNs, for the “normal” ISM models (Figure 9) they do not appear to be particularly metal-poor, in that six of the ten AGNs have $[N \text{ii}] / H\alpha$ ratios greater than the “metal-poor” prediction. The bulk of the AGN sample (seven out of ten sources) lies within the “metal-rich” predictions. Alternatively, at least four AGNs have higher $[N \text{ii}] / H\alpha$ than the “metal-poor” prediction. However, many of the MOSDEF AGNs fall in the overlapping regions of the “metal-rich” and “metal-poor” predictions, such that their locations are not conclusive. It appears that according to these models at least some AGNs at $z \sim 2$ are “metal-rich,” in that the metallicity of the gas in the narrow-line region is higher than that in the host galaxy on larger scales.

To investigate further the metallicity evolution of the AGNs, we show in Figure 11 the $[O \text{iii}] / H\beta$ and $[N \text{ii}] / H\alpha$ ratios of galaxies and AGNs as a function of stellar mass in both MOSDEF and SDSS. Here SDSS sources are shown only if they are above the line luminosity limits of MOSDEF. The left panel is the MEX diagram, while the right panel reflects the mass-metallicity relation in both MOSDEF and SDSS ( Tremonti et al. 2004; Sanders et al. 2014). We show SDSS AGNs identified using the Kauffmann et al. (2003) line with orange contours, as it is likely that the line ratios are impacted for all of “composite” AGNs as well as AGNs above the Kewley et al. (2001) line.
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Figure 9. Same as Figure 3 but here the dark green dot–dashed lines show the predicted locations of star-forming galaxies and AGNs at $z = 2.5$ for the two scenarios presented in Kewley et al. (2013a) with “normal” or local ISM conditions. The left panel shows predictions for metal-enriched AGNs, where the gas near the AGNs is enriched relative to the host galaxy, while the right panel shows those for metal-poor AGNs, where the gas near the AGNs has a similar metallicity as the gas in the host galaxy.

Figure 10. Same as Figure 3 but here the dark green dot–dashed lines show the predicted locations of star-forming galaxies and AGNs at $z = 2.5$ for the two scenarios presented in Kewley et al. (2013a) with “extreme” ISM conditions. As in Figure 9, the left panel shows predictions for metal-enriched AGNs, while the right panel for metal-poor AGNs.

In general, the range of $[\text{O}\text{ iii}]/\text{H}\beta$ that is observed reflects both the AGN accretion rate (which will be higher for AGNs with higher $[\text{O}\text{ iii}]$) and the age of the stellar population. $[\text{N}\text{ ii}]/\text{H}\alpha$ reflects the metallicity of the host galaxy and has an additional contribution to the flux of the $\text{N}\text{ ii}$ line from the ionizing radiation from the AGNs. As discussed above, the appearance of the AGN wing in the BPT diagram is due to a combination of the AGN ionizing radiation and the high stellar mass of the host galaxy. Indeed, the fact that the MEx diagram works well for AGNs in SDSS reflects that the AGN region of the BPT diagram really just depends on AGN luminosity (in both $\text{O}\text{ iii}$ and $[\text{N}\text{ ii}]$) and host stellar mass (in $[\text{N}\text{ ii}]/\text{H}\alpha$).

