ACTIVE GALACTIC NUCLEI IN FOUR METAL-POOR DWARF EMISSION-LINE GALAXIES

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ABSTRACT

We present 3.5 m Apache Point Observatory second-epoch spectra of four low-metallicity emission-line dwarf galaxies discovered serendipitously in Data Release 5 of the Sloan Digital Sky Survey (SDSS) to have extraordinarily large broad Hα luminosities, ranging from $3 \times 10^{41}$ to $2 \times 10^{42}$ erg s$^{-1}$. The oxygen abundance in these galaxies is very low, varying in the range $12 + \log O/H = 7.36$–$7.99$. Such extraordinarily high broad Hα luminosities cannot be accounted for by massive stars at different stages of their evolution. By comparing these with the first-epoch SDSS spectra, we find that the broad Hα luminosities have remained constant over a period of 3–7 yr, which probably excludes Type IIn supernovae as a possible mechanism of broad emission. The emission most likely comes from accretion disks around intermediate-mass black holes, with lower mass limits in the range $\sim 5 \times 10^5$–$3 \times 10^6 M_\odot$. If this is the case, these four objects form a new class of very low metallicity active galactic nuclei (AGNs) that have been elusive until now. The absence of the strong high-ionization lines [Ne v] λ3426 and He ii λ4686 can be understood if the nonthermal radiation contributes less than $\sim 10\%$ of the total ionizing radiation.

Subject headings: galaxies: abundances — galaxies: active — galaxies: irregular — galaxies: ISM — H ii regions — ISM: kinematics and dynamics

1. INTRODUCTION

Active galactic nuclei (AGNs) are thought to be powered by massive black holes at the centers of galaxies, accreting gas from their surroundings. Observations of AGNs show that they generally possess a high metallicity, varying from solar to supersolar metallicities (Storchi-Bergmann et al. 1998; Hamann et al. 2002). Although the derived metallicities do depend on detailed model assumptions, this appears to be a solid conclusion. Gas metallicity is known to be strongly correlated with the stellar mass of the host galaxy (Tremonti et al. 2004). Since AGNs are usually found in massive, bulge-dominated galaxies that have converted most of their gas into stars by the present epoch, their gas metallicities are generally high. A question then arises: Do low-metallicity AGNs exist? If so, can we find them in low-mass galaxies? To address these questions, Groves et al. (2006) have searched the Sloan Digital Sky Survey (SDSS) Data Release 4 (DR4) spectroscopic galaxy sample of over 500,000 objects to select out $\sim 170,000$ emission-line galaxies whose spectra have a high signal-to-noise ratio (S/N). They then use diagnostic line ratios to select out 23,000 Seyfert 2 galaxies. Imposing an upper mass limit of $10^{10} M_\odot$ to restrict themselves to low-mass galaxies, they are left with a sample of only $\sim 40$ AGNs, which they found to occur at lower metallicities around half that of typical AGNs, i.e., solar or slightly subsolar values. The same high-metallicity range is found in the sample of low-mass AGNs of Greene & Ho (2007). Assessing their findings, Groves et al. (2006) are led to another question: “Why are there no AGN with even lower metallicities?” In this paper, we suggest that these low-metallicity AGNs do exist, although they are extremely rare.

