A New Diagnostic Diagram of Ionization Sources for High-redshift Emission Line Galaxies

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Abstract

We propose a new diagram, the kinematics–excitation (KEx) diagram, which uses the [O III] \( \lambda 5007 / H\beta \) line ratio and the [O III] \( \lambda 5007 \) emission line width (\( \sigma_{[O\,III]} \)) to diagnose the ionization source and physical properties of active galactic nuclei (AGNs) and star-forming galaxies (SFGs). The KEx diagram is a suitable tool to classify emission line galaxies at intermediate redshift because it uses only the [O III] \( \lambda 5007 \) and H\( \beta \) emission lines. We use the main galaxy sample of SDSS DR7 and the Baldwin–Phillips–Terlevich (BPT) diagnostic to calibrate the diagram at low redshift. The diagram can be divided into three regions: the KEx-AGN region, which consists mainly of pure AGNs, the KEx-composite region, which is dominated by composite galaxies, and the KEx-SFG region, which contains mostly SFGs. LINERs strongly overlap with the composite and AGN regions. AGNs are separated from SFGs in this diagram mainly because they preferentially reside in luminous and massive galaxies and have higher [O III]/H\( \beta \) than SFGs. The separation between AGNs and SFGs is even cleaner thanks to the additional 0.15/0.12 dex offset in \( \sigma_{[O\,III]} \) at fixed luminosity/stellar mass. We apply the KEx diagram to 7866 galaxies at 0.3 < \( z \) < 1 in the DEEP2 Galaxy Redshift Survey, and compare it to an independent X-ray classification scheme using Chandra observations. X-ray AGNs are mostly located in the KEx-AGN region, while X-ray SFGs are mostly located in the KEx-SFG region. Almost all Type 1 AGNs lie in the KEx-AGN region. These tests support the reliability of this classification diagram for emission line galaxies at intermediate redshift.

At \( z \sim 2 \), the demarcation line between SFGs and AGNs is shifted by \( \sim 0.3 \) dex toward higher values of \( \sigma_{[O\,III]} \) due to evolution effects.

Key words: galaxies: active – galaxies: Seyfert – quasars: emission lines

1. Introduction

Emission line diagnostic diagrams are major tools for understanding the nature of galaxies. They are crucial in evaluating galaxy evolution scenarios such as cosmic accretion and star formation histories. The most widely used diagnostic diagrams, based on ratios of optical emission lines, are the BPT (Baldwin et al. 1981) or VO87 (Veilleux & Osterbrock 1987) diagrams. The advent of spectroscopic sky surveys such as the Sloan Digital Sky Survey (SDSS) maps the distribution of local emission line galaxies on diagnostic diagrams, and these data can be used for comparison with photoionization models (Ferland et al. 1998; Kewley et al. 2001; Dopita et al. 2013) to better understand the ionizing sources and properties of ionized gas such as metallicity, ionization parameter, density etc. Kewley et al. (2001, Kewley01) used a variety of photoionization models of H\( \Pi \) regions to give a theoretical boundary for star-forming galaxies (SFGs) on the BPT diagram. Sources above this line are unlikely to be ionized by stars. Kauffmann et al. (2003, Kauffmann03) used the main sample of SDSS galaxies to map their detailed distribution on the BPT diagram, and proposed that the right branch of the bivariate distribution is populated by active galactic nuclei (AGNs). The sources lying between the two dividing lines are called composite galaxies because their gas may be ionized by AGNs and star-forming (SF) at the same time. Kewley et al. (2006, Kewley06) further proposed criteria relating to low-ionization lines for separating Type 2 AGNs and LINERs. Other refinements of the classification of subtypes are proposed by many authors (e.g., Stasinska et al. 2006; Cid Fernandes et al. 2010, 2011).

Our understanding of the BPT diagram is very comprehensive. The vertical axis of the diagram reflects mainly the ionization parameter while the \( x \)-axis is mostly determined by the metallicity (Storchi-Bergmann et al. 1994; Denicolò et al. 2002; Raimann et al. 2000; Groves et al. 2004a, 2004b, 2006; Pettini & Pagel 2004; Stasińska et al. 2006; Kewley & Ellison 2008). The distinguishing power of the BPT diagram relies on the fact that the radiation from AGNs is harder than that from SFGs at similar stellar mass, AGNs have higher ionization parameters, and they reside predominantly in massive metal-rich galaxies (Kauffmann et al. 2003; Groves et al. 2006).

The BPT diagram, however, suffers from a few limitations. It needs at least four lines ([O III] \( \lambda 5007 \), H\( \beta \), [N II] \( \lambda 6583 \), H\( \alpha \)) to make a classification. The [N II] \( \lambda 6583 \) and H\( \alpha \) emission line will shift out of the optical wavelength range when the redshift is greater than 0.4, making the classification diagram futile for higher redshift sources with optical spectrum only.

With spectroscopic sky surveys pushing to higher redshift and fainter luminosities (e.g., SDSS: York et al. 2000; DESI: Levi et al. 2013; PFS: Takada et al. 2014; Tamura et al. 2016), the need for a good classification diagram for emission line galaxies at higher redshift is compelling. Some efforts have been made to develop diagnostic diagrams with spectral features in a narrower wavelength range. Tresse et al. (1996) and Rola et al. (1997) proposed the use of EW([O II] \( \lambda 3727 \))...
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...equivalent width of [O II] $\lambda 3727$, EW([O III] $\lambda 5007$), and EW(H$\beta$) for galaxy classification. Stasińska et al. (2006) proposed a method that uses the 4000 Å break: $D_0$([O II]), EW([O II] $\lambda 3727$), and EW([Ne II] $\lambda 3870$) (DEW diagram) to select pure AGNs with $z < 1.3$ using only the optical spectra. Trouille et al. (2011) proposed to use $g - z$, [Ne III], and [O II] to clearly separate AGNs from star-forming galaxies at intermediate redshift. A fruitful way to push to high redshift is to retain [O III]/H$\beta$ while replacing [N II]/H$\alpha$ with other quantities such as $H$-band absolute magnitude (Weiner et al. 2006), [O II]/H$\beta$ (Lamareille 2010), $U - B$ color (Yan et al. 2011), or stellar mass (Juneau et al. 2011, 2013, mass–excitation diagnostic, MEx). Marocco et al. (2011) also used $D_0$([O II]) versus [O III]/H$\beta$ for classification of high-$z$ galaxies. These methods take advantage of the fact that AGNs reside in massive, red galaxies in the local universe, and they are in general efficient in separating pure AGNs and star-forming galaxies. Composite galaxies, however, are mixed with Type 2 AGNs or star-forming galaxies on these diagrams.

