Nebular line emission from $z > 7$ galaxies in a cosmological simulation: rest-frame UV to Optical lines

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ABSTRACT

We have performed very large and high resolution cosmological hydrodynamic simulations in order to investigate detectability of nebular lines in the rest-frame ultraviolet (UV) to optical wavelength range from galaxies at $z > 7$. We find that the expected line fluxes are very well correlated with apparent UV magnitudes. The C iv 1549Å and the C iii 1909Å lines of galaxies brighter than 26 AB are detectable with current facilities such as the VLT/XShooter and the Keck/MOSFIRE. Metal lines such as C iv 1549Å, C iii 1909Å, [O ii] 3727Å and [O iii] 4959/5007Å can be good targets for the spectroscopic observation with Thirty Meter Telescope (TMT), European Extremely Large Telescope (E-ELT), Giant Magellan Telescope (GMT) and James Webb Space Telescope (JWST). Hα and Hβ lines are also expected to be detectable with these telescopes. We also predict detectability of the nebular lines for $z > 10$ galaxies that will be found with JWST, Wide-Field Infrared Survey Telescope (WFIRST) and First Light And Reionization Explorer (FLARE) (11 $\leq z \leq 15$). We conclude that the C iv 1549Å, C iii 1909Å, [O iii] 4959/5007Å and Hβ lines even from $z \sim 15$ galaxies can be strong targets for TMT, ELT and JWST. We also find that the magnification by gravitational lensing is of great help to detect such high-$z$ galaxies. According to our model, the C iii 1909Å line in $z > 9$ galaxy candidates is detectable even using the current facilities.

Key words: cosmology – observations; galaxies – evolution; galaxies – formation; galaxies – high-redshift; galaxies – luminosity function, mass function;

1 INTRODUCTION

Understanding physical properties of the high-$z$ galaxies beyond $z = 7$ is very important, because such galaxies are not only building blocks of lower-$z$ galaxies and local galaxies but also the leading candidate of ionizing sources for the cosmic reionization. Such galaxies are much fainter objects because they are very distant objects and less massive systems. Thus, in order to observe these galaxies, ultra deep surveys are necessary. The Wide Field Camera (WFC3) installed on the Hubble Space Telescope (HST) in 2009 have detected many $z > 7$ galaxy candidates using the dropout (Lyman break) technique [Yan et al. 2011; Ellis et al. 2013; McLure et al. 2013; Schenker et al. 2013; Dunlop et al. 2013; Robertson et al. 2013; Ono et al. 2013; Koekemoer et al. 2013; Oesch et al. 2013; Bouwens et al. 2014; Finkelstein et al. 2014; Bouwens et al. 2015]. The combination of gravitational lensing by foreground galaxy clusters and the WFC3 camera have also discovered even intrinsically fainter high-$z$ galaxy candidates [Oesch et al. 2014; Ishigaki et al. 2015].

Many spectroscopic surveys for the Lyα line of $z > 7$ galaxies have been attempted to confirm spectroscopic redshift of these galaxies (e.g., Pentericci et al. 2011, 2015a; Caruana et al. 2012, 2014; Schenker et al. 2012; Shibuya et al. 2012; Finkelstein et al. 2013; Treu et al. 2013; Schenker et al. 2014; Vanzella et al. 2014; Oesch et al. 2015). Now, the highest confirmed redshift using Lyα line is $z = 8.68$ (Zitrin et al. 2015b) which is the first and only example of a successful Lyα line observation at $z > 8$. Other
observations so far have not succeeded in the Lyα line detection at $z > 9$ (Brammer et al. 2013; Bunker et al. 2013; Capak et al. 2013; Matthee et al. 2014). Moreover, the spectroscopic surveys for Lyα revealed that the fraction of high-$z$ galaxies with detectable Lyα emission decreases from $z = 6$ (e.g., Stark et al. 2011; Ono et al. 2012; Tilvi et al. 2014). These observational results imply that Lyα attenuation by the neutral hydrogen in the intergalactic medium (IGM) is significant because the neutral fraction of the hydrogen is high at such higher-z before the completion of the cosmic reionization. The Lyα line detection at $z > 8$ may be very difficult even by future telescopes such as the James Webb Space Telescope (JWST), the European Extremely Large Telescope (E-ELT), the Giant Magellan Telescope (GMT) and the Thirty Meter Telescope (TMT). Thus, it appears to be important to consider the detectability of alternative lines instead of the Lyα line. Furthermore, the detection of high-$z$ metal lines helps to understand when and how the metal enrichment proceeds at very early Universe.

The surveys for the far-infrared (FIR) lines using the Atacama Large Millimetre/submillimetre Array (ALMA) can be very powerful tool to confirm redshifts of very high-$z$ galaxies. The [C II] 158μm line is a well known brightest line in the FIR region. The line has been detected in many QSOs and submm galaxies (SMGs) at various redshifts (Maiolino et al. 2006; Capak et al. 2011; Vieira et al. 2013; Wang et al. 2013). [C II] 158μm line in some high-$z$ LBGs has also been discovered (Capak et al. 2011). Interestingly, almost all survey have failed to detect [C II] 158μm line in high-$z$ Lyman α emitters (LAEs) (Walter et al. 2012; Kanekar et al. 2013; Ouchi et al. 2013; Ota et al. 2014; Watson et al. 2013). This fact disadvantages to explore high-$z$ [C II] 158μm line because the fraction of young galaxies like LAEs increases with redshift. The [C II] 158μm is thought to be originated mainly from photo-dissociation regions (PDRs), the modelling of which is very complicated. This implies that the reliable theoretical prediction for the [C II] 158μm line is very difficult. In our previous work (Iguchi et al. 2014a), we concluded that the [O III] 88μm line from H II regions is potentially the best line to measure redshifts of galaxies in the early Universe. The modelling of this line is simpler than that of the [C II] 158μm line and the ALMA band 7 covers the line at $8.1 < z < 11.3$.