In the course of a long-range program to search for extremely metal-deficient emission-line dwarf galaxies, Izotov et al. (2007a) have used the SDSS DR5 database of 675,000 spectra to assemble a large sample of emission-line galaxies. Two criteria were applied: (1) the [O iii] λ4363 line must be detected to allow for a direct determination of element abundances, and (2) obvious high-metallicity AGN spectra are excluded. Thus, unlike Groves et al. (2006) and Greene & Ho (2007), Izotov et al. (2007a) were not specifically looking for AGNs. These criteria resulted in a sample of $\sim 10,000$ emission-line galaxies (ELGs). While studying that sample to look for ELGs with broad components in their strong emission lines, Izotov et al. (2007a) came across four galaxies with very unusual spectra. The general characteristics of the four galaxies are given in Table 1. Their absolute magnitudes are typical of dwarf galaxies. Because of their relatively large distance ($z \sim 0.1$–$0.3$) and relatively small angular sizes ($\sim 1''$–$2''$), only slightly larger than the seeing disk), their SDSS images (Fig. 1) do not show many details. They possess a compact structure. Two galaxies, J1025+1402 and J1047+0739, have an approximately round shape, while the other two more distant galaxies, J0045+1339 and J1222+3602, have a distorted shape suggestive of mergers. Their colors are not blue like the other ELGs, but vary from red to yellow to green. Their spectra, shown in Figure 2, resemble those of moderate- to very low metallicity, high-excitation H ii regions: their oxygen abundances are in the range 1. In fact, Izotov et al. (2007a) identified five objects as AGN candidates. We have not included here the fifth candidate, J2230–0006 ≈ PHL 293B, because its broad Hα luminosity is only $8.6 \times 10^{41}$ erg s$^{-1}$, some $10^{10}$–$10^{11}$ times lower than those of the other four AGN candidates. The broad Hα luminosity of J2230–0006 was erroneously given in Table 8 of Izotov et al. (2007a) as having 10 times its true value. Given this relatively low luminosity and the fact that a new 3.5 m APO spectrum of J2230–0006 shows that its broad hydrogen lines have a P Cygni profile with a blueshifted absorption, the broad emission probably originates from a stellar wind rather than from an accretion disk around an AGN. Most likely, the broad emission in J2230–0006 is caused by a strong outburst in a bright luminous blue variable (LBV) star. Similar broad hydrogen emission has been detected recently by Pursilnik et al. (2008) in the extremely metal-deficient dwarf galaxy DDO 68.
12 + \log O/H \sim 7.4–7.9; i.e., their heavy element mass fractions vary from $Z_{\odot}/19$ to $Z_{\odot}/5$ if the solar calibration $12 + \log O/H = 8.65$ of Asplund et al. (2005) is adopted. Izotov et al. (2007a) found that there is, however, a striking difference: the strong permitted emission lines, mainly the H$\alpha$ $\lambda6563$ line, show very prominent broad components. These are characterized by somewhat unusual properties.

1. Their H$\alpha$ full widths at zero intensity FWZI vary from 102 to 158 Å, corresponding to expansion velocities between 2200 and 3500 km s$^{-1}$.

2. Their broad H$\alpha$ luminosities $L_{br}$ are extraordinarily large, varying from $3 \times 10^{41}$ to $2 \times 10^{42}$ erg s$^{-1}$. This is to be compared

| Object          | R.A. (J2000.0) | Decl. (J2000.0) | Redshift | $g$  | $M_g$ |
|-----------------|---------------|----------------|----------|-----|------|
| SDSS J0045+1339| 00 45 29.2    | +13 39 09      | 0.29522  | 21.80 | -18.56 |
| SDSS J1025+1402| 10 25 30.3    | +14 02 07      | 0.10067  | 20.36 | -17.66 |
| SDSS J1047+0739| 10 47 55.9    | +07 39 51      | 0.16828  | 19.91 | -19.23 |
| SDSS J1222+3602| 12 22 45.7    | +36 02 18      | 0.30112  | 21.30 | -19.10 |

Note.—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.

Fig. 1.—13′′ × 13′′ SDSS images of low-metallicity AGNs. The angular diameters of the objects vary between 1′ and 2′, barely larger than the seeing disk.
with the range $10^{37}$–$10^{40}$ erg s$^{-1}$ found by Izotov et al. (2007a) for the other ELGs with broad-line emission. The ratio of Hα flux in the broad component to that in the narrow component varies from 0.4 to 3.4, as compared to 0.01–0.4 for the other galaxies.

3. The Balmer lines show a very steep decrement, suggesting collisional excitation and that the broad emission comes from very dense gas ($N_e \gg 10^4$ cm$^{-3}$). Evidently, these galaxies are exceedingly rare, since they constitute only 4/675,000, or 0.0006%, of our original sample.

To account for the broad-line emission in these four objects, Izotov et al. (2007a) considered various physical mechanisms: (1) Wolf-Rayet (WR) stars, (2) stellar winds from Ofp or luminous blue variable stars, (3) single or multiple supernova (SN) remnants propagating in the interstellar medium, (4) SN bubbles, (5) shocks propagating in the circumstellar envelopes of Type IIn SNe, and (6) AGNs. While mechanisms (1)–(4) can account for $L_{br} \sim 10^{38}$–$10^{41}$ erg s$^{-1}$, they cannot provide for luminosities that are 30 to 200 times greater. These very large luminosities are more likely associated with SN shocks or AGNs. Izotov et al. (2007a) considered Type IIn SNe because their Hα luminosities are greater ($\sim 10^{38}$–$10^{41}$ erg s$^{-1}$) than those of the other SN Types IIp and III, and they decrease less rapidly.

