HEAVY DUST OBSCURATION OF \( z = 7 \) GALAXIES IN A COSMOLOGICAL HYDRODYNAMIC SIMULATION

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ABSTRACT

Hubble Space Telescope observations with the Wide Field Camera 3/Infrared reveal that galaxies at \( z \sim 7 \) have very blue ultraviolet (UV) colors, consistent with these systems being dominated by young stellar populations with moderate or little attenuation by dust. We investigate UV and optical properties of the high-\( z \) galaxies in the standard cold dark matter model using a high-resolution adaptive mesh refinement cosmological hydrodynamic simulation. For this purpose, we perform panchromatic three-dimensional dust radiative transfer calculations on 198 galaxies of stellar mass \( 5 \times 10^8 \sim 3 \times 10^{10} \, \text{M}_\odot \) with three parameters: the dust-to-metal ratio, the extinction curve, and the fraction of directly escaped light from stars (\( f_{\text{esc}} \)). Our stellar mass function is found to be in broad agreement with Gonzalez et al., independent of these parameters. We find that our heavily dust-attenuated galaxies \( (A_V \sim 1.8) \) can also reasonably match modest UV–optical colors, blue UV slopes, as well as UV luminosity functions, provided that a significant fraction \((\sim 10\%)\) of light directly escapes from them. The observed UV slope and scatter are better explained with a Small-Magellanic-Cloud-type extinction curve, whereas a Milky-Way-type curve also predicts blue UV colors due to the 2175 Å bump. We expect that upcoming observations by the Atacama Large Millimeter/submillimeter Array will be able to test this heavily obscured model.

Key words: galaxies: high-redshift – galaxies: ISM

Online-only material: color figures

1. INTRODUCTION

Observational techniques based on photometric properties of star-forming galaxies have proven to be successful in identifying galaxies at high redshift (Steidel et al. 1996). In particular, the arrival of recent Wide Field Camera 3/Infrared (WFC3/IR) data taken with the Hubble Space Telescope (HST) has increased the sample of \( z \)-dropout galaxies \((z \sim 7; \text{e.g., Bouwens et al. 2012})\), allowing for the investigation of ultraviolet (UV) properties of the early galaxies. These \( z \sim 7 \) candidates reveal (FUV – NUV) colors close to zero or sometimes negative (Bouwens et al. 2010, 2012, 2013; Wilkins et al. 2011; McLure et al. 2011; Dunlop et al. 2012, 2013; Finkelstein et al. 2012), indicating a very blue ultraviolet (UV) continuum slope \( \beta \sim -1.5 \). Where the UV-continuum slope \( \beta \) relates to the flux density per unit wavelength \((f_{\lambda})\) as \( f_{\lambda} \propto \lambda^{-\beta} \). Given that a small amount of dust can substantially redistribute theSED, the low \( \beta \) value has been taken to indicate a limited amount of dust in these systems.

On the other hand, using Spitzer Infrared Array Camera (IRAC) and WFC3/IR data, Labbé et al. (2010) reported that their \( z \sim 7 \) galaxies have moderate rest-frame optical colors \( U-V \sim 0.3-0.5 \), implying the presence of an evolved stellar population older than 100 Myr. In fact, for a realistic rising star formation (SF) history, the age of the population alone seemed very difficult to explain such colors without significant attenuation by dust and/or nebular line emission (Finlator et al. 2011; Labbé et al. 2010). Several authors pointed out the possibility that these apparently conflicting results are maybe due to contamination by nebular emission lines, such as H\( \beta \) and [O III] 4959, 5007 doublet (Schaerer & de Barros 2010; Labbé et al. 2012; Curtis-Lake et al. 2013; Stark et al. 2013; Schenker et al. 2013; Bouwens et al. 2013), to the IRAC 3.6 \( \mu \)m band. For example, Labbé et al. (2012) claim that the \( z \sim 7 \) galaxies show \( H_{60}-[4.5] \) colors that are much bluer than \( H_{60}-[3.6] \) colors, supporting the view that the high-\( z \) galaxies are young and affected by moderate or little dust attenuation.