There are also various strong lines in the rest-frame UV to optical region. In the High-redshift Emission Line Survey (HiZELS) with narrow-band filters in the $J$, $H$ and $K$ bands, many Hα, [O II] 3727Å and [O III] 5007Å emitters have been discovered at $0.4 < z < 2.2$ (Geach et al. 2008; Sobral et al. 2008, 2014, 2015a). The spectroscopic surveys have also been performed and discovered many lines such as C II] 1909Å, [O II] 3727Å, [O III] 5007Å and Hα in the UV to the optical region at $z < 3$ (Silverman et al. 2014; Kashino et al. 2014; Nakajima & Ouchi 2014; Stark et al. 2014; Sanders et al. 2015). Stark et al. 2015a detected C III] 1909Å emission in two high-$z$ galaxies at $z = 6.029$ and 7.213. The C II] 1909Å emission in unusually luminous galaxy at $z = 7.730$ have been detected by Stark et al. 2015. In addition, Stark et al. 2015b discovered the C IV] 1549Å and O III] 1665Å emission lines in $z = 7.045$ galaxy confirmed by the Lyo emission line. More recently, a strong He II 1640Å was found in $z = 6.6$ LAEs (C7, Sobral et al. 2015). Interestingly, the CR7 has no metal lines. Sobral et al. 2015 suggested the existence of metal-free stars so-called Pop III stars and/or the formation of a direct collapse black hole. Now, the source of strong He II 1640Å in the CR7 is hotly debated (e.g., Agarwal et al. 2015; Hartwig et al. 2013; Pacucci et al. 2014; Pallottini et al. 2013).

The UV to optical lines are very useful for studying the physical properties of galaxies such as the gas metallicity, the radiation field strength and the gas density (e.g., Nagao et al. 2006; Mannucci et al. 2014; Nakajima & Ouchi 2014; Sanders et al. 2015). Nevertheless, there have been only a few line surveys at higher redshift ($z > 6$) using the ground-based telescopes due to the observational difficulty. This is because the wavelength of these lines in the high-$z$ Universe is redshifted into the IR region. The next generation telescopes such as the JWST, the E-ELT, the GMT and the TMT can perform a deeper survey than the current ones in the IR regime. Thus, the metal lines can be good targets for these future telescopes and useful to diagnose the physical properties of very high-$z$ galaxies ($z > 7$). Unfortunately, only small number of bright galaxies at $z > 7$ appropriate for the follow-up survey can be discovered by these telescopes due to their narrow field-of-view (FOV) ($\sim 30$ arcmin$^2$). The Wide-Field Infrared Survey Telescope (WFIRST) and the First Light And Reionization Explorer (FLARE), which are also future telescopes, are the IR deep and wide-field imaging surveyors. The FOV of these telescopes are much larger than the TMT, the E-ELT, or the JWST. Many bright high-$z$ galaxies or very rare objects, which are good targets for spectroscopic follow-up with the TMT, the E-ELT, or the JWST, will be discovered.

Many theoretical studies have been made on very high-$z$ galaxies (e.g., Finlator et al. 2014; Daval et al. 2013; Shimizu et al. 2014; Clay et al. 2014; Feng et al. 2016). In these papers, they investigated the physical properties of star-forming galaxies at high-$z$ such as the halo mass, the stellar mass and the UV magnitude. They also revealed the evolution of the star-formation density, the stellar mass functions (SMFs), the UV luminosity function (LFs) and the metal enrichment in the IGM. There are some studies for high-$z$ galaxies with nebular emission consideration. Schaerer et al. 2004 studied nebular emission effects in the spectral energy distribution (SED). They showed that the estimated stellar mass, the age and the extinction strength change in the cases of with or without the nebular emission. Inoue (2011) performed galaxy SED calculations in the UV-to-optical wavelength range with the nebular emission using the photo-ionisation code CLOUDY (Ferland et al. 2013). In the paper, they discussed criteria of equivalent widths of some lines and broad-band colours to select extremely metal-poor and metal-free galaxies. Wilkins et al. 2013 took into account the effect of the nebular emission on observational colour selections using a large cosmological hydrodynamical simulation. They claimed that the photometric redshift estimation is strongly affected by the strength of the nebular emission. Although there are many studies for very high-$z$ galaxies with the nebular emission, studies about the emission line detectability in these high-$z$ galaxies are few.

In this study, we examine whether some emission lines in the rest-frame UV to optical wavelength of galaxies at $z = 7$–$10$ are detectable with the current and future telescopes. Next, we discuss the detectability of the lines at even $z > 10$ in the future surveys.
In section 2, we describe our numerical simulations and calibrate the parameters therein. We virtually observe the galaxies located in our simulation through a light-cone output and select simulated galaxies by applying a relevant magnitude limit. In section 3, we present some line fluxes in the rest-frame UV to optical wavelength of selected galaxies in our simulation. In section 4, we make predictions using the FLARE, the WFIRST, JWST and TMT telescopes. The final section is devoted to our conclusion.

Throughout this paper, we adopt a ΛCDM cosmology with the matter density Ω_m = 0.3175, the cosmological constant Ω_λ = 0.6825, the Hubble constant \( h = 0.6711 \) in the unit of \( H_0 = 100 \text{ km s}^{-1} \text{ Mpc}^{-1} \) and the baryon density Ω_b = 0.04899. The matter density fluctuations are normalised by setting σ_8 = 0.8344 (Planck Collaboration 2014). All magnitudes are quoted in the AB system (Oke 1990). The assumed initial mass function (IMF) in the observational data and in our simulation is always the Chabrier IMF with the mass range of 0.1–100 M_⊙ (Chabrier 2003).

2 THEORETICAL MODEL

In this section, we describe our cosmological hydrodynamic simulation, calculation of the spectral energy distribution (SED) of the simulated galaxies and the treatment of the dust attenuation for these galaxies.

