MOSFIRE AND LDSS3 SPECTROSCOPY FOR AN [O\textsc{ii}] BLOB AT $z = 1.18$: GAS OUTFLOW AND ENERGY SOURCE

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ABSTRACT

We report our Keck/MOSFIRE and Magellan/Low-Dispersion Survey Spectrograph spectroscopy for an [O\textsc{ii}] Blob, O\textsc{ii} B 10, that is a high-$z$ galaxy with spatially extended [O\textsc{ii}] $\lambda\lambda 3726, 3729$ emission over 30 kpc recently identified by a Subaru large-area narrowband survey. The systemic redshift of O\textsc{ii} B 10 is $z = 1.18$ securely determined with [O\textsc{ii}] $\lambda\lambda 4959, 5007$ and H$\beta$ emission lines. We identify Fe\textsc{ii} $\lambda 2587$ and Mg\textsc{ii} $\lambda\lambda 2796, 2804$ absorption lines blueshifted from the systemic redshift by $80 \pm 50$ and $260 \pm 40$ km s\textsuperscript{-1}, respectively, which indicates gas outflow from O\textsc{ii} B 10 with the velocity of $\sim 80$–260 km s\textsuperscript{-1}. This outflow velocity is comparable with the escape velocity, $250 \pm 140$ km s\textsuperscript{-1}, estimated under the assumption of a singular isothermal halo potential profile. Some fraction of the outflowing gas could escape from the halo of O\textsc{ii} B 10, suppressing O\textsc{ii} B 10’s star-formation (SF) activity. We estimate a mass loading factor, $\eta$, that is a ratio of mass outflow rate to SF rate, and obtain $\eta > 0.8 \pm 0.1$, which is relatively high compared with low-$z$ starbursts including U/LIRGs and active galactic nuclei (AGNs). The major energy source of the outflow is unclear with the available data. Although no signature of AGNs is found in the X-ray data, O\textsc{ii} B 10 falls in the AGN/star-forming composite region in the line diagnostic diagrams. It is possible that the outflow is powered by SF and a type-2 AGN with narrow FWHM emission line widths of 70–130 km s\textsuperscript{-1}. This is the first detailed spectroscopic study of oxygen-line blobs that includes analyses of the escape velocity, the mass loading factor, and the presence of an AGN, and is a significant step to understanding the nature of oxygen-line blobs and the relation between gas outflow and SF quenching at high redshift.

Key words: galaxies: evolution – galaxies: formation – galaxies: high-redshift

Online-only material: color figures

1. INTRODUCTION

Galactic outflows are thought to play a significant role in galaxy formation and evolution. Theoretical studies to reproduce the observed luminosity function of galaxies have claimed the need for physical mechanisms that are able to modulate the efficiency of star formation (SF; e.g., Cole et al. 2000; Springel & Hernquist 2003; Kerese et al. 2009, see also the review of Clarke & Oey 2002; Fujita et al. 2003; Gnedin et al. 2008; Yajima et al. 2009; Razoumov & Sommer-Larsen 2010).

Various observational studies have found evidence for the presence of galactic-scale outflows in local starburst galaxies, including dwarf galaxies (e.g., Lequeux et al. 1995; Heckman et al. 1997, 2001b; Schwartz & Martin 2004) and ultraluminous infrared galaxies (e.g., Heckman et al. 2000; Rupke et al. 2002; Martin 2005; Weiner et al. 2009). These outflows are mostly traced via the blueshifts of interstellar absorption lines with respect to the galaxy systemic redshifts. At high redshifts, outflows in star-forming galaxies have been identified by the detection of blueshifted interstellar absorption lines (e.g., Pettini et al. 2002; Shapley et al. 2003; Tremonti et al. 2007; Steidel et al. 2010; Heckman et al. 2011; Coil et al. 2011; Erb et al. 2012; Martin et al. 2012; Kornei et al. 2012; Jones et al. 2012; Hashimoto et al. 2013; Shibuya et al. 2014). Observational studies as well as theoretical studies have suggested that a critical star-formation rate (SFR) surface density of $\sim 0.1 M_\odot$ yr\textsuperscript{-1} kpc\textsuperscript{-2} exists to launch galactic-scale outflows (Heckman et al. 2002; Murray et al. 2011; Kornei et al. 2012). Outflows appear to be ubiquitous in both nearby and high-$z$ galaxies with such intense SF activities.

Although outflow signatures have been unambiguously detected in many systems, absorption line detections offer limited information on the spatial distribution of the outflowing gas. The spatial distribution of outflowing gas can be measured, if galactic outflows can be observed in the spatially extended emission. In fact, in the last fifteen years, a growing number of observational studies have reported their discoveries of extended H\textalpha Ly$\alpha$.
nebulae at high redshifts (e.g., Fynbo et al. 1999; Steidel et al. 2000, 2011; Frances et al. 2001; Palunas et al. 2004; Ohyama & Taniguchi 2004; Matsuda et al. 2004; Nilsson et al. 2006; Saito et al. 2006; Smith & Jarvis 2007; Yang et al. 2009; Ouchi et al. 2009; Matsuda et al. 2011; Prescott et al. 2012; Momose et al. 2014). Several mechanisms have been proposed to explain the extended Lyα nebulae including strong outflows driven by AGNs and/or SF (e.g., Taniguchi & Shioya 2000; Ohyama et al. 2003; Matsuda et al. 2004; Mori et al. 2004; Bower et al. 2004; Wilman et al. 2005; Colbert et al. 2006; Webb et al. 2009; Weijmans et al. 2010). However, photoionization by AGNs and/or an intense SF is also a plausible origin of the extended Lyα (e.g., Dey et al. 2005; Geach et al. 2009; Overzier et al. 2013). Since Lyα is a resonance line, the extensive distributions of Lyα emission may be produced by the resonance scattering of Lyα photons in the CGM (Laursen & Sommer-Larsen 2007; Hayes et al. 2011; Zheng et al. 2011; Dijkstra & Kramer 2012; Verhamme et al. 2012; Jees-Daniel et al. 2012). Conceivably, an inflowing gas stream into the dark matter halo could also contribute to the extended Lyα emission (e.g., Haiman et al. 2000; Fardal et al. 2001; Dekel & Birnboim 2006; Dijkstra et al. 2006; Dijkstra & Loeb 2009; Goerdt et al. 2010; Momose et al. 2014).

Unlike the resonant Lyα line, the spatially extended metal emission lines are more directly related to galactic outflows. Inspired by the method of Matsuda et al. (2004) who have conducted a systematic search for galaxies with extended Lyα emission, Yuma et al. (2013, hereafter Y13) have used wide and deep narrowband images of the Subaru/Suprime-Cam to systematically search for galaxies with extended emission of non-resonant metal lines. Y13 have identified 12 star-forming galaxies at $z \sim 1.2$ whose $\lambda 3726$, 3729 emissions extend over 30 kpc. These spatially extended $\text{[O II]}$-emitting galaxies, which they call “$\text{[O II]}$ blobs ($\text{OIIBs}$), offer a unique laboratory for investigating the physical properties of galactic-scale outflows, and give clues to understanding the role of the feedback in galaxy formation and evolution.