The velocity dispersion ($\sigma$) of emission lines may trace the kinematics of different components in AGNs and star-forming galaxies. [O III] in AGNs comes from the narrow-line region, which better traces the bulge kinematics (e.g., Ho 2009). [O III] in star-forming galaxies mainly comes from the H II regions, which are located mainly in the disk. The kinematics of the bulge/disk are expected to be different. Catinella et al. (2010) showed that the velocity dispersion is different for bulge- and disk-dominated galaxies at given baryonic mass. Furthermore, emission lines of AGNs may have extra broadening due to outflows (Greene & Ho 2005; Greene et al. 2011; Zhang et al. 2011; Bae & Woo 2014, 2016; Woo et al. 2016). In principle, we could use the width of the narrow emission lines as a proxy for the influence of bulge potential in classification of AGNs/ star-forming galaxies. Following the idea of simplifying the BPT diagram as introduced in the previous paragraph (Weiner et al. 2006; Lamareille 2010; Juneau et al. 2011, 2013; Yan et al. 2011), and the idea of different kinematics of AGNs and star-forming galaxies, we propose to replace [N II]/H$\alpha$ in the BPT diagram with $\sigma_{[O III]}$ (or $\sigma_{gas}$ in general) to separate AGNs from star-forming galaxies at high redshift. In Section 2, we give descriptions of the data we use. In Section 3, a new diagnostic diagram is proposed: the kinematics–excitation (KEx) diagram, and we explain why it works and calibrate it at $z < 0.3$. Section 4 gives the calibration of the KEx diagram at $0.3 < z < 1$, and Section 5 gives the calibration at $z \sim 2$. Discussion is given in Section 6. We use a cosmology with $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_m = 0.3$, and $\Omega_\Lambda = 0.7$ throughout this paper.

2. Sample and Measurements

2.1. Low-redshift Data

We start from the main galaxy sample (Strauss et al. 2002) of the Sloan Digital Sky Survey Data Release 7 (SDSS DR7) (Abazajian et al. 2009). The sample is complete in $r$-band Petrosian magnitude between 15 and 17.77 over 9380 deg$^2$. We limit the redshift range to $z < 0.33$, and there are 835,410 spectroscopic galaxies. To properly measure the emission lines, we use the scheme developed in Hao et al. (2005) to subtract stellar absorptions. They used several hundreds of SDSS low-redshift pure absorption spectra to construct the principal component analysis (PCA) eigenspectra, and used the first eight eigenspectra to fit the continuum. A A-star template is added to represent a young stellar population. A power law is also added when fitting AGN spectra. The continuum-subtracted line emissions are left for refined line fitting. We use a Gaussian function to fit the lines [O II] $\lambda 3727$, [O I] $\lambda 6300$, H$\beta$, [O III] $\lambda 5007$, [N II] $\lambda 6548$, H$\alpha$, [N II] $\lambda 6583$, and [S II] $\lambda 6717, 6731$ (hereafter [O II], [O I], H$\beta$, [O III], [N II] $\lambda 6548$, H$\alpha$, [N II] $\lambda 6583$, and [S II] respectively. $\sigma$ line width, 1/2.35 FWHM in km s$^{-1}$) of the Gaussian profile for [O III] $\lambda 5007$ is denoted as $\sigma_{[O III]}$. The line ratio [N II] $\lambda 6583$/ [N II] $\lambda 6548$ is fixed as 3 and their profile and center are tied to be the same. In addition, we fit H$\alpha$ and H$\beta$ a second time, adding one broad Gaussian to account for possible broad H$\alpha$ and H$\beta$ lines. The lower limit of $\sigma$ of the broad component is 400 km s$^{-1}$. The typical FWHM of the broad H$\alpha$ component of Type 1 AGNs is larger than 1200 km s$^{-1}$ (Hao et al. 2005). We regard the broad H$\alpha$ component as being prominent if an F-test suggests that the improvement is significant at the 3$\sigma$ level. The intrinsic velocity dispersion $\sigma_{int}$ of the emission lines is obtained by subtracting the instrumental resolution of $\sim 56$ km s$^{-1}$ using $\sigma_{int}^2 = \sigma_{obs}^2 - \sigma_{Instrument}^2$. The errors of $\sigma$ and the line strength are obtained by the MPFIT package, which only includes the fitting errors (Markwardt 2009). We perform a simple test to check how well we can measure the line width. We add a Gaussian to a continuum with a given EW. $\sigma$ of the Gaussian is the combination of the intrinsic width of the emission line, $10^{\lambda 58} = 63.1$ km s$^{-1}$ (typical star-forming galaxy), and the instrumental resolution of 56 km s$^{-1}$. Random errors are added according to signal-to-noise ratio (S/N) = 3, 5, 7, 10. We fit the emission line using the MPFIT package, and measure the error of $\sigma$ by comparing the measured value with the input one. The simulation is run 500 times. At EW = 3 (typical value for a star-forming galaxy with $-0.5 < \log([O III]/H$β$ < 1$) and S/N = 3, 5, 7, 10, the errors in emission line width, $\sigma$, are 0.19 dex, 0.08 dex, 0.06 dex, and 0.04 dex. For the worst case—EW = 3, S/N = 3—the error in $\sigma$ is 0.19 dex. For sources with higher [O III]/H$\beta$ and higher emission line width, the measurements are more reliable.

2.2. Intermediate-redshift Data

Our intermediate-redshift galaxy sample is based on observations from the DEEP2 Galaxy Redshift Survey (hereafter DEEP2; Davis et al. 2003; Newman et al. 2013). The DEEP2 survey has a limiting magnitude of $R_{AB} = 24.1$, and it covers 3.2 deg$^2$, spanning four separate fields on the sky. The spectra span a wavelength range of 6500–9100 Å at a spectral resolution of $R \sim 5000$. The DEEP2 DR4 includes 52,989 galaxies. For our study, we limit the redshift range to be $0.32 < z < 0.82$ to ensure the detection of H$\beta$ and [O III] in the DEEP2 wavelength coverage. The sample size is thus cut to 12,739 galaxies. The spectra are obtained with the DEIMOS spectrograph (Faber et al. 2003) at the Keck Observatory and reduced with the pipeline developed by the DEEP2 team at the University of California Berkeley. All the DEEP2 footprints are observed by Chandra Advanced CCD Imaging Spectrometer (ACIS-I) with total exposures across all four XDEEP2 fields ranging from $\sim 10$ ks to 1.1 Ms (Nandra et al. 2005; Laird et al. 2009; Goulding et al. 2012). The intermediate-redshift data are

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3 http://deep.ps.uci.edu/  
4 http://astro.berkeley.edu/~cooper/deep/spec2d/
used for calibration of the new KEx diagnostic diagram at $z < 1$.

2.3. Type 1 AGN Sample

Our KEx diagram uses only the narrow H$\beta$ component and [O III] emission lines so it is straightforward to use Type 1 AGN narrow-line components to calibrate our KEx diagram. We first use a sample of $z < 0.3$ Type 1 AGNs from the main galaxy sample of SDSS DR7 for testing. These sources have a broad H$\alpha$ component with significance greater than $3\sigma$ as described in Section 2.1. The line width of broad H$\beta$ is almost the same as that of H$\alpha$, with FWHM greater than 1200 km s$^{-1}$ ($\sigma \sim 510$ km s$^{-1}$). $\sigma$ of the narrow H$\beta$ line is typically 200 km s$^{-1}$, and rarely exceeds 300 km s$^{-1}$. Usually the difference in width between broad and narrow lines is big enough for a reliable decomposition according to our simple simulation. If the narrow and broad components have similar width, some broad H$\beta$ flux might go into narrow H$\beta$ due to unreliable decomposition. This decreases [O III]/H$\beta$, and makes this source more likely to be classified as an SFG. So it is possible that some Type 1 AGNs are misclassified as SFGs. This is very rare because a narrow broad H$\beta$ line indicates a low-mass black hole, which is very rarely detected in the SDSS survey (Dong et al. 2012), and thus will not influence our result. The typical density in an AGN broad-line region is at least $10^{5}$ cm$^{-3}$ (e.g., Netzer 2008), while the critical density of [O III] $\lambda$5007 is $7 \times 10^{4}$ cm$^{-3}$ (e.g., Osterbrock 1989). Thus [O III] does not have a broad component in Type 1 AGNs, and we do not need to decompose the [O III] emission line into broad and narrow components.