2.1 The Hydrodynamic Simulation

We performed high-resolution numerical simulations with an updated version of the Tree-PM smoothed particle hydrodynamics (SPH) code GADGET-3 which is a successor of Tree-PM SPH code GADGET-2 (Springel 2005). We implemented relevant physical processes to galaxy formation such as the star formation, the supernova (SN) feedback and the chemical enrichment following papers (Okamoto, Nemmen & Bower 2008, Okamoto, & Frenk 2009, Okamoto et al. 2010). In our previous work (Okamoto, Shimizu & Yoshida 2014), the radiation pressure and the AGN feedback were newly implemented. We consequently reproduced various observational quantities such as the stellar mass functions (SMFs), the cosmic star formation history, the galaxy downsizing, and the relation between stellar mass and metallicity from z = 4 to z = 0. The details of these processes are found in the above references.

Here, we briefly introduce settings of our simulations. We employ a total of 2 × 1280^3 particles for dark matter and gas in a comoving volume of 50h^{-1} Mpc cube. The mass of a dark matter particle is 4.44 × 10^4h^{-1} M_⊙ and that of a gas particle is initially 8.11 × 10^4h^{-1} M_⊙, respectively. The softening length for the gravitational force is set to be 2 h^{-1} kpc in comoving unit. The SPH gas particles can spawn star particles when they satisfy a set of standard criteria for star formation, and then, their mass is reduced. SPH particles around evolved star particles get the mass including metal elements due to SNe and the stellar mass loss in the AGB phase, resulting in the mass reduction of the star particles. In order to identify simulated galaxies, we run a friends-of-friends (FoF) group finder with a comoving linking length of 0.2 in units of the mean particle separation to identify groups of dark matter particles as halos. Then, we find gravitationally bound groups of at least 32 total (dark matter + SPH + star) particles as substructures (subhaloes) in each FoF group using SUBFIND algorithm developed by (Springel et al. 2001). We regard substructures that contain at least 10 star particles as our simulated galaxies. We note that the lowest dark halo and stellar masses are around 10^9 M_⊙ and 10^6 M_⊙, respectively.

In order to calibrate parameters in the code such as the SN feedback efficiency, we compare our model with the observed stellar mass function (SMF) of galaxies. Fig. 1 represents our SMF at z = 7 to z = 15. We also plot the observational results (the points with error bars) at z = 7 and z = 8 taken from Gonzalez et al. (2011), Grazian et al. (2013) and Song et al. (2015). Our model reproduces the observed SMF within error-bars. At the massive end of SMFs (> 10^{10} M_⊙), our model may underestimate the SMF because our simulation box is not sufficiently large. On the other hand, our simulation tends to overproduce less massive galaxies (< 10^{7.5} M_⊙) when comparing the observational data at z ∼ 7. This may indicate that the SFR of less massive galaxies in our simulation is ∼ 2 times higher than real ones. In our previous work (Shimizu & Inoue 2013), we argue that the shape of the SMF depends on the definition of the stellar mass, i.e., with or without the remnant mass as the stellar mass. The effect is important for low-z galaxies, but, it is negligible at the high-z discussed in this paper.

2.2 SED Calculation of Simulated Galaxies

After the identification of the simulated galaxies, we calculate their SEDs. The SED of each star particle, which has its own age, metallicity, and mass, is calculated by using the population synthesis code PEGASE2 (Fioc & Rocca-Volmerange 1997). Then, we sum up the SEDs of the star particles composing a simulated galaxy to obtain the total intrinsic SED of the galaxy. We also adopt the nebular continuum and the Hydrogen recombination lines (Lyα, Hα, Hβ, and Hγ) calculated by PEGASE2 with the Case B approximation. Moreover, the metal lines emitting from H II regions are calculated based on Inoue (2011) and Inoue et al. (2014a), in which expected line fluxes are cal-

![Figure 1. The stellar mass functions (SMF) at z = 7 and higher. The line styles and their corresponding redshifts are noted in the panel. For z = 7 and 8, we also plot observational data as the points with error bars taken from Gonzalez et al. (2011), Grazian et al. (2013) and Song et al. (2015).](image-url)
culated by the photo-ionization code cloudy (Ferland et al. 2013). These line luminosity \( L_{\text{line}} \) are proportional to H\( \beta \) luminosity \( L_{\text{H} \beta} \),

\[
L_{\text{line}} = (1 - f_{\text{esc}})C_{\text{line}}(Z)L_{\text{H} \beta},
\]

where \( f_{\text{esc}} \) is the Lyman continuum escape fraction and \( C_{\text{line}}(Z) \) is the metallicity dependent emission efficiency for each line which is calculated in Inoue (2011) and Inoue et al. (2014a), respectively. Measurements of \( f_{\text{esc}} \) of an order of 0.01–0.1 have been obtained at \( z \sim 3 \) (e.g., Inoue et al. 2003; Iwata et al. 2009) and \( f_{\text{esc}} \sim 0.2 \) at \( z > 5 \) has been favoured for cosmic reionization (Inoue et al. 2006; Shapley et al. 2006; Siana et al. 2015). However, we simply assume \( f_{\text{esc}} = 0 \) in this paper, yielding the maximum fluxes of nebular emission lines. It is worth describing explicitly assume

\[
\Sigma_d = e_r M_{\text{metal}} \frac{\pi}{r_{\text{half}}^2},
\]

where \( e_r = e_{\text{Md}}/e_{\text{d}} \) is a global constant for all the galaxies in our simulation. We calibrate \( e_r \) and \( \delta \) so as to reproduce the observed UV luminosity function (LF) at \( z = 7 \), and we keep these values even at higher redshifts. In this study, we adopt \( e_r = 0.01 \) and \( \delta = 0.95 \), respectively. When we calculate band magnitudes, we also apply the IGM absorption for the blue side of 1216 Å following Madau (1995). Inoue et al. (2014a) with an extrapolation for \( z > 7 \). The top panel of Fig. 2 represents the UV LFs from \( z = 7 \) to \( z = 10 \). Observational results are also shown in the same panel. Our model reproduces the observations well up to \( z \sim 10 \). Moreover, we predict the UV LFs beyond \( z = 10 \) in the bottom panel of Fig. 2.