To decide whether Type IIn SNe or AGNs are responsible for the broad emission in these galaxies, it is necessary to monitor their spectral features on the relatively long timescale of several years. If broad features are produced by Type IIn SNe, then we would expect a decrease in the broad-line luminosities. No significant temporal evolution would be expected in the case of an AGN. In addition, higher S/N spectra are necessary to put better constraints on the presence of the high-ionization [Ne v] $\lambda 3426$ and He II $\lambda 4686$ emission lines, which are good indicators of a source of hard nonthermal radiation. In order to check for temporal evolution, we have obtained second-epoch spectra of the above four galaxies with broad emission using the 3.5 m Apache Point Observatory (APO) telescope. We describe the observations in §2. In §3, we discuss the main properties of the broad emission and show that they can be accounted for by low-metallicity, intermediate-mass AGNs. Our conclusions are summarized in §4.

2. OBSERVATIONS

New high-S/N optical spectra were obtained for the four galaxies listed in Table 1 using the 3.5 m APO telescope on the nights

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2 The Apache Point Observatory 3.5 m telescope is owned and operated by the Astrophysical Research Consortium.
of 2007 November 15 and 2008 February 6. The observations were made with the Dual Imaging Spectrograph (DIS) in both the blue and red wavelength ranges. A 1.5′′×360′′ slit was used. In the blue range, we used the B400 grating, with a linear dispersion of 1.83 Å pixel⁻¹ and a central wavelength of 4400 Å, while in the red range we used the R300 grating with a linear dispersion of 2.31 Å pixel⁻¹ and a central wavelength of 7500 Å. The above instrumental setup gave a spatial scale along the slit of 0.8′′ pixel⁻¹ on the night of 2007 November 15 and of 0.4′′ pixel⁻¹ on the night of 2008 February 6 (the latter scale is smaller by a factor of 2 than the previous one because we did not perform pixel binning for the latter spectra). The spectral range was −3600–9600 Å, and the spectral resolution was 7 Å (FWHM). The slit was oriented along the parallactic angle, and the total exposure time was 45 minutes for each galaxy. The observations were broken up into 3 subexposures to allow for removal of cosmic rays. The Kitt Peak spectrophotometric standard stars Feige 110 (2007 November 15), Feige 34, and G191B2B (2008 February 6) were observed for flux calibration. Spectra of He-Ne-Ar comparison arcs were obtained at the beginning of each night for wavelength calibration.

The data reduction procedures are the same as described in Thuan & Izotov (2005). The two-dimensional spectra were bias subtracted and flat-field corrected using IRAF. We then used the IRAF software routines IDENTIFY, REDIDENTIFY, FITCIRC, and TRANSFORM to perform wavelength calibration and correct for distortion and tilt for each frame. Night sky subtraction was performed using the routine BACKGROUND. The level of night sky emission was determined from the closest regions to the galaxy that are free of galaxian stellar and nebular line emission, as well as of emission from foreground and background sources. A one-dimensional spectrum was then extracted from the two-dimensional frame using the APALL routine. An extraction aperture of 1.5″×4″ was adopted. Its area is similar to that of the 3″ round aperture used in the SDSS spectra and allows us to gather ≥90% of the light of our compact galaxies. Comparison of the line intensities of the SDSS (Izotov et al. 2007a) and 3.5 m spectra (Table 2) shows that they agree well, validating our choice of the extraction aperture. Before extraction, the three distinct two-dimensional spectra of each object were carefully aligned using the spatial locations of the brightest part in each spectrum, so that spectra were extracted at the same positions in all subexposures. We then summed the individual spectra from each subexposure after manual removal of the cosmic-ray hits.

The resulting APO spectra of the four galaxies are shown in Figure 2. A strong broad Hα emission line is present in all spectra, very similar to the one seen in the SDSS spectra of the same galaxies obtained 3–7 yr earlier (Izotov et al. 2007a). The broad components in the Hβ emission line are considerably weaker, suggesting a steep Balmer decrement, and hence that the broad emission originates in a very dense gas. In the case of J1047+0739, broad He i is also present, as it is in the SDSS spectrum (Izotov et al. 2007a).