3. Calibration of KEx Using the SDSS Main Galaxy Sample

Since the BPT diagram needs at least [O III], H$\beta$, [N II], and H$\alpha$ for a classification, it is not applicable to sources at $z > 0.4$ with optical spectrum alone. We propose a new diagnostic diagram: [O III]/H$\beta$ versus $\sigma_{[O \text{ III}]}$ to diagnose the ionization source and physical properties of emission line galaxies. We name it the kinematics–excitation (KEx) diagram hereafter. This approach shares similar logic to the work of Yan et al. (2011) and Juneau et al. (2011).

The dividing lines proposed by Kewley et al. (2001, 2006) and Kauffmann et al. (2003) are used to classify emission line galaxies into star-forming galaxies, composite galaxies, Type 2 AGNs, and LINERs, as shown in Figure 1. We require S/N to be greater than 3 for H$\beta$, [O III], [N II], H$\alpha$, and [S II] lines to ensure classification on the KEx diagram into subtypes. The [O I]/H$\alpha$ diagram is shown for reference and not taken into account in the classification. How the different types of galaxies populate the KEx diagram is shown in Figure 1(d).

We plot [O III]/H$\beta$ versus $\sigma_{[O \text{ III}]}$ for different types of emission line galaxies separately in Figure 2. From left to right are star-forming galaxies, composite galaxies, LINERs, and Type 2 AGNs. In panel (a), the star-forming galaxies cluster in the bottom left corner of the diagram; the boundary of the star-forming galaxies is clear and sharp. We derive an empirical line to follow the boundary:

$$\log[\text{O III}]/\text{H}$β = −2 \times \log \sigma_{[\text{O III}]} + 4.2.$$  

This demarcation line can be used to separate AGNs from star-forming galaxies. The detailed distribution of BPT-classified galaxies on the KEx diagram is given in Table 1, 97% (5674/5860) of the BPT-classified Type 2 AGNs (above Kewley01 line) and 35% (5587/16,003) of the BPT-classified composite sources lie above the new classification line and will be classified as AGNs by the KEx diagram. 99% of BPT-classified SFGs are classified as KEx-SFGs. 81% of the KEx-classified AGNs are BPT-classified AGNs (above Kewley01 line). 90% of the KEx-classified SFGs are BPT-classified SFGs. For all the sources on the upper side of the line, 7.7% are classified as star-forming galaxies in the traditional BPT diagram. 65% (10,416/16,003) of BPT composites are in the KEx-SFG region. 47% ((10,416 + 116 + 186)/(16,003 + 998 + 5860)) of non-SF galaxies are on the KEx-SFG side. This means the new diagram is very efficient in selecting AGNs above the Kewley01 line with high completeness and low contamination rate.

One may notice that the composite galaxies cluster near the SFG–AGN dividing line and are clearly separate from Type 2 AGNs. We draw a horizontal line

$$\log[\text{O III}]/\text{H}$β = 0.3$$  

to cut out a region dominated by composites. Above this line, the galaxies are mainly LINERs and Seyfert2s (Sy2s) and we call it the KEx-AGN region. Below the line $\log[\text{O III}]/\text{H}$β = 0.3 but above the SFG–AGN line, composite galaxies dominate, and we name this the KEx-composite region. To be precise, there are 5074 composites in the KEx-composite region, but only 335 Sy2s, 424 LINERs, and 882 star-forming galaxies that together make up 24.4% of non-BPT composites.

We can see in Figure 2 and Table 1 that 116/998 LINERs are classified as star-forming galaxies on the KEx diagram, 426/998 are KEx-composites, and 458 are KEx-AGN. LINER-like emission could be produced by low-luminosity AGNs (Ferland & Netzer 1983; Halpern & Steiner 1983; Groves et al. 2004b; Ho 2008), post-AGB stars (Binette et al. 1994; Yan & Blanton 2012; Singh et al. 2013), fast shocks (Dopita & Sutherland 1995), photoionization by the hot X-ray-emitting gas (Voit & Donahue 1990; Donahue & Voit 1991), or thermal conduction from the hot gas (Sparks et al. 1989). Although the sources of ionization are diverse, the host galaxies of LINERs are massive, making them only weakly overlap with the star-forming galaxies on the KEx diagram. Since our KEx diagram does not include information on low-ionization lines, the LINERs are not well separated from AGNs.

We note that only 1/3 of the BPT-classified composite galaxies are in the KEx-composite region, while most of the remaining 2/3 are in the KEx-SFGs region. Only a small fraction (3%) are in the KEx-AGN region. This may be because the BPT-classified composite galaxies have a diverse origin too. They could be relatively weak AGNs (Kauffmann et al. 2003; Y Randall et al. 2010; Ellison et al. 2011), shock heated (e.g., Rich et al. 2014.), or H II regions with a special physical condition (Kewley et al. 2001). Trouille et al. (2011) showed that the composites are most similar to AGNs in their Trouille-Barger-Tremonti diagram and show not only photoionization properties as AGNs do but also an excess X-ray emission relative to the infrared emission, indicating nonstellar processes. This is a more likely scenario than shocks or varying conditions in HII regions. In the case of shocks, even galaxies with a lot of regions locally dominated by shocks have overall line ratios that place them in the BPT-SFG region instead of the composite region (Rich et al. 2011). Some composites may have an intrinsically less luminous AGN, and gas in the narrow-line region that is
moving more slowly, both in rotation and in outflow. This means that our KEx diagram, which is successful in separating strong AGNs from SFGs, may not have enough diagnostic power to pick out weak AGNs that have low contrast in both the $\text{[O III]}/\text{H} \beta$ ratio and the kinematics relative to SFGs. The KEx diagram has the lowest misclassification rate of composites among all BPT-surrogate diagrams.

In Figure 3, we plot KEx-AGN, KEx-composites, and KEx-SFGs on the BPT diagram. The KEx-composites cluster around the composite region on the BPT diagram. This is somewhat expected as a consequence of the cut in $\log \text{[O III]}/\text{H} \beta = 0.3$. This plot gives us an intuitive impression of what kind of galaxies we are selecting using the KEx diagram. KEx-AGN, KEx-composites, and KEx-SFGs are mostly located in the AGN, composite, and SFG regions on the BPT diagram. The KEx diagram and BPT diagram are very consistent.