Next, we consider the dust attenuation for various emission lines. In this study, we apply the same attenuation law as the continuum to the emission lines but with a different normalization (Calzetti et al. 2000). According to Calzetti et al. (2000), the attenuation for emission lines is a factor of about 2 larger than that for the continuum at the same wavelength, although different factors were suggested by recent studies (e.g., Casas et al. 2013). The line escape probability \( f_{\text{esc}}(\nu) \) at 1500 Å which is the normalization of the attenuation law for emission lines is

\[
\frac{f_{\text{esc}}(\nu)}{f_{\text{esc}}(\nu_{\text{break}})} = 10^{-2.27 \log f_{\text{esc}}(\nu_{\text{break}})},
\]

where \( f_{\text{esc}}(\nu) \) and 2.27 are the normalization of the attenuation law for the continuum (Eq. 2) and the attenuation enhancement for emission lines, respectively.

After calculation of the intrinsic SEDs of simulated galaxies, then, we consider the dust attenuation for the continuum and the lines of them. The procedure of dust attenuation for the continuum is same as our previous work (Shimizu et al. 2014). We adopt the Calzetti law (Calzetti et al. 2000) for the shape of the attenuation law. For the attenuation amplitude, we calculate the escape probability of UV photons at 1500 Å \( f_{\text{esc}}(\nu_{\text{break}}) \). We apply the sandwich model for \( f_{\text{esc}}(\nu_{\text{break}}) \) (Shimizu et al. 2014; Xu & Boul 1993),

\[
f_{\text{esc}}(\nu_{\text{break}}) = \frac{1 - \delta}{2} (1 + e^{-\tau_d}) + \frac{\delta}{2} (1 - e^{-\tau_d}),
\]

where \( \delta \) is a parameter whose value is from 0 to 1 and \( \tau_d \) is the UV (1500 Å) optical depth of the simulated galaxies. The parameter \( \delta \) is the fraction of the thickness of the central star+ dust slab in the total thickness. For the case of \( \delta = 1 \), Eq. 2 corresponds to the well-mixed dusty slab geometry. On the other hand, it is the case with a central infinitely thin dust sheet when \( \delta = 0 \). We calculate the optical depth \( \tau_d \) using the following equation:

\[
\tau_d = 3a_d q_s
\]

where \( a_d \) and \( s \) are a typical size and the material density of dust grains, respectively. We set \( a_d = 0.1 \) Å and \( s = 2.5 \) g cm\(^{-3} \) motivated by SNe dust production models (Fodorini & Ferrella 2001; Nozawa et al. 2003). The dust surface density is defined by the following equation:

\[
\Sigma_d = \frac{M_d}{\pi r_d^2},
\]

where \( M_d \) and \( r_d \) are the total dust mass and the effective radius of the dust distribution in a galaxy, respectively. These values are directly obtained from our simulations as follows. The dust mass \( M_d \) and \( r_d \) are assumed to be proportional to the metal mass, \( M_{\text{metal}} \), and the half stellar mass radius, \( r_{\text{half}} \), of each simulated galaxy, respectively. Therefore, \( M_d \) and \( r_d \) are expressed as \( e_{\text{Md}} M_{\text{metal}} \) and \( e_{\text{d}} r_{\text{half}} \), where \( e_{\text{Md}} \) and \( e_{\text{d}} \) are the proportional constants of the dust mass and the effective radius, respectively. These two parameters can be reduced to one parameter. Thus, equation (2) is reduced to

\[
\Sigma_d = e_r M_{\text{metal}} \frac{\pi}{r_{\text{half}}^2},
\]
2.3 Basic Physical Properties of Simulated Galaxies

Here, we explore whether our simulation is reasonable to predict line detectability. We check essential physical properties of our simulated galaxies such as the stellar mass, the SFR, the dust attenuation and the metallicity which are necessary to calculate the line fluxes. In order to directly compare our model with the observations, we make galaxies distribution on a light-cone from $z = 6$ to $z = 17$ the same as in our previous work (Shimizu et al. 2014). The field-of-view (FOV) in this study is $0.16$ deg$^2$ which is about 150 times wider than the HST FOV. We regard objects brighter than $H_{160} = 32$ as our selected galaxies. Then, we divide them into four redshift subsets at $z \sim 7$ ($6.5 < z \leq 7.5$), $8$ ($7.5 < z \leq 8.5$), $9$ ($8.5 < z \leq 9.5$) and $10$ ($9.5 < z \leq 10.5$).

2.3.1 Star Formation Rate

The Star formation rate (SFR) of simulated galaxies is very important because the line luminosities of various elements are essentially proportional to the SFR. Fig. 4 shows the star formation rates as a function of the stellar mass. The large triangle, square, circle and star points are the median values of SFR in the stellar mass bins for $z \sim 7$, $8$, $9$ and $z \sim 10$, receptively. The boxes and error-bars ranges show 68 % percentile and 90 % percentile in the distributions. We also plot the observational data at $z \sim 6$ also is shown as cross points with error-bars (Salmon et al. 2015). The SFR strongly correlates with their stellar mass. Interestingly, the trend is similar to that of the star forming galaxies at lower-$z$ Universe known as the main sequence distribution (e.g., Daddi et al. 2007; Noeske et al. 2007). We find that the distribution of $z \sim 7$ galaxies is almost same as the observation at $z \sim 6$. Moreover, the evolution from $z \sim 7$ to $z \sim 10$ is very weak. This implies that line luminosities are also proportional to their stellar mass.
2.3.2 Dust Attenuation

Fig. 5 represents the dust attenuation $A_{UV}$ at 1500 Å as a function of $H_{160}$ band magnitude. The large triangle, square, circle and star points are the median values of $A_{UV}$ in $H_{160}$ band magnitude bins for $z \sim 7$, 8, 9 and $z \sim 10$, respectively. The boxes and error-bars ranges show 68 % percentile and 90 % percentile in the distributions. Clearly, there are a few galaxies strongly affected by the dust attenuation. The typical value of the dust attenuation correlates with the UV magnitude even though there is a large scatter. We note that the typical value is smaller than that we find in our previous work Shimizu et al. (2014). In the new code which we use in this study, the radiation pressure and the AGN feedback are newly included in addition to the SN feedback (Okamoto, Shimizu & Yoshida 2014). Especially, the radiation pressure and the SN feedback effectively suppress the star formation in small mass galaxies than the case of the SN feedback only simulation. As a result, less dust attenuation is required to reproduce the UV LFs.