The fact that we see in Figure 11 that MOSDEF AGNs have lower $[\text{N}\text{ ii}]/\text{H}\alpha$ ratios than AGNs in SDSS with the same host galaxy stellar mass, on average, indicates that the narrow-line region of AGNs at $z \sim 2$ are less enriched than those at $z \sim 0$, at a given host stellar mass. It is also unlikely that the gas in the narrow-line region is strongly enriched compared to the host galaxy; otherwise the $[\text{N}\text{ ii}]/\text{H}\alpha$ ratio for the AGNs would be even higher, given the additional contribution to $\text{N}\text{ ii}$ from the AGNs. The left panel of this figure also indicates that the presence of an AGN boosts the $\text{O}\text{ iii}$ line luminosity more so than the $\text{N}\text{ ii}$ line luminosity, in that both SDSS and MOSDEF AGNs have higher $[\text{O}\text{ iii}]/\text{H}\beta$ ratios than galaxies of a similar stellar mass, while the $[\text{N}\text{ ii}]/\text{H}\alpha$ ratios for AGNs are not nearly as elevated compared to galaxies of the same stellar mass. Indeed, the $[\text{O}\text{ iii}]/\text{H}\beta$ ratios of MOSDEF AGNs generally span the range observed for SDSS AGNs, which likely means that the
[O\text{\textsc{iii}}]/Hβ ratio for AGNs is particularly sensitive to the AGN accretion rate and not as sensitive to host galaxy properties, unlike the [N\text{\textsc{ii}}]/Hα ratio. We conclude then that while the gas in the narrow-line region at z \sim 2 may be somewhat more enriched than the gas further out in the host galaxy, the narrow-line regions of AGNs at z \sim 2 are not as enriched, at a given host galaxy stellar mass, as in the local universe.

We note that for the right panel of Figure 11 we show all MOSDEF sources that have S/N > 3 for either of the N\text{\textsc{ii}} or Hα lines, regardless of the S/N of the O\text{\textsc{iii}} or Hβ lines. This results in a sample of 68 galaxies, somewhat larger than the sample shown in Figure 3. We find for this larger sample that there are three additional galaxies with AGN-like [N\text{\textsc{ii}}]/Hα line ratios; in the BPT diagram most MOSDEF X-ray and IR AGNs have log ([N\text{\textsc{ii}}]/Hα) \gtrsim -0.4, roughly corresponding to the location of the Kauffmann et al. (2003) line for the MOSDEF sources with the lowest measured [O\text{\textsc{iii}}]/Hβ values. In the larger MOSDEF galaxy sample shown here, there are a total of two galaxies with [N\text{\textsc{ii}}]/Hα > -0.25 and five galaxies with [N\text{\textsc{ii}}]/Hα > -0.35. Two of these sources have robust [O\text{\textsc{iii}}]/Hβ ratios such that they were already highlighted in Figure 3 with light green outlines (with log ([O\text{\textsc{iii}}]/Hβ) values of -0.11 and -0.34); the rest have a night sky line at the location of Hβ. The source information for these three new optically identified AGN candidates is given in Table 3. Of these three sources, one is very likely to be an AGN, given the measured [N\text{\textsc{ii}}]/Hα value of -0.22. Of the potential “composite” sources (shown with light green outlines), the two with high [N\text{\textsc{ii}}]/Hα ratios appear to be AGNs from this figure (and indeed from the BPT diagram, as discussed above). The other three sources have lower stellar masses and [N\text{\textsc{ii}}]/Hα values near the upper range for their mass. Indeed, one source is near the two cyan points, which are above the Kewley et al. (2013b) line in the BPT diagram, and could be an AGN.

We emphasize again, however, that the AGN incidence in the MOSDEF sample cannot be calculated by simply taking the ratio of the sources with AGN-like line ratios to the full galaxy sample, as one must take into account the targeting weights. Such an analysis will be presented in a future paper.

4.6. Are Weak AGNs Contaminating the BPT Diagram at High Redshift?

It has been suggested that contamination from weak AGNs is causing the “offset” seen for star-forming galaxies in the BPT diagram. Wright et al. (2010) argue from the spatial distributions of [O\text{\textsc{iii}}]/Hβ and [N\text{\textsc{ii}}]/Hα for a single source at z = 1.6 with OSIRIS data that weak AGN contribution can shift the location of a star-forming galaxy in the BPT diagram to the AGN region. Of course while this is possible for individual sources, requiring the entire “offset” observed in the BPT diagram for galaxies at high redshift to be due entirely to AGNs without increasing the width of the star-forming sequence would require most high-redshift galaxies to have at least weak AGNs. As discussed above, at high redshift it is even harder to identify lower luminosity AGNs in the BPT diagram, compared to SDSS, so this is likely not the answer. Additionally, given that star formation rates are generally higher at high redshift, a weak AGN would likely have a lower contrast with the star formation in the host galaxy and therefore not impact the emission line ratios as substantially in the BPT diagram. Indeed for the source in Wright et al. (2010), the high [O\text{\textsc{iii}}]/Hβ and [N\text{\textsc{ii}}]/Hα ratios do not appear to be spatially coincident with the center of the galaxy, as defined in Hα, and could potentially be due to shocks (i.e., Kewley et al. 2013b). For this source it might be useful to measure the [S\text{\textsc{ii}}]/Hα ratio to look for LINER and/or shock emission.