In Y13, three out of the 12 $\text{OIIBs}$ (O II 1, 4, and 8) have been spectroscopically observed in the optical wavelength. Y13 have reported that blueshifted interstellar absorption lines are detected in the rest-frame UV spectra of O II 1 and 4, which is indicative of outflows. Furthermore, Y13 have found that O II 1 is the largest and brightest in their sample, and classified O II 1 as a radio-quiet obscured type-2 AGN based on the detection of [Ne v] emission, a broad $\text{[O II]}$ line width, a high $\text{[O II]}$ equivalent width (EW), and the ratio of mid-infrared to radio fluxes. This indicates that the outflow and the spatially extended $\text{[O II]}$ emission of O II 1 would be powered by the AGN activity. However, the fraction of O II Bs with AGN signatures is unknown. Thus, it is not clear whether the extended $\text{[O II]}$ emission of the O II population and their possible outflows are mainly driven by their AGN activities or if they are powered by other energy sources such as SF.

In this study, we focus on O II 10 (R.A. = 2°17′32″53, decl. = −4°57′46″40), which was originally identified as an O II by Y13. We choose O II 10 as our target for two reasons. The first reason is that O II 10 is expected to have an outflow whose major heating source would be SF. In the available data of O II 10, no AGN signature is found. Moreover, O II 10 is one of the O II Bs with the highest specific star formation rate (SSFR). The second reason is that O II 10 is observed as a mask filler for the other program. We describe this observation in Section 3.1. The aim of this study is to characterize the properties of O II 10 based on our deep optical and near-infrared spectroscopic observations as well as archival multi-wavelength imaging data. These observational data enable us to examine whether an outflow is occurring in O II 10 and to investigate the physical origin of the extended $\text{[O II]}$ nebula of O II 10. This is the first detailed spectroscopic study of oxygen-line blobs that includes analyses of the escape velocity, the mass loading factor, and the presence of an AGN, and is a significant step toward understanding the nature of oxygen-line blobs and the relationship between gas outflow and SF quenching at high redshift.

This paper is organized as follows. We present the target selection and photometric data in Section 2. We describe Keck/MOSFIRE and Magellan/Low-Dispersion Survey Spectrograph (LDSS3) observations and data analyses in Section 3. The results are shown in Section 4. We discuss the nature of O II 10 in Section 5. Section 6 summarizes our findings. Throughout this paper, magnitudes are in the AB system, and we assume a standard ΛCDM cosmology with parameters of $(\Omega_m, \Omega_\Lambda, H_0) = (0.3, 0.7, 70$ km s$^{-1}$ Mpc$^{-1}$). In this cosmology, an angular dimension of 1.0 arcsec corresponds to a physical length of 8.32 kpc at $z = 1.18$.

2. TARGET SELECTION AND MULTI-WAVELENGTH IMAGING DATA

2.1. Target Selection for the Spectroscopic Observations

Y13 have identified twelve O II Bs using a catalog of $\text{[O II]}$ emitters at $z \sim 1.2$ (Drake et al. 2013). These $\text{[O II]}$ emitters show strong $\text{[O II]}$ emission lines falling into the narrowband filter $\text{NB816}$ with a central wavelength of 8150 Å and an FWHM of 120 Å. To select O II Bs from the normal $\text{[O II]}$ emitters, Y13 made the emission-line $\text{NB816}_{\text{corr}}$ image by subtracting a continuum-emission image from the $\text{NB816}$ image. The continuum-emission image, dubbed the “$R_z$ image,” is constructed from the $R$- and $z$-band images. Y13 define the isophotal area as pixels with values above the 2σ sky fluctuation (28 mag arcsec$^{-2}$ or $1.2 \times 10^{-18}$ erg s$^{-1}$ cm$^{-2}$ arcsec$^{-2}$) of the $\text{NB816}_{\text{corr}}$ image. Following the procedures in Matsuda et al. (2004), Y13 classify an object as a candidate of O II B if its isophotal area is above 13 arcsec$^2$ (corresponding to a spatial extent of 30 kpc at $z \sim 1.2$) in the $\text{NB816}_{\text{corr}}$ image. After visual inspection, 12 candidates are identified as O II Bs. More details are described in Y13. From the 12 O II Bs, we select O II B 10 as our target for the spectroscopic observations, because O II B 10 is expected to have an outflow driven by its SF activity. O II B 10 has no signature of AGN in the available data, and the SSFR of O II B 10 is relatively higher than those of other O II Bs. The isophotal magnitude and area of O II B 10 in the $\text{NB816}_{\text{corr}}$ image are 22.89 mag and 14 arcsec$^2$, respectively, as presented with the red diamond in Figure 1.

2.2. Multi-Wavelength Imaging Data and Stellar Population of O II B 10

Our target, O II B 10, is covered by deep optical and infrared imaging data from several ground and space-based surveys: the Subaru XMM-Newton Deep Survey (SXDS; Furusawa et al. 2008), the UKIDSS Ultra Deep Survey (UDS; Lawrence et al. 2007; Warren et al. 2007), and the Spitzer public legacy survey of the UKIDSS UDS (SpUDS; PI: J. Dunlop). Figure 2 shows

\footnote{Y13 detect no UV continuum of O II 8 due to the poor signal-to-noise ratio of their spectrum.}
the multi-wavelength images of O II B 10: the BVRiz images from the SXDS, the JHK images from the UKIDSS UDS, and the IRAC Ch1 (3.6 μm), Ch2 (4.5 μm), Ch3 (5.8 μm), Ch4 (8.0 μm), and MIPS 24 μm images from the SpUDS. We also present the NB816 Nob and Rz images produced by Y13. Although the Herschel SPIRE data are taken by the Herschel Multi-tiered Extragalactic Survey (Oliver et al. 2012) in this field, the image of O II B 10 is severely affected by source confusion. Hence, we do not use the SPIRE data.

The magnitudes in the BVRiz, JHK, 3.6 μm, and 4.5 μm bands are taken from Y13. In this study, we estimate the magnitudes of O II B 10 in the 5.8 μm, 8.0 μm, and 24 μm bands. We obtain the magnitudes of the 5.8 μm and 8.0 μm bands with MAG_AUTO of SExtractor (Bertin & Arnouts 1996). The magnitude of the 24 μm band is estimated from galfit (Peng et al. 2002) modeling, since O II B 10 is significantly blended with the three neighboring objects. We fit four objects, including O II B 10, with point-spread function profiles whose flux amplitudes and positions are free parameters. Table 1 summarizes the magnitudes of O II B 10 estimated from the multi-wavelength imaging data.