Next, we calculate the UV slope $\beta$ with the exactly same formulae as that in the observations Dunlop et al. (2013), Bouwens et al. (2014a), Wilkins et al. (2016):

$$\beta = 4.39 \times (J_{125} - H_{160}) - 2.0,$$

(8)

for $z \sim 7$ galaxies,

$$\beta = 8.98 \times (JH_{140} - H_{160}) - 2.0,$$

(9)

for $z \sim 8$ galaxies,

$$\beta = 9.32 \times (JH_{140} - H_{160}) - 2.0,$$

(10)

for $z \sim 9$ galaxies and

$$\beta = 1.1 \times (H_{160} - [3.6]) - 2.0,$$

(11)

for $z \sim 10$ galaxies, respectively. $J_{125}$ and $JH_{140}$ are WFC3 band filters equipped on the Hubble Space Telescope and [3.6] is the Spitzer IRAC band 1. Fig. 6 shows the slope $\beta$ as a function of the absolute UV magnitude (without dust correction). The large triangle, square, circle and star points are the median values of $\beta$ in the absolute UV magnitude bins for $z \sim 7$, 8, 9 and $z \sim 10$, respectively. The boxes and error-bars ranges show 68 % percentile and 90 % percentile in the distributions. The large cross points are also shown as the observational data Dunlop et al. (2013), Bouwens et al. (2014a), Wilkins et al. (2016). As described our previous paper, the large scatter of the observational data may be due to the observational error and/or uncertainty. The UV brighter galaxies have larger $\beta$ values. This is because the UV brighter galaxies tend to be more evolved and have a smaller fraction of young stellar populations than the UV fainter ones. Moreover, such UV brighter galaxies rapidly proceed metal enrichment. This trend can be seen in high-z galaxy observations Bouwens et al. (2014a), Wilkins et al. (2016). At $z \sim 9$, the $\beta$ distribution of our model shows the large scatter and different trend from other redshift ones. This is because $\beta$ break or line of some $z \sim 9$ (8.5 < $z$ < 9.5) simulated galaxies enters in $H_{140}$ band. If we adopted the same $\beta$ formula as $z \sim 10$ for $z \sim 9$, we would get a similar $\beta$ distribution for $z \sim 9$ to other redshifts. This suggests that some modifications are necessary for $z \sim 9 \beta$ estimator.

3 RESULTS AND DISCUSSION

In this section, using our mock galaxies, we explore expected fluxes of some emission lines. We investigate the observed line fluxes of our simulated galaxies and discuss the detectability of these lines at $z = 7$–10. Then, we predict the detectability in $z > 10$ galaxies.

3.1 Line Flux Prediction

Here, we show some bright and important metal lines for the diagnostics of the gas metallicity. We also present hydrogen recombinantion lines such as Hα and Hβ. The R23-index defined by ([O iii] 4959Å + [O iii] 5007Å + [O ii] 3727Å)/Hβ is well known as a good indicator for gas metallicity. Moreover, the N2 (log([N ii] 6584Å/Hα)) and O3N2 (log(([O iii]
Detectability of nebular lines

The UV slope $\beta$ as a function of the absolute UV magnitude. The large triangle, square, circle and star points are the median values of $\beta$ in the absolute UV magnitude bins for $z \sim 7$, 8, 9 and $z \sim 10$, respectively. The boxes and error-bars ranges show 68% percentile and 90% percentile in the distributions. The large cross points are shown the observational results (Dunlop et al. 2013; Bouwens et al. 2014b; Wilkins et al. 2016).

The nebular metallicity as a function of the stellar mass. The large triangle, square, circle and star points are the median values of the metallicity in the stellar mass bins for $z \sim 7$, 8, 9 and $z \sim 10$, respectively. The boxes and error-bars ranges show 68% percentile and 90% percentile in the distributions. The dashed line is solar metallicity $Z_\odot = 0.02$.

Figure 6. The UV slope $\beta$ as a function of the absolute UV magnitude. The large triangle, square, circle and star points are the median values of $\beta$ in the absolute UV magnitude bins for $z \sim 7$, 8, 9 and $z \sim 10$, respectively. The boxes and error-bars ranges show 68% percentile and 90% percentile in the distributions. The large cross points are shown the observational results (Dunlop et al. 2013; Bouwens et al. 2014b; Wilkins et al. 2016).

Figure 7. The nebular metallicity as a function of the stellar mass. The large triangle, square, circle and star points are the median values of the metallicity in the stellar mass bins for $z \sim 7$, 8, 9 and $z \sim 10$, respectively. The boxes and error-bars ranges show 68% percentile and 90% percentile in the distributions. The dashed line is solar metallicity $Z_\odot = 0.02$.

The diagnostics (R23-index, N2 and O3N2) of the gas metallicity. The small triangle, square, circle and star points are the expected line fluxes of the simulated galaxies at $z \sim 7$, 8, 9 and 10, respectively, while the large points with error-bars represent the average values and their standard deviations in $H_{160}$ band magnitude bins. We also plot the observational results by Stark et al. (2015a), Stark et al. (2015b) and Stark et al. (2016) as the two cross and plus-sign points (the fainter point was demagnified by the quoted lensing magnification) in the C iv 1549Å and the C iii] 1909Å panels, which are very consistent with our prediction.

We explore whether the existing facilities such as the VLT/X-Shooter and the Keck/MOSFIRE can detect the emission lines considered in this paper. The wavelength range of these instruments is about 1–2.5 μm. Although, the detection limit is not deep enough (a few×10^{-18} [erg/s/cm^{2}]) under a practical observational condition, the C iv 1549Å and the C iii] 1909Å lines of the brighter galaxies ($< 26$ mag) are detectable at $z > 7$ without a significant magnification by gravitational lensing. Recently, Zitrin et al. (2015a) reported no C iii] 1909Å line with $H_{160} \sim 28$ was detected under the condition of the detection limit 1.5×10^{-18} [erg/s/cm^{2}]. This is also consistent with our result because typical line fluxes with $H_{160} \sim 28$ are $2 \times 10^{-19}$ [erg/s/cm^{2}] which is below the observational detection limit.