Trump et al. (2011) use HST/WFC3 grism spectroscopy of 28 galaxies at z \sim 2 to measure the spatial extent of the O\text{\textsc{iii}} and Hβ emission lines in stacked spectra of their full sample. They find at the \sim 2.5σ level that the O\text{\textsc{iii}} emission is more centrally concentrated than the Hβ emission, and further find that stacked X-ray emission of all of their sources shows signatures of at least some AGN emission. It is possible again that the more concentrated O\text{\textsc{iii}} profile could have some contribution from shocks, however it is more likely that they have a few AGNs in their sample contributing to their stacked results. Indeed, in a CEx diagram two of their sources are very red and have high [O\text{\textsc{iii}}]/Hβ, putting them in the local AGN region. The presence

Figure 11. Comparison of the [O\text{\textsc{iii}}]/Hβ and [N\text{\textsc{ii}}]/Hα ratios of MOSDEF galaxies (blue triangle) and AGNs (red circles) as a function of stellar mass, compared to galaxies (black contours) and AGNs (orange contours) in SDSS. The left diagram is the MEx diagram of Figure 5, where here we have split the SDSS comparison sample based on location in the BPT diagram; orange contours show SDSS sources above the Kauffmann et al. (2003) line in the BPT diagram. Open blue triangles show galaxies that are not included in Figure 3, due to low S/N in [N\text{\textsc{ii}}] and/or Hα (left panel) or [O\text{\textsc{iii}}] and/or Hβ (right panel).
of two AGNs would account for their results, without implying
detections of AGNs in low mass, low metallicity galaxies, which
seems very unlikely given the selection effects discussed above.

Interestingly, Steidel et al. (2014) find that their sample of
$z \sim 2$ galaxies is substantially offset in the BPT diagram, and
their sample only contains a handful of known AGNs, from UV
spectral lines. Jones et al. (2013) also find offsets in the BPT
diagram for spatially resolved lensed galaxies with no known
AGN contribution; they find that star-forming regions of all radii
in their galaxies are offset. As shown here in Section 4.1, some
of the observed offset in the BPT diagram for high redshift
galaxies is alleviated by comparing with local samples with
similar line luminosity limits (Juneau et al. 2014). There is a
small ($\sim 0.1$ dex) residual offset even after such selection effects
are taken into account, which could in theory be due to changes
in e.g., the ionization parameter at high redshift (e.g., Kewley
et al. 2013a; Steidel et al. 2014).

As discussed above in Section 4.2, while it is known that
there is greater AGN activity at high redshift, there is a similar
increase in star formation, such that it is unlikely that an increase
in AGN activity could substantially move galaxies in the BPT
diagram from the star forming sequence toward the AGN region.
More importantly, there are additional stellar mass and stellar
population selection effects, such that it is easier to identify
AGNs in the BPT diagram in massive, quiescent galaxies. Given
that galaxies at high redshift have younger stellar populations,
on the whole, it appears very unlikely that the line ratios for
galaxies in the star forming sequence in the BPT diagram at
high redshift can be substantially impacted by AGN activity.
Indeed, we have shown that at high redshift the BPT diagram
should identify fewer AGNs than at low redshift, as only high
luminosity AGNs (or shocks) can substantially impact the line
ratios and move sources to the AGN region of the diagram.
In Newman et al. (2014), only those $z \sim 2$ sources above the
Kewley et al. (2001) line have a shift to higher line ratios in the
BPT diagram using spatially resolved line ratios. This result is
consistent with AGN contamination from weak AGNs (which
are likely not above the Kewley et al. 2001 line) not contributing
substantially to the BPT offset for galaxy samples. As discussed
in Shapley et al. (2014) the offset of high-redshift galaxies in the
BPT diagram appears to be due instead to lower mass galaxies
($M_\star < 10^{10}$ $M_\odot$) at these redshift having elevated N/O ratios
(see also Masters et al. 2014; Steidel et al. 2014).