Y13 derived the stellar population properties of O II B 10 by fitting model spectral energy distributions (SEDs) with the observed SED (see Figure 3 of Y13). The model SEDs have been constructed with the Bruzual & Charlot (2003) stellar population synthesis code. Y13 assumed a constant SF history, the Salpeter (1955) initial mass function (IMF) with lower and upper cutoff masses of 0.1 and 100 M⊙, the dust attenuation law of Calzetti et al. (2000), and the solar metallicity. The SED fitting results are presented in Table 2. The color excess is E(B − V) = 0.31 ± 0.02, implying that O II B 10 is moderately dusty. The stellar age and the stellar mass are 270 ± 80 Myr and (1.6 ± 0.2) × 10^10 M⊙, respectively. The SFR is SFRSED = 72 ± 8 M⊙ yr⁻¹. Although we derive SFRs using different SFR indicators in Section 5.6, SFRSED is our best estimate of O II B 10’s SFR. This is because SFRSED does not strongly depend on the metallicity but includes the extinction correction. The SSFR

Table 1

| Band | Magnitude |
|------|-----------|
| B    | 23.78 ± 0.02 |
| V    | 23.42 ± 0.02 |
| R    | 23.23 ± 0.02 |
| i    | 22.90 ± 0.02 |
| z    | 22.44 ± 0.03 |
| J    | 22.05 ± 0.04 |
| H    | 21.76 ± 0.04 |
| K    | 21.39 ± 0.03 |
| m(3.6 μm) | 20.98 ± 0.02 |
| m(4.5 μm) | 21.09 ± 0.03 |
| m(5.8 μm) | 21.6 ± 0.3 |
| m(8.0 μm) | 21.9 ± 0.4 |
| m(24 μm) | 19.0 ± 0.7 |

Note. m(5.8 μm) and m(8.0 μm) are marginally detected at the 2–3 and 1–2σ levels, respectively.

Figure 1. Distribution of isophotal area and magnitudes in the NB816 Nob image. The isophotal area criterion (>13 arcsec²) is shown with the horizontal dashed line. The red diamond shows our target, O II B 10. The black diamonds represent the rest of the 11 O II Bs, and black crosses denote [O II] emitters found by Drake et al. (2013). The two black crosses above the dashed line are [O II] emitters that are not O II Bs, but objects with a large isophotal area made by source blending. (A color version of this figure is available in the online journal.)

Figure 2. Optical to mid-infrared images of O II B 10. We display 20" × 20" images at BVRizJHK, Spitzer/IRAC 3.6 μm, 4.5 μm, 5.8 μm, 8.0 μm, and Spitzer/MIPS 24 μm bands. We also show NB816 Nob and Rz images taken from Y13, which correspond to the [O II] and continuum emission images, respectively. The 5" scale bar is plotted at the bottom left in each image. The yellow contours in the NB816 Nob and Rz images show the isophotal area above 2σ arcsec⁻² in the NB816 Nob image as explained in Section 2.1. (A color version of this figure is available in the online journal.)
A radial profile of each line is estimated with the spatial distribution in the two-dimensional spectrum. We assume that the radial profile is identical in all directions, and calculate a correction factor to be 1.2. The $3\sigma$ limiting flux density is $\sigma \approx 5 \times 10^{-18} \text{ erg s}^{-1} \text{ cm}^{-2} \text{ Å}^{-1}$ in the wavelength range of 9800–11000 Å.

3. OBSERVATIONS AND DATA ANALYSES

3.1. MOSFIRE

We observed O III B 10 with the MOSFIRE instrument (McLean et al. 2012) on the Keck-I telescope on 2013 October 8 (PI: M. Ouchi). A spectrum of O III B 10 was obtained as a mask filler of this observation. We carried out $Y$-band spectroscopy that covered the wavelength range of 9800–11000 Å. Thus, this observation targeted H$\beta$ and [O III] $\lambda\lambda$4959, 5007 emission lines redshifted to $z \sim 1.2$. The slit width was 0′′.7. We used an ABAB dither pattern with individual exposures of 180 s. The total integration time was 2.4 hr, and the average seeing size to be 1.3 by the procedure same as Section 3.1. The $3\sigma$ flux density limit of the VPH-red spectrum is calculated to be $\sigma \approx 8 \times 10^{-18} \text{ erg s}^{-1} \text{ cm}^{-2} \text{ Å}^{-1}$ in the wavelength range of 6700–8600 Å.

3.2. LDSS3

We conducted deep spectroscopic observations for O III B 10 using the LDSS3 on the 6.5 m Magellan II (Clay) telescope on 2013 November 3 (PI: M. Rauch). We adopted a $0′′.8 \times 3′′.5$ slitlet, and used the volume phase holographic (VPH)-red grism with the Sloan-$i$ filter, which provided a spectral coverage from 6700 and 8600 Å. [O III] lines redshifted to $z \sim 1.2$ were targeted in this configuration. In addition, we took spectra with the VPH-blue grism and the w4800–7800 filter, which covered the wavelength range from 4800 Å to 6600 Å. This configuration targeted metal absorption lines such as Mg II and Fe II. The on-source exposure times with the VPH-red and VPH-blue configurations were 0.5 hr ($\sim 1 \times 1800$ s) and 2.5 hr ($\sim 3 \times 3000$ s), respectively. The average seeing size was $0′′.6$ in FWHM. The VPH-red (blue) grism had a spectral resolution of $R \sim 1710$ (1800). The LDSS3 instrument had a pixel scale of $0′′.189$ pixel$^{-1}$. Feige 110 was observed for our flux calibration.

The LDSS3 data are reduced by the Carnegie Observatories reduction package, cosmos. After bias subtraction, flat fielding, wavelength calibration, and rectification, one-dimensional spectra are extracted in the same manner as Section 3.1, except that the spectra are summed over 2′′/27 (12 pixels) along the spatial axis to cover about 95% emission. We estimate a slit-loss correction factor to be 1.3 by the procedure same as Section 3.1.

4. RESULTS

4.1. MOSFIRE

Figure 3 shows our MOSFIRE spectra at the wavelengths of [O III] and H$\beta$. We detect strong [O III] and H$\beta$ emission lines. These lines appear to have two components. Hereafter, we call...
the shorter-wavelength component “the blue component,” and
the longer-wavelength component “the red component.” The red
components appear to be spatially more extended than the blue
components. The implications of these two-component profiles
and the spatial extents are discussed in Section 5.9. The two-
component $H\beta$ line is fitted with two Gaussian functions. The
$[O\text{ III}]$ lines are the doublet lines, and each of the doublet lines
has the blue and red components. Hence, we fit the $[O\text{ III}]$ lines
with four Gaussian functions, assuming that each component of
the $[O\text{ III}]$ doublet lines has the same line width.

The results of the spectral line fittings are presented in Table 3.
The redshift of the blue (red) component of $[O\text{ III}]$ lines is in
agreement with that of the blue (red) component of $H\beta$ line
within the $\sigma$ uncertainties. We derive the average redshifts of
the blue and red components to be $z_{B} = 1.1795 \pm 0.0003$ and
$z_{R} = 1.1806 \pm 0.0004$, respectively, from the $H\beta$ and $[O\text{ III}]$ lines. The velocity difference derived from $z_{B}$ and $z_{R}$
is $170 \pm 50$ km s$^{-1}$. The average redshift of all components is
$z_{\text{sys}} = 1.1800 \pm 0.0002$, and we define this average value as the
systemic redshift of O II B 10.