3. RESULTS AND DISCUSSION

3.1. Element Abundances

We have derived element abundances from the narrow emission-line fluxes. These fluxes were measured using Gaussian fitting with the IRAF SPLIT routine. They have been corrected for both extinction, using the reddening curve of Whitford (1958), and underlying hydrogen stellar absorption, derived simultaneously by an iterative procedure as described by Izotov et al. (1994) and using the observed decrements of the narrow hydrogen Balmer
Hβ λ4101, Hγ λ4340, Hβ λ4861, and Hα λ6563 lines. It is assumed in this procedure that hydrogen line emission is produced only by spontaneous transitions in recombination cascades; i.e., we neglect possible collisional excitation. Such a situation usually holds in low-density H II regions ionized by stellar radiation, such as those considered here. Izotov et al. (2007b) have shown that the use of different reddening curves has little influence on the extinction-corrected fluxes (relative to the Hα flux) in the optical range, and modify the extinction coefficient only slightly. The reason is that the spectra are corrected in such a way that the relative intensities of the extinction-corrected hydrogen lines correspond to their theoretical values. The extinction-corrected fluxes \(100 \times I(\lambda)/I(H/\beta)\) of the narrow lines for each galaxy, together with the extinction coefficient \(C(H/\beta)\), the equivalent width of the Hβ emission line \(EW(H/\beta)\), the observed H/β flux \(F(H/\beta)\), and the equivalent widths of the underlying hydrogen absorption lines \(EW(\text{abs})\), are given in Table 4. The physical conditions and element abundances of the H II regions in the four AGN candidates are derived from the narrow-line fluxes following Izotov et al. (2006). The element abundances derived from the 2.5 m SDSS spectra (Izotov et al. 2007a) and from the 3.5 m spectra (this paper) are shown in Table 3. We find that the abundances and the abundance ratios obtained for the four galaxies from the two sets of observations agree well. The derived abundances are in the range characteristic of low-metallicity dwarf emission-line galaxies (Izotov et al. 2006). This implies that the narrow emission lines arise primarily from regions ionized by stellar ionizing radiation, and that any contribution of a possible AGN component to the narrow-line emission is small.

### TABLE 3

| Object          | 2.5 m SDSS 12 + log O/H | 3.5 m APO 12 + log O/H |
|-----------------|------------------------|------------------------|
| J0045+1339...... | 7.94 ± 0.08            | 7.86 ± 0.05            |
| J1025+1402...... | 7.36 ± 0.08            | 7.48 ± 0.08            |
| J1047+0739...... | 7.99 ± 0.05            | 7.85 ± 0.02            |
| J1222+3602...... | 7.94 ± 0.09            | 7.88 ± 0.05            |

### TABLE 4

| Object          | 2.5 m SDSS 10^{-16} erg s^{-1} cm^{-2} | 3.5 m APO 10^{-16} erg s^{-1} cm^{-2} |
|-----------------|---------------------------------------|---------------------------------------|
| J0045+1339...... | 16.4 ± 1.7                            | 18.0 ± 0.7                            |
| J1025+1402...... | 165.0 ± 5.7                           | 192.5 ± 0.8                           |
| J1047+0739...... | 289.2 ± 9.1                           | 224.2 ± 2.1                           |
| J1222+3602...... | 16.1 ± 1.8                            | 22.4 ± 1.3                            |

* Flux errors are derived taking into account photon statistics in non-flux calibrated spectra.

3.2 Broad Emission and Diagnostic Diagrams

Using Gaussian fitting, we measured the fluxes of the broad component of the Hα line after subtraction of the narrow component. These fluxes are shown in Table 4. A comparison of SDSS and APO broad Hα fluxes shows that they have remained nearly constant (with variations ≤20%) over a period of ~3–7 yr. This likely rules out the hypothesis that the broad-line fluxes are due to Type IIb SNe, because their Hα fluxes should have decreased significantly over this time interval. There is one known exception, SN 1996er, where the Hα flux has remained constant for 7 yr (Bauer et al. 2008), although in that case the Hα luminosity is only ~10^{38} erg s^{-1}. Maintaining an Hα luminosity of 10^{41}–10^{42} erg s^{-1} for such durations in our objects would require nearly the entire energy budget of a SN (>10^{50}–10^{51} erg). We thus rule out Type IIb SNe.