In order to detect these nebular lines, we need the future facilities with a wider wavelength coverage (the rest-frame UV to optical) and a stronger light-gathering power. The JWST and the TMT have potential to detect the nebular

5007Å/Hβ)/([N ii] 6584Å/Hα)) indices are also used to estimate the oxygen abundances. Nagao et al. (2006) suggests that the line ratio [Ne iii] 3869Å/[O ii] 3727Å is also a useful metallicity indicator for high-$z$ galaxies, especially when the R23-index or other diagnostics involving [O iii] 5007Å or [N ii] 6584Å are not available. Fig. S represents the observed line fluxes of those important emission lines in the rest-frame UV to optical wavelength as a function of observed $H_{160}$ band magnitude. We calculate all elements for the diagnostcs (R23-index, N2 and O3N2) of the gas metallicity. The small triangle, square, circle and star points are the expected line fluxes of the simulated galaxies at $z \sim 7$, 8, 9 and 10, respectively, while the large points with error-bars represent the average values and their standard deviations in $H_{160}$ band magnitude bins. We also plot the observational results by Stark et al. (2015a), Stark et al. (2015b) and Stark et al. (2016) as the two cross and plus-sign points (the fainter point was demagnified by the quoted lensing magnification) in the C iv 1549Å and the C iii] 1909Å panels, which are very consistent with our prediction.

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In order to detect these nebular lines, we need the future facilities with a wider wavelength coverage (the rest-frame UV to optical) and a stronger light-gathering power. The JWST and the TMT have potential to detect the nebular
line of very high-z galaxies. We consider the detectability of the nebular lines using the JWST and the TMT. The JWST/NIRSPEC, the JWST/MIRI and the TMT/IRMS provide spectroscopy over the wavelength range of 0.6–5 μm, 5–28 μm and 0.8–2.5 μm, respectively. The point-source detection limits of the JWST/NIRSPEC, JWST/MIRI and TMT/IRMS, which depend on the observed wavelength are a few×10^{-19} [erg/s/cm^2], a few×10^{-18} [erg/s/cm^2] and a few×10^{-20} [erg/s/cm^2], respectively, if the integration time is 1.0 × 10^5 [sec] and the signal to noise ratio (S/N) is 5. We note that only C iv 1549Å and the C iii] 1909Å lines at z = 7–10 can be available for the TMT/IRMS due to the wavelength coverage shorter than 2.5 μm. Interestingly, the redshift evolution of the each line flux against the apparent H_{\alpha} band magnitude is not seen. This is because the SFR and metallicity evolutions of the simulated galaxies are weak as shown in Fig. 4 and Fig. 7. Moreover, the evolution of the dust attenuation is also weak as shown in Fig. 5. Almost all these lines are detectable by these instruments if the band magnitude are brighter than about 28 mag. This means that we may detect some lines even at z > 10 galaxies if the galaxies are bright enough (< 28 mag) and we can confirm the spectroscopic redshift using these lines. Moreover, we can study the gas metallicity of high bright-z galaxies (< 28 mag) through the line ratio diagnostics. Finally, we comment on Hett 1640Å in the CR7 (Sobral et al. 2015b). We also calculate the line and search the CR7 candidates around z = 6.6. However, we can not find any CR7 like Hett 1640Å bright galaxies in our simulation. This suggests that in order to reproduce such an object, we should consider the first star formation and/or intermediate black-hole formation (e.g., Agarwal et al. 2015, Hartwig et al. 2015, Pacucci et al. 2015, Pallottini et al. 2015). This is beyond the scope of this paper. It will be our future work.

3.2 Line Equivalent Width Prediction

The equivalent width (EW) of lines is also very interesting to discuss detectability of lines in high-z galaxies because the value strongly depends on the star formation history and the IMF. Fig. 9 represents the rest-frame EWs of various lines in the rest-frame UV to optical wavelength as a function of line fluxes. The large triangle, square, circle and star points are the median values of EWs in the observed line flux bin for z ~ 7, 8, 9 and z ~ 10, respectively. The boxes and error-bars ranges show 68 % percentile and 90 % percentile in the distributions. We also plot the observational results by Stark et al. (2015a), Stark et al. (2015b) and Stark et al. (2016) as the cross and plus-sign points in the C iv 1549Å and the C iii] 1909Å panels. The strong lines exceeding 100 Å can be seen in some lines such as [O ii] 4959/5007Å, Hα and Hβ. In the fainter line fluxes (less massive galaxies) regime (<10^{20} [erg/s/cm^2]), the EWs are proportional to their line fluxes. The EW represents the current SFR divided by an average of SFR over a certain time duration, and the line flux is almost proportional to the SFR. The metallicity effect on the line emissivity is secondary because the simulated galaxies have more or less a metallicity about ~ 0.1 solar (see Fig. 7). If we choose galaxies emitting a weak line flux, they are in a low SFR phase, so that the EW is small. In the brighter line fluxes (massive galaxies) regime (>10^{20} [erg/s/cm^2]), EWs are almost constant (or very slowly decrease with increasing line fluxes). These galaxies are in an on-going star-formation episode (or starburst) and their EW (or SFR/ < SFR >) reaches an asymptotic value. Interestingly, only the Hα and Hβ lines show a decreasing EW as increasing the line flux rather than a constant. This is because stronger line flux galaxies tend to have a higher metallicity and the LyC photons production efficiency per nonionizing photon decreases with the metallicity increasing. On the other hand, for metal lines, the effect is cancelled out by an increase of the line emissivity due to increasing metallicity. Finally, we mention higher Hα EW galaxies than theoretical expectation reported by Shim et al. (2011) and Smit et al. (2016). In our simulation, there is no object which can reproduce such a very high EW. This implies that in order to reproduce such higher EW galaxies, we may need to include the metal-free star formation and/or a top-heavy IMF which we are not considered in this study.