The estimated FWHM line widths are also summarized in Table 3. These FWHM line widths are corrected for the instrumental broadening on the assumption that their intrinsic profiles are Gaussian. The FWHM line widths of the $[O\text{ III}]$ lines are comparable to those of the $H\beta$ line within the $\sigma$ uncertainties. The average FWHM line widths of blue
and red components are $\langle \text{FWHM}_B \rangle = 90 \pm 50$ km s$^{-1}$ and
$\langle \text{FWHM}_R \rangle = 120 \pm 40$ km s$^{-1}$, respectively.

We correct the fluxes for reddening by adopting the Calzetti et al. (2000) extinction law and $E(B - V) = 0.31$ mag presented
in Table 2. The fluxes after the dust-extinction correction are shown in Table 3.

4.2. LDSS3

Figure 4 presents our LDSS3 VPH-red grism spectrum at the
wavelength of $[O\text{ II}]$. We identify $[O\text{ II}]$ emission lines at the high
significance level. In contrast to the MOSFIRE spectra of the $H\beta$
and $[O\text{ III}]$ lines, the LDSS3 spectrum of the $[O\text{ II}]$ line does not
show two components but one component. The non-detection
of the blue and red components of the $[O\text{ II}]$ doublet lines is due to
the low resolution of the LDSS3 VPH-red data. The resolution of
the LDSS3 VPH-red data ($R \sim 1710$) is lower than that of the
MOSFIRE data ($R = 3388$), and the velocity difference of
$170 \pm 50$ km s$^{-1}$ (Section 4.1) is not resolved in the LDSS3 data.
Thus, each of the doublet lines has a one-component profile, and
we fit $[O\text{ II}]$ doublet lines with two Gaussian functions.

Table 3

| Line        | $z_{B/\text{II}}$ | $f_{\text{obs}}^{\text{B}}$ | $f_{\text{obs}}^{\text{R}}$ | $f_{\text{B}}^{\text{sys}}$ | $f_{\text{R}}^{\text{sys}}$ | FWHM$_{\text{B}}$/FWHM$_{\text{R}}$ |
|------------|------------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| $[O\text{ II}]\lambda3726$ | $1.1800 \pm 0.0007^a$ | $35.3 \pm 11.6$ | $6.5 \pm 1.8$ | $\ldots$ | $\ldots$ | $120 \pm 60^a$ |
| $[O\text{ II}]\lambda3729$ | $1.1800 \pm 0.0007^a$ | $37.5 \pm 11.6$ | $6.9 \pm 1.8$ | $\ldots$ | $\ldots$ | $120 \pm 60^a$ |
| $H\beta$ | $1.1794 \pm 0.0004/1.1807 \pm 0.0007$ | $53.2 \pm 12.3$ | $14.3 \pm 2.6$ | $3.5 \pm 1.8$ | $10.8 \pm 1.9$ | $70 \pm 50/130 \pm 50$ |
| $[O\text{ III}]\lambda4959$ | $1.1797 \pm 0.0007/1.1806 \pm 0.0005$ | $26.9 \pm 6.8$ | $7.4 \pm 1.5$ | $3.4 \pm 1.0$ | $4.1 \pm 1.0$ | $120 \pm 100/100 \pm 50$ |
| $[O\text{ III}]\lambda5007$ | $1.1797 \pm 0.0007/1.1806 \pm 0.0005$ | $90.2 \pm 21.2$ | $25.2 \pm 4.5$ | $10.3 \pm 3.1$ | $15.0 \pm 3.1$ | $120 \pm 100/100 \pm 50$ |

Notes. All fluxes and FWHM line widths are in units of $10^{-17}$ erg s$^{-1}$ cm$^{-2}$ and km s$^{-1}$, respectively. All FWHM line widths are corrected for the instrumental broadening. The columns are as follows. (1) Redshifts for the blue ($z_{B}$) and red ($z_{R}$) components. (2) Total flux of two components after the slit-loss and dust-extinction corrections. (3) Total flux of the two components corrected only for the slit loss. (4) and (5) Fluxes of blue ($f_{\text{B}}$) and red ($f_{\text{R}}$) components after the slit-loss correction. (6) FWHM line widths of the blue (FWHM$_{\text{B}}$) and red (FWHM$_{\text{R}}$) components.

$^a$ The blue and red components of the $[O\text{ III}]$ lines are not resolved.
offsets of Mg~ii~ are identified at the 5.5 and 2.7 levels, respectively. In the top panels, black lines represent spectra of O~ii~ B 10 and red lines denote the best-fit functions. The velocity offsets of Mg~ii~ 2796, 2804 and Fe~ii~ 2587 lines from the systemic velocity are $\Delta v = -260 \pm 40 \text{ km s}^{-1}$ and $\Delta v = -80 \pm 50 \text{ km s}^{-1}$, respectively. The bottom panels show the background sky spectra. The units of the vertical axes are arbitrary.

(A color version of this figure is available in the online journal.)

### Table 4

| Line             | EW (Å)      | $\Delta v$ (km s$^{-1}$) | FWHM (km s$^{-1}$) |
|------------------|-------------|--------------------------|-------------------|
| Mg~ii~ λ2796     | -2.6 ± 0.7 | -260 ± 40                | 240 ± 110         |
| Mg~ii~ λ2803     | -3.1 ± 0.7 | -260 ± 40                | 240 ± 110         |
| Fe~ii~ λ2587     | -3.0 ± 1.1 | -80 ± 50                 | 180 ± 120         |

**Notes.** Columns—1: rest-frame equivalent width, 2: velocity offset from the systemic redshift, and 3: FWHM line width corrected for the instrumental broadening.

### 5. DISCUSSION

#### 5.1. Signature of Outflow

In Section 4.2, we identify the Mg~ii~ λ2796, 2804 and Fe~ii~ λ2587 absorption lines blueshifted by $|\Delta v| = 260 \pm 40 \text{ km s}^{-1}$ and $|\Delta v| = 80 \pm 50 \text{ km s}^{-1}$, respectively. These blueshifted absorption lines are evidence of outflows, because blueshifted photons are absorbed by the outflowing gas along the line of sight to the stars. From the blueshifted Mg~ii~ and Fe~ii~ absorption lines, the outflow velocities are estimated to be 260 ± 40 and 80 ± 50 km s$^{-1}$, respectively. The difference of these outflow velocities may be significant; the implications of this difference are discussed in Section 5.3. Rupke et al. (2005a, 2005b) suggest that outflow velocities of O~ii~ driven winds are 20–500 km s$^{-1}$, while those of galaxies hosting AGNs are 70–600 km s$^{-1}$.

Thus, the low outflow velocity of O~ii~ starburst galaxy at z = 0.69 would be dusty.