It is possible that the KEx diagram can be used to further diagnose the real nature of the composite galaxies. Figure 2(b) also suggests that the $\text{[O III]}$ line width could potentially be used to further constrain the nature of composite galaxies. For example, a broad emission line width is usually regarded as a tracer of shock (e.g., Rich et al. 2011, 2014). The different line widths between subpopulations of composites could potentially be used to constrain the relative importance of AGNs and SF processes. Meanwhile, we note that the KEx diagram alone does not allow one to distinguish the LINERs from AGNs and composite sources. One would need additional information, such as the color of the host galaxy, host morphology, or other emission line measurements to further identify LINERs. We provide an intuitive impression of what kind of galaxies we are selecting using the KEx diagram. KEx-AGN, KEx-composites, and KEx-SFGs are mostly located in the AGN, composite, and SFG regions on the BPT diagram. The KEx diagram and BPT diagram are very consistent.
leave the exploration of the power of the KEx diagram to diagnose subclasses for future studies.

4. KEx Diagram Calibration at 0.3 < z < 1

Application of the KEx diagram at high redshift needs calibration because the properties of star-forming galaxies and AGN host galaxies are different. To calibrate, we need a sample of AGNs and star-forming galaxies that are already classified. There are several methods for calibration:

1. There are many Type 1 AGNs from SDSS in the range 0.3 < z < 1. Type 1 AGNs can be identified by their blue color or broad emission lines. We use them as independently identified AGNs to perform a sanity check of the KEx classification when considering only the narrow-line components in Section 4.1. We make the assumption that the Type 1 and Type 2 sources have identical narrow-line features in the frame of the unification model (Antonucci 1993). Some minor differences in narrow lines do exist due to stratification of narrow-line regions, outflow, or the narrow-line Baldwin effect (Veilleux 1991; Zhang et al. 2008, 2011; Stern & Laor 2013), but the assumption is largely valid.

2. X-ray identification may act as an independent reference for calibration of AGN/SFG classification (Juneau et al. 2011, 2013; Yan et al. 2011). There are several drawbacks with this method: X-ray AGNs and optical AGNs may not be the same population (Hickox et al. 2009) and sources with reliable deep X-ray data are limited. In addition, X-ray surveys are less sensitive to moderate-luminosity AGNs in galaxies of lower stellar masses (Aird et al. 2012) or to heavily obscured Compton-thick AGNs. Yan et al. (2011) estimated that, at $L_{bol} > 10^{44}$ erg s$^{-1}$, about 2/3 of the emission line AGNs with $0.3 < z < 0.8$ and $I_{bol} < 22$ will not be detected in the 2–7 keV band in the 200 ks Chandra images due to absorption and/or scattering of the X-rays in the Extended Groth Strip. Using X-ray AGNs to do a sanity check is reliable overall despite the drawback listed above. We use DEEP2 data and X-ray identification for KEx calibration in Section 4.2. DEEP2 contains both SFGs and AGNs, but mostly SFGs. This can help us constrain our calibration on the SF side.

3. If near-IR (NIR) spectra are available, the [N II] and H$\alpha$ emission lines could be used for optical classification using the BPT diagram. The use of the BPT diagram at high redshift remains valid (Trump et al. 2011b; Kashino et al. 2013, 2017; Kewley et al. 2013b, 2016; Juneau et al. 2014; Steidel et al. 2014; Coil et al. 2015; Kartaltepe et al. 2015; Kriek et al. 2015; Sanders et al. 2016). However, a public database of NIR spectra for large samples of high-redshift galaxies is not available. We leave the use of the BPT diagram for calibration of the KEx diagram at high z for future work.

We use Method (1) and Method (2) in the following paragraphs.

4.1. Calibration of the KEx Diagram Using Type 1 AGNs

We apply an S/N threshold of 3 to H$\beta$ and [O III] narrow lines, and plot these z < 0.3 Type 1 AGNs described in Section 2.3 in the KEx diagram in Figure 4(a). The [O III]/H$\beta$ lines only include the narrow component of H$\beta$. These sources (4624) reside mostly in the KEx-AGN and KEx-composite regions, while only 414 (9%) of them are in the KEx-SFG region.

We further plot a sample of intermediate-z Type 1 AGNs selected from the QSO catalog of SDSS DR4 with 0 < z < 0.8 on the KEx diagram. The sources in this sample have small contamination from host galaxies in their optical light, and their properties and data reduction are described in Dong et al. (2011). Detailed analysis of narrow-line properties, especially the [O III] line, can be found in Zhang et al. (2011, 2013a, 2013b). The bolometric luminosity range of these sources is $10^{44}$-$10^{47}$ erg s$^{-1}$. In the left panel of Figure 4, we plot this sample on the KEx diagram in orange. Almost all (96%) of the sources lie in the KEx-AGN region, and a small fraction of the Type 1 sources (4%) lie in the KEx-composite region. Only 13 (0.3%) Type 1 sources are classified as KEx-SFGs. According to the unification model, if these Type 1 sources are viewed edge-on, almost all of them would be correctly classified as AGNs.

One may notice that some Type 1 AGNs lie outside the low-z locus. Some sources have higher [O III]/H$\beta$ line ratio and some have larger $\sigma_{(H\alpha)}$. These could be partly understood by the orientation effect. The Type 1 AGNs are found to have higher ionization state than Type 2 AGNs (Veilleux 1991;
Table 1
Statistics of Galaxy Classification in the KEx Diagram

| Type               | Star-forming Galaxies | Composites | LINERs | Type 2 (DR7 galaxy sample) | Type 1 AGNs (DR4 quasar sample) | Quasars | DEEP2 |
|--------------------|-----------------------|------------|--------|---------------------------|---------------------------------|---------|-------|
| (1)                | (2)                   | (3)        | (4)    | (5)                       | (6)                             | (7)     | (8)   |
| Total number       | 97,484                | 16,003     | 998    | 5860                      | 4624                            | 4158    | 7866  |
| KEx-SFGs           | 96,322                | 10,416     | 116    | 186                       | 414                             | 13      | 7024  |
| KEx-composite      | 882                   | 5074       | 424    | 335                       | 718                             | 274     | 344   |
| KEx-AGN            | 280                   | 513        | 458    | 5339                      | 3492                            | 3871    | 498   |

Note: Columns: (1) Classifications on KEx diagram, (2) Star-forming galaxies from the SDSS main galaxy sample, (3) Composite galaxies from SDSS, (4) LINERs from SDSS, (5) Type 2 AGNs from SDSS, (6) Type 1 AGNs from the SDSS main galaxy sample, (7) Type 1 AGNs from Dong et al. (2011), (8) Galaxies from DEEP2 survey.

Schmitt et al. 2003a, 2003b); this is because high-ionization lines arise from regions closer to the nuclei and thus are more likely to be blocked when viewed edge-on. The inclination effect may play a role in the greater width of [O III] emission here. The [O III] emission line is known to show a blue-wing asymmetric profile (Heckman et al. 1981; Zhang et al. 2011; Bae & Woo 2014, 2016; Woo et al. 2016) and this is believed to be due to outflows from narrow-line regions. When the outflows are viewed in a face-on orientation, we would see a larger overall outflow velocity, which would lead to a larger line width.