3.3 Detectability of the Lines beyond z ~ 10

We have presented the detectability of multiple emission lines in the rest-frame UV to optical wavelength at z ~ 7–10. Here, we discuss the detectability of these lines at even higher-z, z = 11–15. The number of bright galaxies decreases with increasing redshift, thus, a very wide survey is necessary to discover sufficiently bright very high-z galaxies. In this study, we feature high-z galaxies which will be detected with the Wide-Field Infrared Survey Telescope (WFIRST) and the First Light And Reionization Explorer (FLARE). The surveys with these facilities are potentially the most efficient one to detect very high-z galaxies thanks to the wide survey area and the depth. We notice that the instrument design of these facilities has not been determined yet. In the survey strategy, they expect to detect many high-z galaxy candidates at 11 ≤ z ≤ 15. In order to compare our model with the future observations, we make a mock galaxy catalogue at 11 ≤ z ≤ 15. We can identify a few galaxies at z ~ 15 even though the FOV of our simulation is very narrow (~0.15 deg^2).

Fig. 10 and 11 represent the evolution of SFR and nebular metallicity, respectively. These results suggest that a weak redshift evolution of the line flux–magnitude relation even at z > 11 as lower-z discussed in the previous section. Thus, some line emissions with K band magnitude <26 mag can be detected even at z ~ 15 with the JWST/NIRSPEC and the JWST/MIRI. Next we estimate the line fluxes of these selected galaxies.

Fig. 12 represents the expected line fluxes in the rest-frame UV to optical wavelength as a function of K band magnitude. The point styles and their corresponding redshifts are noted in the panel. The points with error-bars represent the average values and the standard deviations in K band magnitude bins. The line flux–magnitude relations of different redshifts are almost the same as found in the cases of z ≤ 10 as expected. We find that the C iv 1549Å and the C iii] 1909Å lines of simulated galaxies with K band magnitude < 28 mag are detectable even at z ~ 12 with the TMT/IRMS. On the other hand, in our simulation, there are

1 http://wfirst.gsfc.nasa.gov/
2 http://mission.lam.fr/flare/
Figure 8. The observed line flux in the rest-frame UV to optical wavelength as a function of the apparent $H_{160}$ band magnitude. The large triangle, square, circle and star points are the median values of line fluxes in the $H_{160}$ band magnitude bins for $z \sim 7$, 8, 9 and $z \sim 10$, respectively. The boxes and error-bars ranges show 68% percentile and 90% percentile in the distributions. The large cross and plus-sign points are observational results (Stark et al. 2015a,b, 2016). The solid, dot-dashed and dashed lines are the detection limits of the JWST/NIRSPEC ($\lambda_{\text{obs}} = 0.6–5$ [$\mu$m]), the JWST/MIRI ($\lambda_{\text{obs}} = 5–28$ [$\mu$m]) and the TMT/IRMS ($\lambda_{\text{obs}} = 0.8–2.5$ [$\mu$m]) at the wavelength of the line for a $z = 9$ galaxy, respectively, if the integration time is $10^4$ [sec] and the signal-to-noise ratio (S/N) is 5.

Figure 10. Same as Fig. 4, but for $11 < z < 15$.

Figure 11. Same as Fig. 7, but for $11 < z < 15$.

no galaxies at $z \sim 15$ that are bright enough. This implies that the survey area of our simulation (FOV $\sim 0.15$ deg$^2$) is not wide enough to have galaxies emitting line fluxes bright enough to be detectable with the JWST or the TMT. Therefore, a much wider survey area is imperative to discover line detectable galaxies beyond $z \sim 11$. We can detect some emission lines using the JWST or the TMT if the bright galaxy candidates are discovered at any redshifts because there is no evolution in the relation between apparent UV magnitude and line fluxes along the redshift. We also present the rest-frame EWs as a function of observed line fluxes in Fig. 13.

3.4 Nebular Emission Line Luminosity Functions

We have not discussed yet how many line emitting galaxies can be detected by the future telescopes. This topic is very important for future plans. We show cumulative luminosity functions (LFs) of various emission lines at $7 \leq z \leq 15$ in Fig. 14. Here, we discuss only the C iv 1549Å and the C iii] 1909Å lines because the line have strong potential to be detected even at $z > 10$ with the TMT and the
Figure 9. The rest-frame EW of various lines in the rest-frame UV to optical wavelength as a function of observed line fluxes. The large triangle, square, circle and star points are the median values of EWs in the observed line flux bins for $z \sim 7$, 8, 9 and $z \sim 10$, respectively. The boxes and error-bars ranges show 68% percentile and 90% percentile in the distributions. The large cross and plus-sign points are observational results (Stark et al. 2015a, b, 2016).

Figure 12. Same as Fig. 9 but for $11 < z < 15$. The solid, dot-dashed and dashed lines are the detection limit of the JWST/NIRSPEC, the JWST/MIRI and the TMT/IRMS at the wavelength of the line for a $z = 12$ galaxy, respectively, if the integration time is $10^4$ [sec] and the signal-to-noise ratio (S/N) is 5.
Detectability of nebular lines

Figure 13. Same as Fig. 9, but for \(11 < z < 15\).

JWST. Typical detection limits of TMT/IRMS (dashed line), JWST/NIRSPEC (solid line) and JWST/MIRI are also shown in Fig. 14 if the integration time is \(10^{4}\) [sec] and the signal-to-noise ratio (S/N) is 5. The detection limit for TMT/IRMS is around \(10^{-19}\) [erg/s/cm\(^2\)]. Thus, one or more C IV 1549Å and C III] 1909Å emitters at \(z < 12\) can be detected by TMT/IRMS if the survey volume is about \(10^5\) [Mpc\(^3\)] which is equivalent to \(> 200\) FOVs of the TMT and the JWST. On the other hand, the wavelength of the line at \(z > 12\) is beyond the coverage of the instrument. The JWST/NIRSPEC can cover that wavelength range and the detection limit is around \(10^{-18}\) [erg/s/cm\(^2\)]. In this case, a larger survey volume is necessary to detect the emitters because there is no detectable galaxy in our small FOV (\(\sim 0.15\) deg\(^2\)) simulation. We emphasise again that a wide imaging survey with the WFIRST and the FLARE is very useful to discover very higher-z line emitters.