In some galaxy spectra, the Mg~ii~ doublet emission in a starburst galaxy at z = 0.69 whose rest-frame EW is 3.6 Å. Assuming this EW, we can exclude the presence of the Mg~ii~ doublet emission in our LDSS3 VPH-blue data at the 3.6σ level. Weiner et al. (2009) suggest that the Mg~ii~ emission could be a weak AGN activity signature and/or backscattered light in the outflow. They report that blue and low-mass star-forming galaxies have Mg~ii~ emission lines stronger than red and high-mass star-forming galaxies. Martin et al. (2012) present the same trend, and suggest that this trend may be attributed to dust attenuation. Massive and red star-forming galaxies are dusty, and Mg~ii~ photons are absorbed by dust grains in the foreground gas. Thus, the non-detection of the Mg~ii~ emission line in our spectrum implies that O~ii~ B 10 would be dusty.

#### 5.2. Outflow Rate and Mass Loading Factor

Following the procedures of Rubin et al. (2010), we estimate the column density of the outflowing gas with the ratio of the Mg~ii~ doublet lines, $E_W(2796)/E_W(2803)$, varies from two to one for optical depth, $\tau_0$, increasing from zero to infinity. The Mg~ii~ doublet ratio is approximately equal to $F(2\tau_0)/F(\tau_0)$, where $F(\tau_0)$ is given by

$$F(\tau_0) = \int_0^\infty (1 - e^{-\tau_0} \exp(-x^2)) dx.$$  

(1)

After the doublet ratio is estimated, we numerically derive $\tau_0$. Once $\tau_0$ is given, we calculate the column density in atoms, $N(\text{Mg~ii})$, using the equation from Spitzer (1968):

$$\log N(\text{Mg~ii}) = \log \frac{|E_W(2803)|}{\lambda} - \log \frac{2F(\tau_0)}{\pi^{1/2} \tau_0} - \log \lambda f_{2803} - \log C_1 + 20.053,$$

(2)

where $\log \lambda f_{2803} = 2.933$ and $C_1$ is the covering fraction. Here we assume $C_1 = 1$. The EW ratio, $E_W(2796)/E_W(2803)$ of O~ii~ B 10 is 0.86 ± 0.30, whose best-estimate value is smaller than unity. If we adopt the 1σ upper limit of the EW ratio, $E_W(2796)/E_W(2803) = 1.16$, we obtain $\tau_0 = 5.9$, which corresponds to the 1σ lower limit. This 1σ lower limit yields $N(\text{Mg~ii}) > 4.9 \times 10^{14} \text{ cm}^{-2}$. We assume $N(\text{Mg~ii}) = N(\text{Mg})$ and the abundance ratio of $\log(\text{Mg/H}) = -4.35$. The abundance ratio is derived from the metallicity of O~ii~ B 10, 12 + log[O~ii~/H] = 8.97, estimated in Section 5.7. We adopt an Mg depletion onto dust of −1.3 dex, that is taken from Jenkins (2009) with an assumption of $n(\text{H}) \sim 1 \text{ cm}^{-3}$. The column density of hydrogen is estimated to be $N(\text{H}) > 2.2 \times 10^{20} \text{ cm}^{-2}$. It should be noted that Equation (2) can be applied in the case of one absorbing cloud, but that this equation has also been shown to work adequately for the optical depth $\tau_0 < 5$. Because the calculated optical depth is $\tau_0 > 5.9$, this column density estimate would include some systematic uncertainties.

We calculate a mass outflow rate, $\dot{M}$, assuming a thin shell geometry. Weiner et al. (2009) give the mass outflow rate,

$$\dot{M} \simeq 22 M_\odot \text{ yr}^{-1} C_f \frac{N(\text{H})}{10^{20} \text{ cm}^{-2}} \frac{R}{5 \text{ kpc}} \frac{v}{300 \text{ km s}^{-1}},$$

(3)
where $R$ and $v$ are the radius of the shell wind and the outflow velocity, respectively. We adopt $R \sim 7.8$ kpc, which is half of the spatial extent of the [O II] emission in the N88B16$_{\mathrm{core}}$ image. If we take $v = 220 \pm 30$ km s$^{-1}$ as the average of the outflow velocities derived from Mg II and Fe II lines, the mass outflow rate is estimated to be $M > 55 \pm 6 M_\odot$ yr$^{-1}$. The error of the mass outflow rate only includes the uncertainty of the average outflow velocity.

A mass loading factor, $\eta$, characterizes a relation between a mass outflow rate and an SFR, and is defined as $\eta = M/\mathrm{SFR}$. This mass loading factor serves as a critical function in models of galaxy evolution. Hopkins et al. (2012) predict mass loading factors of 0.5–2 in SF-driven winds by the theoretical study. Observationally, the mass loading factors of AGNs and non-AGN U/LIRGs are estimated to be $\eta = 0.1$–1.1 and $\eta = 0.02$–0.6, respectively (Arribas et al. 2014; corrected for the Salpeter IMF). Rupke et al. (2005c) report the mass loading factors of starburst-dominated galaxies to be $\eta = 0.01$–1. Using the mass outflow rate lower limit and the SFR$_{\mathrm{SED}}$ for O B 10, we estimate the mass loading factor of O B 10 to be $\eta > 0.8 \pm 0.1$. This mass loading factor is relatively high compared with those of the galaxies of Arribas et al. (2014) and Rupke et al. (2005c).

### 5.3. Difference of the Velocities of Mg II and Fe II

The outflow velocities derived from Mg II and Fe II absorption lines are 260 ± 40 and 80 ± 50 km s$^{-1}$, respectively. Although this difference may not be true due to the marginal 2.7σ detection of the Fe II line (Section 4.2), the difference of these two velocities could be explained by three possibilities. The first possibility is emission filling. As the Mg II transitions are resonantly trapped, these absorption lines are affected by filling from resonance emission lines. This resonance emission is generated by the foreground gas of the outflow. The resonance emission fills the absorption near the systemic redshift. This emission filling shifts the centroid of Mg II absorption to a bluer wavelength (e.g., Weiner et al. 2009; Kornei et al. 2012; Martin et al. 2012, 2013). However, we cannot conclude whether the emission filling occurs or not, because of the limited signal-to-noise ratio.

The second possibility is the difference of their oscillator strengths, as discussed in Kornei et al. (2012). Ionization potentials of Mg (15.0 eV) and Fe (16.1 eV) are nearly the same, while the oscillator strengths are different. The oscillator strength of the Mg II line at 2796 Å ($f_{\odot} = 0.60$) is larger than that of the Fe II line at 2587 Å ($f_{\odot} = 0.07$). This difference indicates that Mg II is optically thick at a low density where Fe II is optically thin. Because of the large cross-section for absorption, Mg II is a tracer of the low-density gas better than Fe II. Note that such low-density gas is found far from galaxies, and that the speed of the galactic wind increases with increasing galactocentric radius (e.g., Martin & Bouché 2009; Steidel et al. 2010; Dalla Vecchia & Schaye 2012). This physical picture explains that the velocity offset of the Mg II absorption line is larger than that of the Fe II line.