However, some hydrodynamic simulations in a cold dark matter cosmology predict that galactic metal enrichment occurs in a very short time scale (e.g., Finlator et al. 2011), leading to the formation of galaxies of stellar mass \( 10^{10} \, \text{M}_\odot \) with a metallicity close to solar at \( z \sim 7 \). Given that galaxies are more compact and denser at higher redshift (e.g., Ferguson et al. 2004; Trujillo et al. 2006; van Dokkum et al. 2008), one may expect that the simulated galaxies are significantly dust attenuated, and may be in conflict with observations. In this study, we test this idea by confronting simulated UV luminosity and stellar mass functions (SMFs) and UV and optical colors of \( z = 7 \) galaxies with observations. A self-consistent three-dimensional radiative transfer calculation on galaxies produced by a cosmological simulation with \( \sim 30 \) times better spatial resolution \((29 \, h^{-1} \, \text{pc})\) is a significant improvement over previous studies (Devriendt et al. 2010; Salvaterra et al. 2011; Finlator et al. 2011). More importantly, we show that, with a Small-Magellanic-Cloud-(SMC)-type extinction curve, our substantially dust-attenuated galaxies can also simultaneously explain the observed red UV–optical colors, blue UV colors, as well as UV luminosity functions (UVLFs) if the escape fraction of stellar photons is \( \sim 10\% \).

The outline of this paper is as follows. We first describe the simulation details in Section 2. In Section 3, simulated galaxies with different assumptions on dust properties are compared with observations. Finally, we discuss the implications of these results and conclude in Section 4.

2. SIMULATIONS

The cosmological simulation is performed with the Eulerian hydrodynamics code \textsc{enzo} (Bryan 1999; O’Shea et al. 2005; Joung et al. 2009; Bryan et al. 2013). For more details on the simulation setup and implemented physics, the reader is referred to Cen (2012). Briefly, this is a large zoom-in simulation of \( 21 \times 24 \times 20 \, h^{-3} \, \text{Mpc}^3 \) embedded in a \( 120 \, h^{-1} \, \text{Mpc} \) periodic
box. The simulation includes a uniform Haardt–Madau UV background where the cosmic reionization occurs at \( z = 9 \), a shielding of UV radiation by neutral hydrogen, metal-dependent radiative cooling down to 10K, SF, and supernova feedback (Cen 2012). The physical prescriptions have been validated by a large suite of independent observations, including the cosmic SF history (Cen 2011), and damped Lyman alpha systems at redshift \( z = 0–5 \) (Cen 2012). The maximum spatial resolution is \( 29 h^{-1} \) pc, and dark matter particles of \( 10^8 M_\odot \). Note that the attenuated spectra is redshifted within the zoomed-in region. The initial condition is generated with the cosmological parameters that are consistent with the WMAP7 results (Komatsu et al. 2011): \( \Omega_m, \Omega_b, h, \sigma_8, n_s = 0.28, 0.046, 0.72, 0.82, 0.96 \).