4.2. Calibration Using the DEEP2 Survey

Our intermediate-redshift galaxy sample is based on observations from the DEEP2 Galaxy Redshift Survey. Most of the galaxies in DEEP2 surveys are star-forming galaxies, as indicated by X-ray studies (Nandra et al. 2005; Laird et al. 2009; Goulding et al. 2012). It is interesting to check whether the X-ray and the KEx classifications are consistent and what causes the differences. An X-ray luminosity threshold of \( L_{2-10\,\text{keV}} > 10^{42} \, \text{erg s}^{-1} \) is adopted. There are no star-forming galaxies with X-ray luminosity higher than this value in the local universe (Fabbiano 1989; Bauer et al. 2004; Colbert et al. 2004). However, weak AGNs with \( L_{2-10\,\text{keV}} < 10^{42} \, \text{erg s}^{-1} \) do exist even though they are more difficult to differentiate from star-forming or starburst galaxies without additional information. For DEEP2 X-ray data, the sensitivity of the shallowest data could ensure the detection of luminous X-ray sources (\( L_{2-10\,\text{keV}} > 10^{42} \, \text{erg s}^{-1} \)).

\([\text{O III}]/H\beta\) is plotted versus \( \sigma_{\text{[O III]}} \) for DEEP2 emission line galaxies as gray triangles in the right panel of Figure 4. We use the method described in Section 3 for spectral fitting. We apply an S/N cut of 3 to H\( \beta \) and [O III] \( \lambda 5007 \). 7866 sources are selected according to these criteria. We convert the hard 2–8 keV X-ray flux to rest-frame 2–10 keV luminosities (\( L_X(2-10\,\text{keV}) \)) by assuming a power-law spectrum with photon index (\( \gamma = 1.8 \)). The sources with \( L_X(2-10\,\text{keV}) > 10^{42} \, \text{erg s}^{-1} \) are classified as starburst AGNs, and sources with \( L_X(2-10\,\text{keV}) < 10^{42} \, \text{erg s}^{-1} \) are classified as star-forming galaxies. The X-ray sources are plotted as pink and purple triangles in the right panel of Figure 4. We can see that most of the X-ray AGNs/SFGs are consistently classified as optical AGNs/SFGs. Out of the 93 X-ray AGNs, 48 (52%) are classified as KEx-AGN, 18 (19%) are KEx-composite, and 27 (29%) are KEx-SFGs.

Out of the 83 X-ray SFGs in our sample, 19 are KEx-AGN, 14 are KEx-composite, and 49 (59%) are KEx-SFGs. In Juneau et al. (2011), for the X-ray starbursts, 50% (8/16) are classified as MEx-SFGs, while 19% (3/16) are in the intermediate region, and the remaining 31% (5/16) reside in the AGN region. The two results are consistent.

On the other hand, we notice that some sources are optically classified as SFGs but have very powerful X-ray emission, indicating that they harbor active nuclei. 29% of X-ray AGNs are classified as star-forming galaxies on the KEx diagram. In Juneau et al. (2011), 20% of their X-ray AGNs are classified as MEx-intermediate and 15% are MEx-SFGs. Considering that the “intermediate” region is mixed with the star-forming region on the MEx diagram, our result is consistent with theirs. Yan et al. (2011) found that 25% of their X-ray AGNs reside in the star-forming region of their optical classification diagram, which replaces [NII]/H\alpha in the BPT diagram with rest-frame U – B color. This is consistent with our result too.

Castelló-Mor et al. (2012) studied the sources that have \( L_X(2-10\,\text{keV}) > 10^{42} \, \text{erg s}^{-1} \) and are classified as AGNs on the BPT diagram. These sources have large thickness parameter (\( T = f_X/F_{\text{[O III]}} \)), large X-ray to optical flux ratio (\( X/\lambda > 0.1 \)), broad H\beta line width, steep X-ray spectra, and they display soft excess. These mismatches illustrate that neither X-ray nor optical classification is complete. Different classification schemes are complementary to each other. Judging from Figure 4, the evolution in \( \sigma_{\text{[O III]}} \) is comparable to or even larger than rotation velocity (\( \sigma \)). Since we use the integrated emission line profile, the increase in velocity dispersion further broadens the

5. Calibration of the KEx Diagram at \( z \sim 2 \)

In this section, we discuss extrapolating the KEx diagram to redshifts greater than 2, and use \( z > 2 \) emission line galaxies to test the validation of the diagram. The epoch of \( 2 < z < 4 \) is critical to galaxy formation and evolution. During this epoch, the Hubble sequence was not fully established (Förster Schreiber et al. 2006, 2009; Kriek et al. 2009), but the bimodality was in place (Kriek et al. 2009). It is in this range of redshift that the star formation density and AGN activity peak (e.g., Barger et al. 2001; Elbaz & Cesarsky 2003; Hopkins 2004; Di Matteo et al. 2005; Hopkins & Beacom 2006; Hopkins et al. 2006).

Star-forming galaxies in this redshift range are different from local galaxies in kinematics, ionization state, and metallicity. Unlike local disk galaxies, which are totally rotation-supported with \( v_{\text{rot}}/\sigma = 10–20 \) (e.g., Dib et al. 2006), a large fraction of high-redshift star-forming galaxies have velocity dispersion comparable to or even larger than rotation velocity (Förster Schreiber et al. 2006, 2009; Law et al. 2007; Wright et al. 2007; Genzel et al. 2008; Cresci et al. 2009; Vergani et al. 2012). Since we use the integrated emission line profile, the increase in velocity dispersion further broadens the
emission line. Even after extracting the rotation velocity using integrated field spectroscopy (IFS) for these high-redshift galaxies, the derived Tully–Fisher relation (TFR) is still different from the local well-defined relation. The rotation speed of $z \sim 2$ galaxies is $\sim 0.2$ dex higher than that of local galaxies of similar stellar mass (Cresci et al. 2009; Gnerucci et al. 2011). Meanwhile, the $[\text{O III}]/\text{H}$ ratio of star-forming galaxies is known to be higher at high redshift (Shapley et al. 2005; Erb et al. 2006a; Groves et al. 2006; Brinchmann et al. 2008; Liu et al. 2008; Shirazi et al. 2014). Both theory (e.g., Groves et al. 2006) and observations (e.g., Coil et al. 2015) have shown low-metallicity AGNs to populate the bottom left part of the BPT diagram, and thus overlap with SFGs. Thus, we expect the demarcation line of AGNs and star-forming galaxies on the KEx diagram to shift toward higher $\sigma_{\text{gas}}$, or higher $[\text{O III}]/\text{H}$ because of the evolution of the TFR and $[\text{O III}]/\text{H}$ with redshift. There are thousands of emission line galaxies identified in this redshift range, and most of them are detected using dropout techniques (e.g., Steidel et al. 1996, 1998, 2003, 2004, 2014; Pettini et al. 1998, 2001) or color selection (Franx et al. 2003; Daddi et al. 2004; Kong et al. 2006). We compile a sample of Lyman-break galaxies (LBGs) and color-selected BzK galaxies at $z > 2$ that have measurements of $[\text{O III}]$ and $\text{H}\beta$ emission line ratio and gas velocity dispersion from the literature. Our sample include 10 galaxies (3 are AGNs) from Kriek et al. (2007), 1 LBG from Teplitz et al. (2000), 6 LBGs from Pettini et al. (1998, 2001), and 2 gravitationally lensed star-forming galaxies from Hainline et al. (2009). Samples of $z \sim 2$ galaxies with NIR spectra are increasing thanks to the deployment of NIR spectrographs such as FMOs on Subaru (Kashino et al. 2013, 2017; Kartaltepe et al. 2015) and MOSFIRE on Keck (Steidel et al. 2014; Kriek et al. 2015). These data, once they become public, will improve the calibration of the KEx diagram at $z \sim 2$ significantly. The AGN fraction of this sample is very small because LBGs have very low AGN fraction (about 3%–5%, Steidel et al. 2002; Reddy et al. 2005; Erb et al. 2006b). We further compile radio galaxies that are confirmed to be AGNs and see how they are distributed in the KEx diagram. We use four radio AGNs from Nesvadba et al. (2008, 2011) and CDFS-695—a shock or/and AGN from van Dokkum et al. (2005), and 74 Type 1 AGNs from Shen (2016). The SFGs are color-coded in blue while AGNs are in red.