The third possibility is the Fe II absorption made by a foreground galaxy. In Section 4.1, we detect the two-component emission lines in our MOSFIRE spectrum. If O B 10 is a galaxy merger, the two components correspond to two merging galaxies. The velocity offset of the blue component is $-70 \pm 50$ km s$^{-1}$, comparable to that of the Fe II absorption.

### 5.4. Can the Outflowing Gas Escape from O B 10?

Comparing the outflow velocity with the local escape velocity, we examine whether the outflowing gas can escape from the gravitational potential of O B 10. Following the study of Weiner et al. (2009), we estimate the escape velocity, $v_{\mathrm{esc}}$, at $r$ (see also Rubin et al. 2010; Martin et al. 2012). Under the assumption of a singular isothermal halo truncated at $r_h$, the escape velocity is

$$v_{\mathrm{esc}}(r) = v_c \sqrt{2 \left[ 1 + \ln \left( \frac{r_h}{r} \right) \right]^2},$$

where $v_c$ is the circular velocity (Binney & Tremaine 1987). Although we do not have the $r_{\mathrm{esc}}/r$ estimate, this escape velocity very weakly depends on $r_{\mathrm{esc}}$, thus, we obtain $v_{\mathrm{esc}} \simeq (2.6–3.3) v_c$. The escape velocity is $v_{\mathrm{esc}} \simeq (3.0 \pm 0.4) v_c$. The relation between the circular velocity and the velocity dispersion, $\sigma$, of the [O II] emission line is $\sigma \simeq (0.6 \pm 0.1) v_c$ (Rix et al. 1997; Kobulnicky & Gebhardt 2000; Weiner et al. 2006). Combining this relation, we obtain the escape velocity of $v_{\mathrm{esc}} \simeq (5 \pm 1) \sigma$. Adopting the velocity dispersion of the [O II] emission lines of O B 10, $\sigma = 51 \pm 26$ km s$^{-1}$, we calculate the escape velocity to be $v_{\mathrm{esc}} = 250 \pm 140$ km s$^{-1}$. This escape velocity is comparable to the outflow velocity, $v = 80–260$ km s$^{-1}$, implying that some fraction of the outflowing gas can escape from O B 10. Recently, the analytic models of Igarashi et al. (2014) predict the slowly accelerated outflows with increasing radius in the gravitational potential of a cold dark matter halo and a central super-massive black hole. Igarashi et al. (2014) apply their model to the Sombrero galaxy, and the model agrees with the radial density profile measured by observations. If the outflow is accelerated in O B 10 as claimed by Igarashi et al. (2014), a larger fraction of the gas would escape from O B 10. The escape of the outflowing gas indicates that the SF activity may be suppressed in O B 10, and that the IGM would be chemically enriched by this outflow process.11

### 5.5. Does O B 10 Have an AGN?

The next question is what is the energy source of the outflow of O B 10 that would be powered by AGN activity and/or SF? To examine the presence of the AGN, we search for a counterpart of O B 10 in the X-ray source catalog provided

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10 We use SFR$_{\mathrm{SED}}$, which is the best estimate of O B 10's SFR (see Section 2.2). The mass loading factor does not strongly depend on the choice of the SFR.

11 Y13 roughly calculate the escape velocity to be $v_{\mathrm{esc}} \simeq \sqrt{2GM_{\mathrm{halo}}/r}$, where $M_{\mathrm{halo}}$ is the halo mass and $r$ is the radius of the galaxy. The escape velocity of O B 10 derived from this equation is $v_{\mathrm{esc}} \simeq 510$ km s$^{-1}$, if we substitute $M_{\mathrm{halo}} = 6 \times 10^{12} M_\odot$ estimated from the relationship between the stellar and halo masses at $0.74 < z < 1.0$ of Leauthaud et al. (2012), and $r = 19.2$ kpc, which is the Petrosian radius measured in the $R_C$ continuum image with the Petrosian factor of 0.2.
by Ueda et al. (2008). We find no detection within the circle of the X-ray positional error at the O II B 10 position. It indicates that O II B 10 does not harbor an X-ray luminous AGN with a 2–10 keV luminosity brighter than $10^{43}$ erg s$^{-1}$. However, we cannot rule out the possibility that O II B 10 hosts a heavily obscured AGN with a faint X-ray luminosity.

The Baldwin–Phillips–Terlevich (BPT) diagram (Baldwin et al. 1981) is the diagram of [N ii] $\lambda 6584$/$H\alpha$ versus [O iii] $\lambda 5007$/$H\beta$, which is widely used to distinguish AGNs and star-forming galaxies. The upper left panel of Figure 6 shows the BPT diagram. We plot SDSS galaxies taken from the data of SDSS DR7 (Abazajian et al. 2009). The blue and red classification lines are obtained from Kauffmann et al. (2003) and Kewley et al. (2001), respectively. We classify the SDSS galaxies into pure star-forming galaxies, composites, and AGNs, in order to compare them with O II B 10 in the blue, MEx, and CEx diagrams. The blue and red lines are boundaries of pure star-forming galaxies, composites, and AGNs, which are obtained by Kauffmann et al. (2003) and Kewley et al. (2001), respectively. The dots denote the SDSS galaxies. The pure star-forming galaxies, composites, and AGNs are shown with the dots and density contours of blue, red, and green colors, respectively. The upper right panel is the blue diagram. The black line is a boundary between pure star-forming galaxies and AGNs that is empirically determined by Lamareille (2010). The lower left panel is the MEx diagram. The black lines are boundaries defined by Juneau et al. (2011). The lower right panel shows the CEx diagram. The black line is a boundary of Yan et al. (2011). In these three diagrams, contours of the AGN or the composite regions, as well as in the pure star-forming galaxy regions. In the CEx diagram, O II B 10 is denoted by black filled and open circles, which correspond to the extinction-corrected and uncorrected line ratios, respectively.

12 The emission-line data are taken from the following Web site: http://www.mpa-garching.mpg.de/SDSS/DR7/.

(A color version of this figure is available in the online journal.)

Figure 6. BPT, blue, MEx, and CEx diagrams. The upper left panel shows the BPT diagram. We cannot plot O II B 10 in the BPT diagram because the [N ii] $\lambda 6584$/$H\alpha$ ratio is not available in our study. However, we use the BPT diagram to classify SDSS galaxies into pure star-forming galaxies, composites, and AGNs, in order to compare them with O II B 10 in the blue, MEx, and CEx diagrams. The blue and red lines are boundaries of pure star-forming galaxies, composites, and AGNs, which are obtained by Kauffmann et al. (2003) and Kewley et al. (2001), respectively. The dots denote the SDSS galaxies. The pure star-forming galaxies, composites, and AGNs are shown with the dots and density contours of blue, red, and green colors, respectively. The upper right panel is the blue diagram. The black line is a boundary between pure star-forming galaxies and AGNs that is empirically determined by Lamareille (2010). The lower left panel is the MEx diagram. The black lines are boundaries defined by Juneau et al. (2011). The lower right panel shows the CEx diagram. The black line is a boundary of Yan et al. (2011). In these three diagrams, contours of the pure star-forming galaxies, composites, and AGNs are plotted with the colors, the same as they are in the BPT diagram.