5. CONCLUSIONS

Using MOSFIRE data for $\sim 50$ galaxies and 10 X-ray and
IR-selected AGNs at $z \sim 2.3$ from the first season of the
MOSDEF survey, we investigate the identification and
completeness of optical AGN diagnostics at $z \sim 2$. We present
the location of X-ray and IR-selected AGNs in the BPT, MEx, and
CEx diagrams for our sample and compare with BPT-identified
AGNs in SDSS. Our main conclusions are as follows.

1. Measurements of $[\text{N} \text{~II}]/H\alpha$ are required to optically iden-
tify AGNs at $z \sim 2$, as AGNs have a wide range of $[\text{O} \text{~III}]/
H\beta$ values that overlaps the $z \sim 2$ galaxy population, such
that $[\text{O} \text{~III}]/H\beta$ alone is insufficient to identify AGNs. It
may even be possible to use $[\text{N} \text{~II}]/H\alpha$ alone to identify
AGNs in the MOSDEF sample, given that the $[\text{O} \text{~III}]/H\beta$
ratios are uniformly high.

2. The BPT diagram works well at $z \sim 2$, in that X-ray
and IR-selected AGNs separate cleanly from the star-
forming galaxy population in the MOSDEF sample. The
$z \sim 0$ AGNs/star-forming galaxy classifications appear to
need to shift by only $\sim 0.1$--$0.2$ dex at $z \sim 2$ to robustly
separate these populations. The new Meléndez et al. (2014)
classification also appears to work well at $z \sim 2$.

3. The MEx diagram does not appear to work as well at
$z \sim 2$, in that the classification lines at $z \sim 0$ need to be
shifted substantially at high redshift, more so than predicted
in the literature (Juneau et al. 2014). Additionally, the
MEx diagram fails to identify some of the optical AGN
candidates identified by the BPT diagram. The CEx diagram
cannot be used at $z \sim 2$, as there is not a simple shift in
the CEx classification line that would cleanly separate star-
forming galaxies and AGNs at these redshifts. We conclude
that it is preferable to use the BPT diagram for optical AGN
selection at high redshift.

4. AGN identification using the BPT diagram is subject to
selection biases, in that AGNs are easier to detect in the
BPT diagram if they reside in massive and/or quiescent
host galaxies. While this is true at both low and high
redshift, these selection biases become stronger at high
redshift where massive galaxies show a larger diversity in
color and star formation rate.

5. While AGN identification using the BPT diagram cannot
provide a complete AGN sample, it can be used to identify
a “pure” AGN sample with little contamination from star-
foming galaxies. However, AGN identification using the
BPT diagram will be incomplete if only sources above the
Kewley et al. (2001) line are classified as AGNs. Therefore
one should include BPT “composite” sources when creating
more complete AGN samples. An updated classification line for
“composite” sources at $z \sim 2$ will require the full MOSDEF sample,
though the Meléndez et al. (2014) classification may work well for
this purpose.

6. Contamination from AGNs cannot be shifting the bulk of
the galaxy population at high-redshift to the AGN region of
the BPT diagram, causing the observed offset in the galaxy
population.

7. In at least some MOSDEF AGNs, the gas in the narrow-
line region appears to be more enriched than gas in the host
galaxy. Overall, however, AGNs at $z \sim 2$ are less enriched
than local AGNs with the same host stellar mass.

With data from the first observing season of the MOSDEF
survey, we have demonstrated the power of the survey for AGN
studies. As the sample size increases we will further study
the demographics and host galaxy properties of optical versus
X-ray and IR-selected AGNs, as well as the X-ray emission
of MOSDEF galaxies as a function of key galaxy physical
properties such as stellar mass, SFR, stellar age, and metallicity.

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