Figure 5 shows that the $z > 2$ LBGs are not confined to the KEx-SFGs region of local galaxies. Most of them lie in the KEx-AGN or KEx-composite region. If we shift the dividing line 0.3 dex to the right, most of the galaxies are correctly classified. AGNs are clearly separated from the star-forming galaxies on the KEx diagram after shifting the boundary by 0.3 dex. We further check the $[\text{O III}]$ width distribution of a sample of $z \sim 2$ QSOs from Netzer et al. (2004) and plot the histogram in the lower panel of Figure 5. Only one source has $[\text{O III}]$ width less than 100 km s$^{-1}$, and most of the QSOs have $\sigma_{\text{O III}} \sim 300$ km s$^{-1}$. There is no doubt that these QSOs would have high $[\text{O III}]/\text{H}$ ratio even though we do not have their detailed values. Therefore, they are likely to separate from the $z \sim 2$ star-forming galaxies. Strong outflow driven by AGNs is reported in radio galaxies (Nesvadba et al. 2008, 2011), so the large line width in $[\text{O III}]$ is at least partly due to the outflow. Judging from our empirical results, the KEx diagram works after shifting the dividing line 0.3 dex to the right at $z \sim 2$. More data are needed to better constrain the boundary.

6. Discussion

6.1. Why Does the KEx Diagram Work?

Compared to the widely used BPT diagram, the KEx diagram uses $\sigma_{[\text{O III}]}$ instead of the $[\text{N II}]/\text{H}\alpha$ ratio as the horizontal axis to diagnose the ionizing source and physical properties of emission line galaxies. We showed that it gives very consistent results with the BPT diagram. Here we discuss the physical reasons behind the diagram and why it works. $\sigma_{[\text{O III}]}$ in principle traces the motion of the gas. To first order, this motion is determined by the gravitational potential of the galaxy. The emission line width correlates well with the stellar velocity dispersion in almost all types of emission line galaxies (e.g., Nelson 2000; Wang & Lu 2001; Greene & Ho 2005; Bian et al. 2006; Dumas et al. 2007; Komossa & Xu 2007, 2008;
Chen et al. 2009; Ho 2009). In AGNs, several other sources of line broadening may be at work in addition to the stellar kinematics (Greene & Ho 2005). So the basic principle behind the KEx diagram is the different kinematics of emitting gas in AGNs and star-forming galaxies.

The boundary between star-forming galaxies and AGNs on the KEx diagram indicates that there is a maximum $\sigma_{\text{H} \beta}$ for star-forming galaxies. In local star-forming galaxies, $[\text{O} \text{III}]$ comes from the H II region, which is more tightly correlated with the kinematics of the disk. It was found that the width of narrow emission lines of star-forming galaxies could efficiently trace the maximum rotation velocity of a galaxy (Rix et al. 1997; Mallén-Ornelas et al. 1999; Weiner et al. 2006; Mocz et al. 2012). The rotation speed is directly linked to the luminosity of the galaxy through the Tully–Fisher relation (Tully & Fisher 1977). The most luminous spiral galaxies also rotate fastest. A reasonable hypothesis is that the galaxies near the maximum $\sigma_{\text{H} \beta}$ boundary in the KEx diagram are the most luminous ones. We plot $[\text{O} \text{III}]/\beta$ versus $R$-band absolute magnitude for all the star-forming galaxies in our sample in Figure 6. The star-forming galaxies cluster to the bottom left of the diagram, and show a clear boundary. We draw a magenta boundary curve to define the maximum luminosity a star-forming galaxy can reach at a given $[\text{O} \text{III}]/\beta$. Using the Tully–Fisher relation obtained for SDSS galaxies by Mocz et al. (2012), we convert the luminosity in the curve to the velocity dispersion of ionized gas ($\sigma_{\text{gas}}$), and obtain a curve of $[\text{O} \text{III}]/\beta$ versus $\sigma_{\text{gas}}$, which is shown as the dashed line in Figure 2(a). We can see that the dashed line encompasses the regions where SFGs and composites are located, separating Type 2 AGNs from SFGs and composites. This illustrates that SFGs and composites are consistent with the TFR prediction, while AGNs are located outside the locus.

We plot the distribution of Type 2 AGNs (red dots) on diagrams of $[\text{O} \text{III}]/\beta$ versus $M_{R}$ (absolute Petrosian magnitude) and $[\text{O} \text{III}]/\beta$ versus $M_{*}$ (stellar mass) (MEx diagram, Juneau et al. 2011) in Figure 6. The magenta lines in the right
panel are the MEx dividing lines. The sources above the upper curve are MEx-AGN and the region between the solid upper curve and dashed line is the MEx-composite region. The stellar mass is drawn from the MPA-JHU catalog. Type 2 AGNs occupy the bright and massive end of Figure 6. This is consistent with previous findings that Type 2 AGNs reside exclusively in massive, luminous galaxies (e.g., Kauffmann et al. 2003). 4% (246/5860) of Sy2s are on the MEx-SF side, while 3% (186/5860) are on the KEx-SF side. On the plot of [O III]/Hβ versus MR, 7.7% (450/5960) of Sy2s lie on the SFG side of the dividing curve shown in the left panel of Figure 6.

The fraction of BPT-classified Type 2 AGNs that are misclassified as SFGs is higher on these two diagrams than on the KEx diagram. There is an additional enhancement in σ_[O III] at fixed luminosity or stellar mass for AGNs relative to SFGs. This enhancement helps AGNs separate further from SFGs on the KEx diagram. In Figure 7, we plot the median σ_[O III] derived from five emission lines against MR and stellar mass in the left and right panels. We focus on σ_[O III] (blue line) first and discuss other emission lines later. The errors are calculated using the bootstrap method. We can see that at a given

Figure 6. Left panel: [O III]/Hβ vs. R-band absolute magnitude. The blue contours are star-forming galaxies and the red dots are AGNs above the Kewley01 line. The lowest contour level is the 90th percentile. The dashed line is the boundary line we draw around the distribution. Its corresponding line on the KEx diagram after transformation by the Tully–Fisher relation is shown in Figure 2(a). Right panel: [O III]/Hβ vs. stellar mass. The blue contours are star-forming galaxies and the red dots are AGNs. The lowest level is the 90th percentile. The solid and dashed lines are the demarcation lines of the MEx diagram (Juneau et al. 2011). AGNs and SFGs are not separated as far on these two diagrams as on the KEx diagram.