In the blue, MEx, and CEx diagrams, O II B 10 is denoted by black filled and open circles, which correspond to the extinction-corrected and uncorrected line ratios, respectively. In the blue diagram, we find that O II B 10 lies in the composite region. In the MEx diagram, O II B 10 is located not only in the composite region, but also on the edge of the AGN or the pure star-forming galaxy regions. In the CEx diagram, O II B 10 lies on the edge of the AGN or the composite regions, as well as in the pure star-forming region. While it is likely that O II B 10 is a composite of an AGN and star-forming regions from these three diagrams,
the possibilities of an AGN and a pure star-forming galaxy still remain.

As described in Section 4, the FWHM emission line widths of O Ⅱ B 10 are narrow, 70–130 km s$^{-1}$. It is widely known that type-1 AGNs have spectra with very broad permitted lines whose FWHM line widths are $\approx (1–5) \times 10^3$ km s$^{-1}$, and with moderately broad ($\sim 500$ km s$^{-1}$) forbidden lines such as [O Ⅲ] $\lambda\lambda 4959, 5007$. The typical FWHM emission line width of type-2 AGNs is 500 km s$^{-1}$, which is similar to those of the forbidden lines in type-1 AGNs. However, Kewley et al. (2006) report that the FWHM emission line widths of type-2 AGNs and composites are 100–600 km s$^{-1}$. Star-forming galaxies typically show line widths narrower than those of AGNs (Osterbrock 1989). Although the narrow line widths of O Ⅱ B 10 generally imply that O Ⅱ B 10 would be a star-forming galaxy, these line widths are consistent with those of some type-2 AGNs and composites.

5.6. Stellar Population of O Ⅱ B 10

The multi-wavelength SED of O Ⅱ B 10 is shown in Figure 7. Figure 7 compares the SED of O Ⅱ B 10 with those of local starburst templates (Silva et al. 1998). The mid-infrared SED shape of O Ⅱ B 10 is similar to those of Arp220, NGC 6090, and M82. This indicates that O Ⅱ B 10 is a dusty starburst galaxy, consistent with the non-detection of the Mg Ⅱ emission line discussed in Section 5.1.

We calculate the SFR of O Ⅱ B 10 using the [O Ⅲ] or Hβ emission line luminosity with the formulae of Kennicutt (1998). We estimate the Hα luminosity from our extinction-corrected Hβ luminosity with the line ratio of $L$(Hα) : $L$(Hβ) = 2.86:1, under the assumption of Case B recombination in a nebula with a temperature of $T = 10,000$ K and an electron density of $n_e = 100$ cm$^{-3}$ (Osterbrock 1989).

The SFRs derived from the [O Ⅱ] and Hβ luminosities are SFR$_{[O\text{~II}]} = 81 \pm 27$ and SFR$_{H\beta} = 96 \pm 20$ $M_\odot$ yr$^{-1}$, respectively. They are consistent with the SFR from the SED fitting, SFR$_{SED} = 72 \pm 8$ $M_\odot$ yr$^{-1}$.

5.7. Metallicity and Ionization Parameter

In this section, we examine the metal abundance and ionization state of the ISM in O Ⅱ B 10. For simplicity, we assume that O Ⅱ B 10 is dominated by the starburst, and adopt photoionization models. The $R_{23}$-index and the ratio of [O Ⅲ]/H$eta$ luminosity is (45–60) $\times 10^{-10}$ yr$^{-1}$. This SSFR is higher than those of Arp220, NGC 6090, and M82, that are 25, 1.7, and 3.1 $\times 10^{-10}$ yr$^{-1}$, respectively (Silva et al. 1998).

We also estimate the SFR with our MIPS 24 μm flux. Following the equations in Rieke et al. (2009), we obtain SFR$_{24,\mu m} = 100 \pm 70$ $M_\odot$ yr$^{-1}$. These SFRs are summarized in Table 2. The SSFR of O Ⅱ B 10 derived from the [O Ⅲ] or Hβ luminosities is (45–60) $\times 10^{-10}$ yr$^{-1}$. This SSFR is higher than those of Arp220, NGC 6090, and M82, that are 25, 1.7, and 3.1 $\times 10^{-10}$ yr$^{-1}$, respectively (Silva et al. 1998).
are high- and low-metallicity solutions, respectively. The SED fitting results presented in Section 2.2 reveal that the stellar mass of O II B 10 is relatively high, $1.6 \times 10^{10} M_\odot$. We assume that this high stellar mass is due to the past SF that largely contributes to the metal enrichment of the ISM. Moreover, as discussed in Section 5.6, O II B 10 is a dusty starburst galaxy. Thus, O II B 10 should have the high-metallicity solution, $(12 + \log(O/H), q_{OII} = 10^{6} \text{ cm} \text{s}^{-1}) = (8.97 \pm 0.08, 1.3 \pm 0.7)$, which indicates the high ionization parameter. The ionization parameter of O II B 10 is comparable to those of the $z > 2$ galaxies. However, the metallicity of O II B 10 is significantly higher than those of the $z > 2$ galaxies, and similar to those of the SDSS metal-rich galaxies in Figure 8.

5.8. Comparison with Other Galaxies

We compare the properties of O II B 10 with those of other O II BAs. Y13 study O II B 1, 4, and 8 with the optical spectroscopic data, and find that O II B 1 and 4 have outflow signatures. The outflow velocity of O II B 10 is comparable to that of O II B 4 ($\approx 200 \text{ km s}^{-1}$), and much less than that of O II B 1 ($500–600 \text{ km s}^{-1}$), which exhibits the AGN activity. Mg II $\lambda\lambda 2796, 2804$ and Fe II $\lambda 2587$ absorption lines, which are found in O II B 10, are also detected in O II B 4. In O II B 1, however, only the Fe II $\lambda 2587$ absorption line is marginally detected. These facts imply that the outflow mechanism of O II B 10 may be similar to that of O II B 4. The ionization parameter of O II B 10 is $q_{\text{ion}} = (1.3 \pm 0.7) \times 10^{6} \text{ cm} \text{s}^{-1}$, corresponding to $\log U = -2.36 \pm 0.26$. This ionization parameter is lower than that of O II B 1, $\log U > -1.0$, which is estimated from the $[O II] \lambda 3727/Fe \text{II} \lambda 2613$ ratio.