To compute the SEDs of each galaxy, we post-process the simulation output at \( z = 7 \) using a three-dimensional dust radiation transfer code \textsc{sunrise} (Jonsson 2006; Jonsson et al. 2010). The main advantage of \textsc{sunrise} is the use of a polychromatic algorithm, which can trace information in all wavelengths per each ray. It makes use of the standard dust cross-sections (e.g., Weingartner & Draine 2001; Draine & Li 2007) to simulate absorption and multiple scattering by dust. The input stellar spectrum is taken from \textsc{stARBurst}99 (Leitherer et al. 1999) assuming a Kroupa initial mass function with the low (high) mass cut-off of \( 0.1 M_\odot (100 M_\odot) \). \textsc{sunrise} also uses the spectrum of \textsc{HII} or photo-dissociation regions (PDRs) computed by a photo-ionization code \textsc{MAPPINGSIII} (Dopita et al. 2005; Groves et al. 2008) to take into account the immediate absorption and emission by birth clouds. It is done by replacing the SEDs of young (\( \leq 10 \) Myr) star particles with reprocessed SEDs of a population with constant SF for 10 Myr by \textsc{MAPPINGSIII} (see Jonsson et al. 2010). The fraction of light processed by PDRs is controlled by a parameter \( f_{\text{PDR}} \), which we adopt \( f_{\text{PDR}} = 0.2 \) following Jonsson et al. (2010). The amount of dust is inferred from the amount of metals by assuming an adjustable dust-to-metal ratio \( (D/M) \). We use the maximum resolution available from the adaptive mesh refinement (AMR) hydrodynamic simulation (\( \sim 29 h^{-1} \)) to compute absorption and scattering by dust. We test the convergence of the \textsc{sunrise} results by degrading the most refined cells in each halo by one level, before performing dust radiative transfer. We find that the attenuated UV and UV–optical colors are well converged (within \( \sim 0.01 \) dex). Note that the attenuated spectra is redshifted to \( z = 6.7 \) in order to match the typical redshift of the \( z \sim 7 \) sample (e.g., Bouwens et al. 2013) and then convolved with WFC3/IR F125W, F160W, and IRAC [3.6 \( \mu \)m] filter throughputs to yield \( J_{125}, H_{125}, \) and [3.6] mag in AB magnitude, respectively.

3. RESULTS

Our simulated sample consists of 198 galaxies of stellar mass \( 5 \times 10^8 \leq M_{\star} \leq 2.5 \times 10^9 M_\odot \) at \( z = 7 \). The simulated galaxies with \( M_{\star} \simeq 5 \times 10^9 M_\odot \) have the specific star formation rate (sSFR) of \( \sim 6 \) Gyr\(^{-1} \), with more massive galaxies having smaller sSFR (see also Cen 2011), compatible with the recent measurements by Schaerer & de Barros (2010), Bouwens et al. (2012), and Stark et al. (2013). A simple fit to the stellar mass and SFR gives \( \dot{M}_{\star} \simeq 55 M_\odot \) yr\(^{-1} \left( M_{\star}/10^9 M_\odot \right)^{0.76} \).

The predicted stellar (gas) metallicities of galaxies with \( M_{\star} \simeq 10^9 \) and \( 10^{10} M_\odot \) are \( \geq 0.5 \) and 1.0\( Z_\odot \) (0.6, and 0.5 \( Z_\odot \)) respectively, indicating that more massive galaxies have more metal-rich populations. We note that similar metal enrichment...
is found in Finlator et al. (2011, Figure 11), which is based on an entirely independent numerical technique and feedback prescription.

3.1. Calibrations to Stellar Mass and UV Luminosity Functions

The left panel of Figure 1 shows the SMF of simulated galaxies at \( z = 7 \), which is seen to reasonably well match the observed SMF based on SED fitting with HST+Spitzer data (González et al. 2011; Labbé et al. 2010). However, we note that nebular emission lines, such as \( H\beta \) or [O iii] 5007, may contribute to Spitzer/IRAC 3.6 \( \mu m \) bands, resulting in possible overestimation of stellar mass of observed galaxies (Schaerer & de Barros 2010; Stark et al. 2013; Curtis-Lake et al. 2013). Bearing this in mind, we also discuss a model in which stellar mass and stellar and gas metallicities are artificially lowered by a factor of 2.5, such that galaxies with \( M_{\text{star}} \approx 10^7 \) \( M_\odot \) have stellar metallicity of \( \pm 0.2 \) Z_\odot.