Figure 7. Left panel: widths of different narrow lines against R-band absolute magnitude. The solid lines and dashed-dotted lines are median values of σ at given R-band absolute magnitude for Sy2s and star-forming galaxies respectively. Different colors represent different emission lines as indicated above the curves. Right panel: the median σ of different narrow lines against stellar mass. The legend is the same as in the left panel. At fixed R-band luminosity/stellar mass, AGNs show 0.15/0.12 dex higher σ_[O III] than SFGs. This enhancement helps AGNs separate further from SFGs on the KEx diagram.
luminosity that covers both AGNs and SFGs, $\sigma_{\text{O III}}$ is on average 0.15 dex higher for Type 2 AGNs than for SFGs. And at a given stellar mass, Type 2 AGNs are 0.12 dex higher than SFGs. These offsets are critical to the clean separation between Type 2 AGNs and star-forming galaxies on the KEx diagram. Other emission lines gave similar results.

What gives rise to the difference in $\sigma_{\text{O III}}$ for AGNs and SFGs? One main reason for it is that the emission lines in Type 2 AGNs are produced by gas in the narrow-line region that extends into the bulge, while the emission lines in SFGs are produced by gas in the HII region in the disk. The disk and bulge of a galaxy have different matter distributions and kinematics. It is shown in Catinella et al. (2012) that at a given luminosity or baryon mass, disk-dominated galaxies show 0.1 dex smaller stellar velocity dispersion ($\sigma_*$ measured from the SDSS 3" fiber) than bulge-dominated galaxies. At a given mass, bulge-dominated galaxies, which are more concentrated, show a higher $\sigma_*$ than disk-dominated galaxies. Besides the difference in host galaxies, several other physical reasons may be behind the fact that Type 2 AGNs have broader emission lines. Greene & Ho (2005) found that the excess [O III] line width relative to the kinematics of stellar or lower-ionization lines is about 30%--40% (0.11--0.15 dex), with small variations depending on AGN luminosity, AGN Eddington ratio, star formation rate, etc. When considering only the core of [O III], the excess in [O III] line width goes away (Greene & Ho 2005; Komossa et al. 2008). This supports the idea that the [O III] core is produced by ionized gas in the bulge while another source of broadening related to AGNs (such as possibly winds or outflows from an accretion disk) is at work. A radio jet may play a part in broadening the emission line too (Mullaney et al. 2013).

The differences in $\sigma_{\text{gas}}$ and $\sigma_*$ between AGNs and SFGs are more pronounced against $M_R$ than against $M^*$. In particular, $\sigma_*$ is significantly higher in AGN hosts at a fixed $M_R$ but not so different at a fixed stellar mass. This means that AGN hosts have higher mass-to-light ratios, which can be interpreted as having more important bulge components. More massive bulges host more massive black holes, and therefore may be detectable as Type 2 AGNs down to lower Eddington ratios. Conversely, lower mass AGNs are only identified as Type 2 AGNs for comparatively higher Eddington ratios, and their excess [O III] line width could be more pronounced relative to other lines than for higher mass AGNs if the Eddington ratio is the factor driving additional broadening (e.g., Greene & Ho 2005; Ho 2008).

In summary, the demarcation line between SFGs/ composites and AGNs on the KEx diagram is defined by the Tully–Fisher relation of the most luminous and massive galaxies. The AGNs reside in luminous and massive galaxies and at a given luminosity/stellar mass, their $\sigma_{\text{O III}}$ are 0.15/0.12 dex higher than SFGs. These effects make the KEx diagram an efficient classification tool for emission line galaxies.

### 6.2. Comparison with Previous Classification Diagrams

Tresse et al. (1996) and Rola et al. (1997) proposed to use EW([O III]), EW([O III]), and EW(H$\beta$) for galaxy classification at high redshift. Stasinska et al. (2006) studied using [O II] for galaxy classification, and proposed a method that uses $D_n(4000)$, EW([O II]), and EW([Ne III]) (DEW diagram) to select pure AGNs with $z < 1.3$ using only the optical spectrum. However, different types of galaxies overlap with each other severely on these classification diagrams.

Trouille et al. (2011) proposed to use $g - z$, [Ne III], and [O II] to clearly separate AGNs from SFGs. This method is very efficient in separating different types of galaxies, but the [Ne III] emission line is weak even in AGNs, thus this diagram requires spectra of galaxies with high S/N for reliable classification. This is particularly hard for high-redshift objects, which are usually faint.

Our KEx diagram has a similar logic to the color–excitation (CEX) and mass–excitation (MEx) diagrams proposed by Yan et al. (2011) and Juneau et al. (2011). The CEX diagram makes use of the fact that AGNs reside locally in red or green galaxies. But this is likely to be invalid at higher redshift (Trump et al. 2011b). The MEx diagram and the one using rest-frame $H$-band magnitude (Weiner et al. 2006) are based on the fact that AGNs are harbored by massive galaxies. This is more robust at high redshift considering the AGN downsizing effect. Trump et al. (2011b) tested the validity of these two diagrams at $z > 1.5$ and found that the MEx remains effective at $z > 1$ but CEX needs a new calibration. Coil et al. (2015) also find that the MEx diagram fails to identify all of the AGNs identified in the BPT diagram, and the CEx diagram is substantially contaminated at $z \sim 2.3$. As discussed in Section 3.2, the KEx diagram can separate AGNs and SFGs because AGNs reside in massive galaxies and have $\sigma_{\text{O III}}$ 0.12 dex higher than star-forming galaxies of similar stellar mass as an enhancement. This enhancement makes the KEx diagram more efficient at separating AGNs from SFGs. One advantage of the KEx is that it requires only a spectrum that covers a small spectral range to obtain all required quantities.

### 6.3. Shift of High-redshift SFGs and AGNs on the KEx Diagram

It is found that the [O III]/H$\beta$ ratio in SFGs gets higher at $z \sim 1$–2 (Shapley et al. 2005; Erb et al. 2006a; Brinchmann et al. 2006; Liu et al. 2008; Hainline et al. 2009; Wright et al. 2010; Trump et al. 2011a; Shirazi et al. 2014). The explanations for this trend include: high-redshift galaxies have elevated ionization parameter $U$ (Brinchmann et al. 2008; Shirazi et al. 2014), higher electron densities and temperatures (Liu et al. 2008), AGNs or shocks (Groves et al. 2006; Wright et al. 2010). It is interesting to check how [O III]/H$\beta$ evolves with redshift at given $\sigma_{\text{O III}}$ in the KEx diagram.

In the right panel of Figure 4, we plot the median [O III]/H$\beta$ at given $\sigma_{\text{O III}}$ for the SDSS galaxies at $z < 0.33$ and the DEEP2 galaxies on the KEx diagram. The blue, dark green, green, yellow, orange, and red lines are median [O III]/H$\beta$ at given $\sigma_{\text{O III}}$ for KEx-SFGs at $z \sim 0.1$, $0.3 < z < 0.4$, $0.4 < z < 0.45$, $0.5 < z < 0.6$, $0.6 < z < 0.7$, and $0.7 < z < 0.8$ respectively. The $\sigma$ values are corrected for instrumental broadening. We can see in Figure 4 that the [O III]/H$\beta$ versus $\sigma_{\text{O III}}$ relation does not evolve from $z \sim 0.3$ to $z \sim 0.8$, but these galaxies have on average 0.2 dex higher [O III]/H$\beta$ than the local galaxies at given $\sigma_{\text{O III}}$. One possible reason for this apparent evolution is that SDSS has a fixed aperture of 3" that acquires the light from the center of the galaxy, while DEEP2 spectra are obtained through long slits, which enable them to include light from the outskirts of the galaxy. The outskirts have lower metallicity and larger rotation speed than the center. This would shift the [O III]/H$\beta$ versus $\sigma_{\text{O III}}$ relation to higher [O III]/H$\beta$ and higher $\sigma_{\text{O III}}$. A better
constraint on the systematics is need to test the evolution in the $[O\text{ III}]/H\beta$ versus $\sigma_{[O\text{ III}]}$ relation from $z = 0$–0.8.