3.5 Gravitationally-lensed \(z > 9\) Galaxy Candidates Found to Date

Here, we mention detectability of galaxies magnified by gravitational lensing. Recently, many surveys with lensing magnification have been actively performed. Many faint galaxies have been discovered by the combination the HST/WFC3 and gravitational lensing. Thanks to the magnification by gravitational-lensing, some lensed galaxies which are candidates of \(z > 9\) objects are detectable by even the current facilities such as the VLT/X-Shooter and the Keck/MOSFIRE.

Let us discuss the detectability of the C III] 1909Å emission line from \(z > 9\) galaxy candidates found by surveys for galaxy cluster lensing fields like the Cluster Lensing And Supernova survey with Hubble (CLASH) and the Hubble Frontier Field (HFF) with instruments currently available. The C III] 1909Å line is the second strongest emission line after Ly\(\alpha\) in the UV range and can be observed with ground-based 8-10 m class telescopes at \(z < 12\). Table 1 is a summary of the candidates to be discussed here. First, we estimate the range of their real apparent \(H_{160}\) magnitudes by demagnifying with the quoted magnification factor \(\mu\) and its uncertainty. Next, we select the galaxies within the magnitude range and satisfying appropriate colour selection criteria from our simulation. Then, we obtain the magnification factor for each simulated galaxy so as to be observed as the observed \(H_{160}\) magnitude. Finally, we magnify the C III] 1909Å emission line flux by this factor, and obtain the distribution of the expected C III] 1909Å line fluxes. Fig. 15 shows the result for the five \(z > 9\) candidates. The currently reachable limit is \(1 \times 10^{-18}\) [erg/s/cm\(^2\)] (e.g., Stark et al. 2014). The C III] 1909Å line from MACS0647JD is detectable with a high probability, 73 or 85% for the two quoted magnification factors. The detectability of the line from MACS0647JD1 is also relatively high (57%). The other three candidates have a detectability of < 5%. Therefore, MACS1149JD and MACS0647JD1 are the two best targets for the follow-up spectroscopy aiming to detect the C III] 1909Å line even with the current facilities. In order to study higher-z (\(z > 7\)) line emitting galaxies, the combination of the GMT, the TMT or the JWST and gravitational lensing effect could be one of the most powerful ways.
4 CONCLUSION

We have performed a large and high resolution cosmological hydrodynamic simulation to investigate the detectability of nebular lines in the rest-frame UV to optical wavelength range at $z > 7$. Our new simulation code based on Okamoto et al. (2010) and Okamoto, Shimizu & Yoshida (2014) can reproduce not only the stellar mass function, the downsizing, the mass-metallicity ratio but also the statistical properties of star forming galaxies such as Lyman break galaxies (LBGs), Lyman $\alpha$ emitters and sub-mm galaxies (Shimizu, Yoshida & Okamoto 2011, 2012; Shimizu et al. 2014). First, we calibrate our model parameters so as to reproduce not only the stellar mass function at $z > 7$ but also the UV luminosity function from $z \sim 7$ to $z \sim 10$. Then, we generate a light-cone output which extends from $z = 6$ to $z = 17$ using a number of simulation outputs. After making this light-cone output, we adopt the same colour selection criteria the same as in the observations with the HST/WFC3 camera (Bouwens et al. 2014b; Oesch et al. 2014). Using the colour selected galaxies, we explore expected emission line fluxes in the rest-frame UV to optical wavelength such as C IV 1549Å, C III] 1909Å, [O III] 5007Å and Hα, etc. These lines are very important not only to confirm spectroscopic redshift of the galaxies but also to perform the diagnostics of the gas metallicity. We find that the redshift evolution of the line flux as a function of the $H_{160}$ magnitude is fairly weak because the metallicity evolution is very weak as shown in Fig. 4. The C IV 1549Å and the C III] 1909Å lines from galaxies with the band magnitude < 26 AB at $z > 7$ are detectable even by the current telescopes such as the VLT/X-Shooter and the Keck/MOSFIRE. Indeed, Stark et al. (2015a) successfully detected the lines from two galaxies at $z \sim 7$ and their detections are fully consistent with our prediction. Many important lines are detectable with the JWST/NIRSPEC, JWST/MIRI and the TMT/IRMS if the $H_{160}$ band magnitude is brighter than 28 mag. Especially, the C IV 1549Å, C
for them. This does not mean that we cannot detect emission lines of nebular lines for $z > 9$ galaxy candidates found so far. For MACS1149 JD, there are two estimates for the magnification factor and we show two cases (solid and dotted histograms).

Finally, we predict the detectability of nebular lines for $z \geq 11$ galaxies satisfying K band magnitude < 30 mag. The redshift evolution of the line flux K band magnitude relation is very weak even at $z \geq 11$. We find that the C iv 1549 Å and the C iii] 1909 Å lines are detectable by the JWST/NIRSPEC, and TMT/IRMS even at $z \sim 12$. However, there are few galaxies at $z \sim 15$ to exceed the detection limit of the future telescopes in our small FOV simulation. This does not mean that we cannot detect emission lines from $z \sim 15$ galaxies. In fact, the JWST and the TMT can detect emission lines from galaxies with < 28 AB mag at any redshift which would be discovered, for example, by a > 100 deg$^2$ survey planned with the future telescope such as the WFIRST and the FLARE. We can detect $z \sim 15$ galaxies with a help of magnification by gravitational lensing even narrow FOVs. We predict that, according to our model, the C iii] 1909 Å line in $z > 9$ galaxy candidates (MACS1149 JD and MACS0647JD1) is detectable using even the current facilities such as the VLT/X-Shooter and the Keck/MOSFIRE with high probability. The survey with the combination of gravitational lensing and the GMT, the TMT, or the JWST is a good way to study higher-$z$ ($z > 7$) line emitting galaxies.

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