There remains the AGN scenario. Can accretion disks around black holes in these low-metallicity dwarf galaxies account for their spectral properties? The spectra of the four objects do not show clear evidence for the presence of an intense source of hard nonthermal radiation: the [Ne v] λ3426, [O iv] λ3727, He ii λ4686, [O iii] λ5007, [Ne v] λ3426, and [S ii] λ6716, 6731 emission lines, which are usually found in the spectra of AGNs, are weak or not detected. However, aside from He ii λ4686, the apparent weakness of such emission lines may be accounted for by the low metallicities of our galaxies. None of our objects were detected in the NVSS or FIRST radio catalogs, demonstrating that they are faint radio sources. Another way to check for the presence of an AGN in a galaxy is to check for its location in the emission-line diagnostic diagram of Baldwin et al. (1981) (hereafter “BPT diagram”). It can be seen in Figure 3a that all four objects lie in the region corresponding to star-forming galaxies (SFGs), to the left of the region occupied by AGNs with low-mass black holes and with metallicities ranging from 2 to 1/4 solar (Greene & Ho 2007). However, their locations in the SFG region do not necessarily disqualify them as AGN candidates. Photoionization models of AGNs show that lowering their metallicity moves them to the left of the BPT diagram, so that they end up in the SFG region (Groves et al. 2006; Stasińska et al. 2006). Thus, the BPT diagram is unable to distinguish between SFGs and low-metallicity AGNs.

If we assume that there is an AGN in our dwarf galaxies, can we account for the weakness of the high-ionization lines? Photoionization models with only AGN nonthermal ionizing radiation do predict detectable He ii λ4686 and [Ne v] λ3426 emission lines. To make the observed spectra agree with the models, one solution is to dilute the nonthermal ionizing radiation from the AGNs with thermal radiation from surrounding hot massive stars.
In Figure 3a, we show the results of our CLOUDY calculations (Ferland 1996; Ferland et al. 1998) of H α regions ionized by a composite radiation consisting of different proportions of stellar and nonthermal radiation. Two curves, characterized by different metallicities, are shown by solid lines. The lower one represents 12 + log O/H = 7.3, and the upper one represents 12 + log O/H = 7.8, which are typical values of the metallicities of our objects. Each model point is labeled by the ratio R of nonthermal to thermal ionizing radiation. A slope α = −1 has been adopted for the nonthermal power-law spectrum over the whole wavelength range under consideration (fν ∝ ν^n). The calculations were done with a number of ionizing photons Q_hα = 10^{53} s^{-1} for stellar radiation, Q_nonth = RQ_hα for nonthermal radiation, and N_e = 10^4 cm^{-3}. Higher densities would move the curves to the right. For the ionizing stellar radiation, we adopt Costar models by Schaerer & de Koter (1997), with a heavy element mass fraction Z = 0.004 and an effective temperature of 53,000 K, corresponding to a starburst age of ≲3 Myr. The dotted lines in Figure 3a represent the corresponding models with α = −2. They are very similar to the models with α = −1 when R ≤ 1, but fall below for R ≥ 1. It is seen that models with 12 + log O/H = 7.8 and in which the nonthermal ionizing radiation contributes ≤10% of the total ionizing radiation can account well for the location of all four galaxies in the BPT diagram, independently of the slope of the power-law spectrum.

What about the high-ionization lines? Can their absence be due to high dust extinction in the central part of the galaxy? We consider this possibility unlikely because in this case, broad Hα emission from the accretion disk surrounding the black hole would not be seen either. We turn next to the properties of the ionizing spectrum for an explanation. In Figure 3b, we show the diagnostic diagram for [Ne v] λ3426/Hβ versus [N ii] λ6583/Hα (thick lines) and He ii λ4686/Hβ versus [N ii] λ6583/Hα (thin lines). As in Figure 3a, CLOUDY models with α = −1 and −2 are shown by solid and dotted lines, respectively. They are also characterized by Q_bα = 10^{53} s^{-1} for stellar radiation, Q_nonth = RQ_hα for nonthermal radiation, and N_e = 10^4 cm^{-3}. Higher densities would shift curves to the right. The vertical dashed line separates models with 12 + log O/H = 7.3 (Fig. 3b, left) from those with 12 + log O/H = 7.8 (Fig. 3b, right). The shaded rectangle shows the region of the upper limits of ~1%~2% of the Hβ flux, set for [Ne v] λ3426/Hβ and He ii λ4686/Hβ in our objects, in the observed range of their [N ii] λ6583/Hα ratio.