In the right panel of Figure 1, we present rest-frame UVLFs at \( z = 7 \). The absolute UV magnitude (\( M_{1600} \)) is measured by integrating the SED at \( \lambda = 1600 \) Å through a square filter of width 100 Å. We find that the intrinsic UV of simulated galaxies (gray dotted line) would be too bright compared with observations (Bouwens et al. 2011; Lorenzoni et al. 2013; Dunlop et al. 2013) by about 2–3 mag. Performing dust radiative transfer substantially improves the agreement of simulated UVLFs with observations. We find that a dust-to-metal ratio of \( D/M = 0.06 \) successfully reproduces the observed UVLFs up to \( M_{1600} \approx -19.5 \) (corresponding to 3–10 \( \times 10^8 \) \( M_\odot \), e.g., Stark et al. 2013), above which our simulation is incomplete. The resulting attenuation in FUV is found to be \( 1 \leq A_{1600} < 5 \). On the other hand, adopting the dust-to-metal ratio \( D/M = 0.4 \), inferred from local metal-rich galaxies (e.g., Dwek 1998; Draine et al. 2007), we find that the simulated galaxies would suffer from too much extinction (dashed lines). This is the case regardless of whether the extinction curve is a Milky-Way-(MW)-type (green lines) or an SMC-type (orange lines), as the dust extinction cross-section around 1600 Å is similar in the two cases (e.g., Weingartner & Draine 2001).

We stress that it is possible that our simulation underresolves the porosity of the interstellar medium (ISM), potentially giving rise to a higher covering fraction of dusty gas around young stars (cf., Wise & Cen 2009). In this case, the number of UV photons directly coming out of galaxies may be underestimated. We exploit this possibility by introducing a free parameter, \( f_{\text{esc}} \), which quantifies the fraction of directly escaped light from stars. Conceptually, \( f_{\text{esc}} \) differs from \( f_{\text{FR}} \) in the sense that the former is related to the global ISM structure, while the latter is only applicable to young stars and their birth clouds. We find that adding 10% of the intrinsic stellar light to the strongly attenuated spectrum with \( D/M = 0.4 \) can also give a reasonable match to the observed UVLF (orange dotted line), indicating that there is a degeneracy between a dust-to-metal ratio and the escape fraction. This particular case may be viewed as the model with the maximum \( f_{\text{esc}} \), as opposed to the models with \( f_{\text{esc}} = 0 \) (MW.06 or SMC.06). The resulting difference between the two cases is the differential reddening in UV and optical bands, as we discuss in the next section.

It is worth noting that our simulated galaxies represent actively star-forming, dusty galaxies. In the case of the model with SMC-type extinction, \( D/M = 0.4 \), and \( f_{\text{esc}} = 0.1 \) (SMC.4_f0.1), galaxies with \( 5 \times 10^8 \leq M_{\text{star}} < 3 \times 10^{10} \) \( M_\odot \) turn out to have \( A_V \approx 1.8 \pm 0.3 \). Given that high-z galaxies are generally more compact than their local counterparts (e.g., Ferguson et al. 2004), such heavy attenuation may not be too surprising. As aforementioned, however, if our galaxies formed too many stars and overproduced metals, the extinction is likely to be overestimated. To quantify a possible change in the extinction, we compare an ad hoc case (SMC.4_f0.2rm) in which stellar mass, metallicity, and gas metallicity are reduced by a factor of 2.5 before performing radiative transfer calculations. We use an escape fraction of 20% to match the observed UVLFs in this case. Even in this model with smaller galaxy masses and smaller amounts of dust, it turns out that the galaxies still show more significant attenuation of \( A_V \approx 1.4 \) compared to \( A_V \approx 1 \) derived based on a single dust screen model fitting of the observed SED (Schaerer & de Barros 2010).