The narrow-line regions of high-redshift galaxies have lower metallicity than local AGNs (Kewley et al. 2013b), even local AGNs with the same host stellar mass (Coil et al. 2015). The lower metallicity would elevate $[O\text{ III}]/H\beta$ (Groves et al. 2006; Kewley et al. 2013a, 2013b; Feltre et al. 2016; Hirschmann et al. 2017). Considering that $[O\text{ III}]/H\beta$ of SFGs would increase in high-redshift galaxies, SFGs and AGNs will still be separated well in terms of $[O\text{ III}]/H\beta$ on the KEx diagram as shown in Figure 5.

6.4. Comparison of Different Narrow-line Widths

In the KEx diagram, we use the width of the $[O\text{ III}]$ emission line as a diagnostic. In order to check if different lines have different widths, in Figure 7 we plot the median value of $\sigma$ against $R$-band absolute magnitude and stellar mass for different narrow lines using galaxies from SDSS DR7. We plot the stellar velocity dispersion ($\sigma_*$) as a red line for reference. The PCA continuum fitting cannot give the stellar velocity directly. We use $\sigma_*$ stored in the SDSS spectrum file header. 32 giant K and G stars in M67 are used as stellar templates. These stellar templates are convolved with the velocity dispersion to fit the rest-frame wavelength range 4000–7000 Å by minimizing $\chi^2$. The final estimation is the mean value of the estimates given by the “Fourier-fitting” and “Direct-fitting” methods. We found that SFGs show similar $\sigma$ for all emission lines. The Type 2 AGNs, however, show some systematics in line width. The $[O\text{ III}]$ line is broader than other low-ionization lines and recombination lines. This is expected, because the $[O\text{ III}]$ emitting region is more concentrated due to its high ionization potential (Veilleux 1991; Trump et al. 2011b). Unexpectedly, $H\beta$ shows the smallest line width, and the discrepancy is largest for high luminosity and high stellar mass. One possible cause of this discrepancy is that the Balmer absorption fitting is not perfect. The incorrect absorption fitting affects the resulting emission line flux and profile. Groves et al. (2012) found a significant discrepancy in $H\beta$ when different versions of the continuum-fitting models were used. $H\alpha$, which should arise from the same emitting region as $H\beta$, does not follow the behavior of $H\beta$ but shows the same trend as low-ionization lines because the absorption correction is much milder.

When comparing the line width of emission lines and $\sigma_*$, we found that the difference between $\sigma_*$ in SFGs and Type 2 AGNs of similar stellar mass is very small. At high stellar masses, galaxies tend to have bulges, and the kinematics of a bulge would increase the measured $\sigma_*$. However, if the ionized gas in SFGs still comes from the disk, the velocity dispersion will not be affected by the bulge. Also, one can expect $\sigma_{\text{gas}} < \sigma_*$ because the gas is more dissipative than the stars and can slow down dynamically (Ho 2009). The excess velocity width of emission lines in AGN hosts relative to SFGs can be due to a combination of bulge kinematics, narrow-line region kinematics, and wind/outflows. For AGNs of low to intermediate luminosity (on average), the broadening from outflows may not be as strong as for more luminous quasars (e.g., Greene & Ho 2005). A final discrimination of the relative importance of the mechanisms for emission line broadening may require spatially resolved kinematics (e.g., Davies et al. 2016).

7. Summary and Conclusion

We propose a new diagram, the kinematics–excitation (KEx) diagram, using the $[O\text{ III}]/H\beta$ line ratio and the $[O\text{ III}]$ λ5007 emission line width ($\sigma_{[O\text{ III}]}$) to diagnose the emissions of AGNs and star-forming galaxies. The KEx diagram uses only the $[O\text{ III}]$ λ5007 and $H\beta$ emission lines, thus it is a suitable tool to classify emission line galaxies at higher redshift than more traditional line ratio diagnostics because it does not require the use of the [N II]/$H\alpha$ ratio. Using the main galaxy sample of SDSS DR7 and the BPT diagnostic, we calibrate the diagram at low redshift. We find that the diagram can be divided into three regions: one occupied mainly by pure AGNs (KEx-AGN region), one dominated by composite galaxies (KEx-composite region), and one containing mostly SFGs (KEx-SFG region). The new diagram is very efficient for selecting AGNs with high completeness and low contamination rate. We further apply the KEx diagram to 7866 galaxies at $0.3 < z < 1$ in the DEEP2 Galaxy Redshift Survey, and compare the KEx classification to an independent X-ray classification using Chandra observations. Almost all Type 1 AGNs at $z < 0.8$ lie in the KEx-AGN region, confirming the reliability of this classification diagram for emission line galaxies at intermediate redshift. At $z \sim 2$, the demarcation line between star-forming galaxies and AGNs should be shifted to 0.3 dex higher $\sigma_{[O\text{ III}]}$ due to evolution.

AGNs are separated from SFGs in this diagram mainly because in addition to preferentially residing in luminous and massive galaxies, they show 0.15/0.12 dex higher $\sigma_{[O\text{ III}]}$ than star-forming galaxies at given luminosities/stellar masses. Higher $\sigma_{[O\text{ III}]}$ also arise from AGN-driven broadening effects (such as winds or outflows). When we push to higher redshift, the evolution of $[O\text{ III}]/H\beta$ and the TFR result in a shift of the dividing line between AGNs and SFGs. KEx needs high enough spectral resolution to measure $\sigma_{[O\text{ III}]}$, and this diagnostic diagram is purely empirical now because it is hard to link ionization and kinematics theoretically. Despite the caveats, it provides a robust diagnostic of ionization source when only [O III] and $H\beta$ are available. The KEx diagram would be a powerful tool for forthcoming spectroscopic surveys such as DESI and PFS to a redshift of about 1.2, and even to $z \sim 7$–10 with the advent of space-based NIR spectroscopes (e.g., James Webb Space Telescope). As we have discussed in this paper, the physical properties of high-redshift galaxies are different from those in the local universe. Their location on the KEx diagram would shift. It will be interesting to see how the locations of SFGs and AGNs on the KEx diagram evolve. Conversely, the locations of galaxies on the KEx diagram could help to diagnose the physical properties of the ionized gas. It would be valuable to construct a galaxy model with realistic kinematics and ionization state to explore how locations on the KEx diagram are linked to variation of physical parameters such as rotation velocity, metallicity, temperature, density, and ionization parameters. A cluster of galaxies on the KEx diagram might hint at intrinsic correlations between these parameters.

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