There are several points to be made concerning Figure 3b. First, in contrast to the low-ionization line fluxes (Fig. 3a), the predicted fluxes of the high-ionization lines are more strongly dependent on the slope of the power-law spectrum of the nonthermal radiation. Second, while there is no significant change of the predicted fluxes of the He ii λ4686 emission line with metallicity, the predicted flux of the [Ne v] λ3426 line linearly scales with 12 + log O/H. Third, at a given metallicity, the detectability of the high-ionization lines depends on two parameters: one is the ratio R of nonthermal to thermal ionizing radiation, and the other is the slope of the power-law ionizing spectrum. If we adopt 12 + log O/H = 7.8 as typical for our galaxies, then Figure 3b shows that models that satisfy the nondetectability limit of the high-ionization lines, i.e., that fall within the shaded box) are characterized either by a steep slope and a not excessively small R (α = −2 and R ∼ 0.1) or by a shallower slope and a very low R (α = −1 and R ∼ 0.03). We expect intermediate-mass black holes to have accretion disks that are hotter than those around supermassive black holes, and hence their ionizing spectrum to have a shallower slope, closer to −1 than −2. If that is the case, then the fraction of ionizing nonthermal to thermal radiation is very small in our dwarf galaxies, ~3%. It is also possible that the absence of strong high-ionization lines is caused by a high
covering factor of the accretion disk. In this case, the hard radiation would be absorbed inside the dense accretion disk, and no high-ionization forbidden lines would be formed.

3.3. Black Hole Virial Masses

We now estimate the masses of the central black holes. It has been shown (see e.g., Kaspi et al. 2000) that continuum and broad-line luminosities in AGNs can be used to determine the size and geometry of the broad emission-line region and the mass of the central black hole. Examining a large sample of broad-line AGNs, Greene & Ho (2005) found that the Hα luminosity scales almost linearly with the optical continuum luminosity, and that a strong correlation exists between the Hα and Hβ line widths. On the basis of these two empirical correlations, those authors have derived the following relations for the central black hole mass:

\[
M_{\text{BH}} = 2.0 \times 10^6 \left( \frac{L_{\text{H}\alpha}}{10^{42} \text{ erg s}^{-1}} \right)^{0.55} \left( \frac{\text{FWHM}_{\text{H}\alpha}}{10^3 \text{ km s}^{-1}} \right)^{2.06} M_\odot, \tag{1}
\]

and

\[
M_{\text{BH}} = 4.4 \times 10^6 \left( \frac{L_{5100}}{10^{42} \text{ erg s}^{-1}} \right)^{0.64} \left( \frac{\text{FWHM}_{\text{H}\beta}}{10^3 \text{ km s}^{-1}} \right)^{2} M_\odot, \tag{2}
\]

where \(L_{\text{H}\alpha}\) and \(L_{5100}\) are respectively the broad Hα and continuum (at \(\lambda = 5100 \text{ Å}\)) luminosities, and \(\text{FWHM}_{\text{H}\alpha}\) and \(\text{FWHM}_{\text{H}\beta}\) are respectively the full widths at half-maximum of the Hβ and Hα emission lines.

In Table 5, we list the extinction-corrected broad Hα luminosities \(L(\text{H}\alpha)\) and continuum luminosities \(L(L_{5100})\) for the four galaxies, as derived from the SDSS spectra. The extinction coefficient is set equal to the one derived for the narrow Balmer hydrogen lines. Since the reddening due to dust extinction in dense regions may be larger than that derived from the narrow hydrogen emission lines, the derived \(L(\text{H}\alpha)\) values should be considered as lower limits. The \(L(\text{H}\alpha)\) and \(L(L_{5100})\) of our galaxies closely follow the correlation between Hα and continuum luminosities found by Greene & Ho (2005). This implies that our galaxies are very likely the same type of objects as those considered by Greene & Ho (2005). Therefore, we can use equations (1)–(2) for the determination of the central black hole masses. For the flux and luminosity determinations, we first fit the line profiles by a single Gaussian. However, we find that single-Gaussian fits do not reproduce well the broad low-intensity wings of the Hα line. This suggests that the line broadening is caused not only by gas motions but also by light scattering. This hypothesis is supported by a steep Balmer decrement (the Hα-to-Hβ flux ratio is greater than ~7 in our four galaxies), implying high gas densities and possibly high optical depths in the Hα line. Therefore, in addition to a single-Gaussian profile fit, we have also fitted the Hα line by a Voigt profile, which is a superposition of both a Gaussian profile and a Lorentzian profile. The FWHM is that of the Gaussian profile.