3.2. UV and Optical Colors

Figure 2 shows the UV slope (\( \beta \)) as a function of UV luminosity, where \( \beta \) is computed from the UV color as \( \beta = 4.43(J_{125} - H_{160}) - 2 \) (Dunlop et al. 2013). The latest determinations of the slope from two independent studies, Bouwens et al. (2013) and Dunlop et al. (2013), are shown as filled squares and triangles. Several interesting features can be found in this figure. First, our simulated galaxies show intrinsically blue UV colors (\( \beta \approx -2.2 \)) with little dependence on luminosity. Although SFRs of our simulated galaxies increase with increasing stellar mass, we find that a considerable scatter in the \( M_{\text{star}} - M_{\text{star}} \) relation \((\sim 0.3 \text{ dex})\) leads to the scatter in the intrinsic \( M_{\text{UV}} \) for a
given stellar mass, weakening the dependence on the UV slope (Figure 2, gray squares). Second, the UV slope in the models with MW-type dust turns out to be too steep for bright galaxies ($M_{UV} \lesssim -20$) regardless of the amount of dust (MW.4_f0.1 and MW.06). This is because the dust cross-sections in $J_{125}$ and $H_{160}$ bands are comparable due to the 2175 Å bump. For the same reason, the models predict a much smaller scatter in the UV slope than observed. These suggest that dust in the $z \sim 7$ galaxies is unlikely to share the same grain distribution as the MW. Third, the model in which SMC-type dust pervades (SMC.06) predicts a too shallow UV slope ($\beta \sim -0.5$) than observed due to stronger attenuation at FUV than at NUV wavelengths. We find that predicted UV slopes of luminous galaxies ($M_{UV} \lesssim -19.5$) are broadly consistent with observations, within error bars, only in the models with SMC-type dust and a large escape fraction (SMC.4_f0.1 and SMC.4_f0.2rm). For the less luminous bins ($M_{UV} \gtrsim -19.5$), our simulation is incomplete (Figure 1), and thus may not be directly compared to the observations. Nevertheless, the correlation between the UV slope and luminosity in this model appears to be weak in the bright regime, consistent with observations. It is also noteworthy that the scatter in the UV slope is more notable than that of MW-type dust, as there is a mixture of galaxies with different attenuation for a given UV luminosity.

Another factor that can alter the UV slope is the covering fraction of the PDR ($f_{PDR}$). As shown in Figure 6 from Groves et al. (2008), a covering fraction close to one considerably reddens the UV spectrum of young stellar populations. We examine how sensitive the predicted UV slope is to the choice of $f_{PDR}$, and find that our results do not depend strongly on the parameter. In the case of $f_{PDR} = 0$, the UV slope of the input SED (i.e., MAPPSHII + STARBURST99) is only slightly steeper ($\Delta \beta = -0.045 \pm 0.034$) than the one with the fiducial value, $f_{PDR} = 0.2$. Conversely, setting $f_{PDR} = 0.5$ makes the slope shallower by only $+0.09$ dex. After extinction, the difference becomes even smaller. Such a small change in $\beta$ is essentially because (1) the impact of $f_{PDR}$ on the UV slope is only prominent at $f_{PDR} \gtrsim 0.5$, and (2) a significant fraction ($\sim 40\%$) of the intrinsic UV flux arises from the stars older than 10 Myr. However, even when $f_{PDR} = 1$ is assumed, the change in the slope of the input SED is found to be $\Delta \beta \sim 0.4$, which is a smaller effect than that of attenuation by the intervening interstellar dust or the escape fraction.

An interesting puzzle of $z \sim 7$ galaxies is their red UV–optical color ($H_{160}$-$[3.6]) \sim 0.6$–0.9. As pointed out by Finlator et al. (2011), obtaining such a red UV–optical color is not trivial for actively star-forming galaxies with little dust. In accord with Finlator et al. (2011), we predict that our simulated galaxies are indeed very blue, ($H_{160}$ – [3.6]) \sim -0.1, in the absence of dust attenuation and nebular emission lines, shown as gray filled circles in Figure 3. For a fair comparison with Labb{é} et al. (2010), we present average colors and their 1σ dispersions by dividing the simulated galaxy sample into three $H_{160}$ magnitude bins, $25 < H_{160} \leq 26.6$, $26.6 < H_{160} \leq 27.5$, and $H_{160} > 27.5$. Note that the last bin ($M_{UV} \gtrsim -19.5$) is incomplete due to finite resolution (Figure 1), and displayed as empty circles.