Then, we compare O II B 10 with typical star-forming galaxies at $z \sim 1.5$ and 2.2. Masters et al. (2014, hereafter M14) study the emission line galaxies at $z \sim 1.5$ and 2.2 with near-infrared spectroscopic data. Their galaxies have strong [O III] and/or Hα emission lines. Thus, the average spectrum of these galaxies in M14 represents typical star-forming galaxies. The [O III] line width of O II B 10 presented in Table 3 is comparable to that of the average spectrum in M14, 75 km s$^{-1}$. The ionization parameter of O II B 10, $\log U = -2.36 \pm 0.26$, is also similar to that of the average spectrum in M14, $\log U = -2.49 \pm 0.07$. However, the metallicity of O II B 10, $12 + \log(O/H) = 8.97 \pm 0.08$, is higher than that of the average spectrum in M14, $12 + \log(O/H) = 8.37$. This indicates that O II B 10 is more metal-rich than the typical star-forming galaxies at $z \sim 1.5$ and 2.2.

5.9. What is O II B 10?

We discuss the physical origin of O II B 10. As described in Section 4.1, we identify the two-component emission lines in O II B 10, and the red components appear to be spatially more extended than the blue components. The origin of the two components is unknown, but there are three possibilities: (1) two strong star-forming regions, (2) a galaxy merger, and (3) a combination of a galaxy and an outflow knot. The first possibility is that O II B 10 has two strong star-forming regions that make the two emission line components. The velocity difference of the two components ($170 \pm 50 \text{ km s}^{-1}$) may be due to a rotation or an infall of these two star-forming regions. The second possibility is that O II B 10 is a merger system, and that the two components correspond to the two galaxies. When galaxies merge, large amounts of the ISM fall on the central regions. This leads to the starburst processes. As discussed in Section 5.6, O II B 10 is a dusty starburst galaxy, which supports this merger-triggered starburst scenario. Generally, merging galaxies have broad ($FWHM \geq 350 \text{ km s}^{-1}$) and narrow ($FWHM \leq 350 \text{ km s}^{-1}$) emission lines that are produced by a shocked gas and H II regions, respectively (e.g., Rich et al. 2011; Soto et al. 2012; Rupeke & Veilleux 2013). However, we do not detect broad lines in O II B 10. The non-detection of the broad lines implies that the shock excitation would not be dominant in O II B 10. The third possibility is that H II regions and one collimated outflow knot of the ionized gas are responsible for the two components, respectively. As discussed in Section 5.1, O II B 10 has the outflow. If the outflow is beamed to us, the faint blue component of the emission line would be the outflow knot. In this case, the bright red component is originated from the H II regions. The outflow velocity should be comparable to the velocity difference of the two emission line components, $170 \pm 50 \text{ km s}^{-1}$ (Section 4.1). With $z_R$ and the absorption line velocities, we estimate the outflow velocity for the red component to be $160–390 \text{ km s}^{-1}$, comparable to the velocity difference of the two components. None of these three possibilities can be conclusively ruled out given current observational results but the fact that the red components appear to be more extended than the blue components.

The next question of O II B 10 is the energy source of the outflow found in Section 5.1. From the diagrams of Figure 6, it is likely that O II B 10 is a composite of an AGN and star-forming regions. The narrow emission line widths of O II B 10, 70–130 km s$^{-1}$ (Section 4), are comparable not only to star-forming galaxies but also to type-2 AGNs and composites. Thus, a type-2 AGN and SF would drive the outflow of O II B 10. For further investigation of the outflow and the presence of an AGN, observations with adaptive optics (AO) would be necessary.

6. SUMMARY

We present the Keck/MOSFIRE and Magellan/LDSS3 spectroscopy and the archival imaging data of 13 bands for the object with the spatially extended [O II] $\lambda\lambda 3726, 3729$ emission at $z = 1.18$, [O II] blob 10 (O II B 10). Following the study of Yuma et al. (2013), our data provide new insight into the physical properties of O II B 10. This is the first detailed spectroscopic study of oxygen-line blobs that includes the analyses of the escape velocity, the mass loading factor, and the presence of an AGN, and is a significant step for understanding the nature of oxygen-line blobs and the relationship between gas outflow and SF quenching at high redshift. The major results of our study are summarized below.

1. By our MOSFIRE observations, we identify Hβ and [O III] $\lambda\lambda 4959, 5007$ emission lines, all of which show the profiles of the two components that are called blue and red components. The average redshift of all components is $z_{\text{sys}} = 1.1800 \pm 0.0002$, which is defined as the systemic redshift of O II B 10. The velocity difference of the blue and red components is $170 \pm 50 \text{ km s}^{-1}$. We estimate the average FWHM line widths of the blue and red components to be $FWHM_B = 90 \pm 50 \text{ km s}^{-1}$ and $FWHM_R = 120 \pm 40 \text{ km s}^{-1}$, respectively.

2. We detect [O II] $\lambda\lambda 3726, 3729$ emission lines in our LDSS3 VPH-red grism spectrum. Although we identify the doublet lines of [O II], the blue and red components are not resolved in our spectrum. The redshift of [O II] lines is $z = 1.1800 \pm 0.0007$, consistent with the systemic redshift. The FWHM line width is estimated to be $120 \pm 60 \text{ km s}^{-1}$.
3. In our LDSS3 VPH-blue grism spectrum, we identify blueshifted Mg II λλ 2796, 2804 and Fe II λ 2587 absorption lines. The velocity offsets from the systemic velocity are $\Delta v = -260 \pm 40$ km s$^{-1}$ and $\Delta v = -80 \pm 50$ km s$^{-1}$ for the Mg II and FeII absorption lines, respectively. These blueshifted absorption lines indicate that O II B 10 has an outflow whose velocity is 80–260 km s$^{-1}$.

4. The escape velocity of O II B 10 is estimated to be $v_{\text{esc}} = 250 \pm 140$ km s$^{-1}$. The outflow velocity of O II B 10, 80–260 km s$^{-1}$, is comparable to this escape velocity, implying that some fraction of the outflowing gas would escape from O II B 10. This indicates that the SF activity could be suppressed by the outflow, and that the chemical enrichment of IGM may take place.

5. To examine the presence of the AGN, we investigate line ratios, the stellar mass, and the colors with the “blue,” MEx, and ClEx diagrams. These diagrams indicate that O II B 10 would be a composite of an AGN and star-forming regions, but do not rule out the possibilities of an AGN and a pure star-forming galaxy. While the narrow line widths of O II B 10 are suggestive of a star-forming galaxy, they are also consistent with an AGN or a composite.

6. The SED of O II B 10 suggests that O II B 10 is a dusty starburst galaxy, because the mid-infrared SED shape is similar to those of local starburst galaxies. We estimate the metallicity and ionization parameter of O II B 10 to be $12 + \log(O/H) = 8.97 \pm 0.08$ and $q_{\text{ion}} = (1.3 \pm 0.7) \times 10^{8}$ cm s$^{-1}$, respectively.

7. The two-component emission lines found in our MOSFIRE spectrum indicate three possibilities: (1) two strong star-forming regions, (2) a galaxy merger, and (3) a combination of a galaxy and an outflow knot. These three possibilities are all consistent with the results from our observations. The outflow may be driven by a composite of SF and a type-2 AGN.

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