4. CONCLUSIONS

We have studied the broad-line emission in four low-metallicity star-forming dwarf galaxies with \(12 + \log \text{O/H} \sim 7.4–8.0\), i.e., with metallicities between 1/19 and 1/5 that of the Sun. We have arrived at the following conclusions.

1. The steep Balmer decrements of the broad hydrogen lines and the very high luminosities of the broad Hα line in all four galaxies \((3 \times 10^{41}–2 \times 10^{42} \text{ erg s}^{-1})\) suggest that the broad emission arises from very dense and high-luminosity regions, such as those associated with Type IIa SNe or with accretion disks around black holes. However, the relative constancy of the broad Hα luminosities over a period of \(3–7\) yr likely rules out the SN mechanism. Thus, the emission of broad hydrogen lines is most likely associated with accretion disks around black holes. If so, these four objects would harbor a new class of AGNs that are extremely rare (in 0.0006% of all galaxies). These AGNs would be intermediate-mass black holes residing in low-metallicity dwarf galaxies, with an oxygen abundance that is considerably lower than the solar or supersolar metallicity of a typical AGN.

2. There is no obvious spectroscopic evidence for the presence of a source of a nonthermal hard ionizing radiation in all four galaxies. High-ionization emission lines such as He ii \(\lambda 4686\) and

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**Table 5**

| OBJECT                  | \(L_{\text{H}\alpha}\) (erg s\(^{-1}\)) | Gaussian\(^a\) (km s\(^{-1}\)) | Voigt\(^b\) (km s\(^{-1}\)) | \(\lambda L_{5100}\) (erg s\(^{-1}\)) | \(M_{\text{BH}}(\text{H}\alpha)\) (M\(_\odot\)) | \(M_{\text{BH}}(5100)\) (M\(_\odot\)) |
|-------------------------|------------------------------------------|---------------------------------|-------------------------------|--------------------------------------|----------------------------------|----------------------------------|
| J0045+1339              | \(2.74 \times 10^{41}\)                  | 1700                            | 1540                          | \(7.59 \times 10^{42}\)             | \(2.43 \times 10^6\)             | \(2.00 \times 10^6\)             |
| J0125+1402              | \(3.21 \times 10^{41}\)                  | 1580                            | 680                           | \(3.62 \times 10^{42}\)             | \(5.07 \times 10^5\)             | \(2.50 \times 10^5\)             |
| J1047+0739              | \(1.57 \times 10^{41}\)                  | 1920                            | 1050                          | \(2.32 \times 10^{43}\)             | \(3.05 \times 10^6\)             | \(1.91 \times 10^6\)             |
| J1222+3602              | \(2.80 \times 10^{41}\)                  | 1600                            | 790                           | \(7.17 \times 10^{42}\)             | \(6.34 \times 10^5\)             | \(5.10 \times 10^5\)             |

\(^a\) Parameters are derived from the 2.5 m SDSS spectra (Izotov et al. 2007a).

\(^b\) Derived by fitting a Gaussian profile.

\(^c\) Derived by fitting a Voigt profile, a combination of Gaussian and Lorentzian profiles. The FWHM is that of the Gaussian profile.
[Ne v] λ3426 were not detected at a level ≤1%-2% of the Hβ flux. We have calculated a series of CLOUDY models with ionizing spectra that include both thermal stellar and nonthermal power-law ionizing radiation in order to account for the absence of high-ionization lines. We find that the predicted fluxes of the high-ionization lines are below the detectability level if the spectral energy distribution $f_\nu \propto \nu^\alpha$ of the ionizing nonthermal radiation has $\alpha \sim -1$ and the nonthermal ionizing radiation is significantly diluted by thermal stellar ionizing radiation contributing ≤3% of the total ionizing radiation, or if the ionizing spectrum is steeper ($\alpha \sim -2$) and the nonthermal ionizing radiation contributes ≥10% of the total ionizing radiation.

3. The lower limits of the masses of the central black holes $M_{\text{BH}}$ of $\sim 5 \times 10^5 - 3 \times 10^6 M_\odot$ in our galaxies are among the lowest found thus far for AGNs.

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