The inclusion of nebular emission lines can improve the agreement by increasing the flux in the optical band. Strictly speaking, several strong emission lines, such as $[O ii]$ 3726/3729 doublet or $[O iii]$ 4959, 5007, do not fall within Spitzer/IRAC [3.6] window for $z = 7$ galaxies. However, for galaxies at redshift $z = 6.7$, $[O ii]$ 4959, 5007 lines can contribute to the [3.6] flux. In order to take into account the contribution, we add the emission lines corresponding to the equivalent width of $\lesssim 320$ Å, motivated by observations1 (Labbe et al. 2012; Schenker et al. 2013). This means that the UV bright (faint) galaxies are likely to have moderate (blue) UV–optical continuum colors. Nevertheless, inclusion of nebular emission does not suffice to account for the observed colors, indicating that it may not be fully responsible for the observed red $H_{160}$-[3.6] colors (see also Finlator et al. 2011; cf. Stark et al. 2013).

We find that red UV–optical colors can naturally arise by dust extinction. Figure 3 clearly shows that the models with a zero escape fraction (MW.06 and SMC.06) produce sufficiently red galaxies ($H_{160} - [3.6] \gtrsim 1$), as the dust extinction cross-section is larger in the UV wavelengths than in the optical range (Weingartner & Draine 2001). In particular, the models showing reasonable UV slopes (SMC.4_f0.1 and SMC.4_f0.2rm) predict UV–optical colors that are compatible with observations. Note that the contribution from nebular line emission (0.3 dex) is already included in theses calculations, and dust extinction accounts for the reddening of $\sim 0.4$ dex in the two models (SMC.4_f0.1 and SMC.4_f0.2rm). We expect that higher dark matter resolution would lead to better agreement, as more stars

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1 We could directly compute the equivalent width of the emission lines from the SUNRISE output, but we decided not to do so, mainly because the prediction is uncertain in the case of the models with a non-zero escape fraction. Accordingly, we removed the emission lines from the simulated SEDs, and then increased the [3.6] mag by 0.3 dex, motivated by observations (Labbe et al. 2012; Schenker et al. 2013).
would form in smaller dark matter halos at earlier epochs. For example, we find that increasing the mean stellar age from 100 Myr to 200 Myr can easily redden the UV–optical colors by 0.2 dex without changing UV slopes significantly. Thus, we conclude that our heavily obscured galaxies with SMC-type dust and a high escape fraction can also simultaneously explain the blue UV colors and moderate UV–optical continuum colors.

4. CONCLUSIONS AND DISCUSSION

Utilizing an ab initio cosmological AMR hydrodynamic simulation with high resolution (29 h−1 pc), we investigate FUV–NUV and UV–optical colors of 198 simulated galaxies at z = 7. We post-process our metal-rich galaxies (z ∼ 0.1–1.0 Z⊙) through three-dimensional panchromatic dust radiative transfer calculations by varying three parameters, the dust-to-metal ratio (D/M), the extinction curve, and the fraction of directly escaped light (fesc). By matching simulated UVLFs to the ones observed, we identify two sets of models with (D/M, fesc) = (0.06, 0) or (0.4, 0.1), corresponding to the cases with the minimum and the maximum escape fraction.

We find that the observed moderate UV–optical continuum colors as well as blue UV colors of z ∼ 7 galaxies can be simultaneously reproduced with SMC-type dust, a large dust-to-metal ratio of 0.4, and fesc = 10%. The resulting attenuation in the V band is found to be more significant (⟨A_V⟩ ∼ 1.8) than the one derived based on a single dust screen model fitting of the observed SED (Schaffer & de Barros 2010). On the other hand, the model with a zero escape fraction and D/M = 0.06 produces galaxies with too shallow UV slopes (∼ −0.5) compared with observations (Dunlop et al. 2013; Bouwens et al. 2013).

After searching through the parameter space, the fact that the model with a fesc = 0.1% is favored over a model with much smaller fesc is worth noting. Observations of cosmological reionization infer the Thomson optical depth τ_r = 0.089 ± 0.014 (Hinshaw et al. 2012), indicating a reionization redshift of z_re = 10.6 ± 1.1 (assuming a sudden reionization picture). In order to reionize the universe at this redshift range by stellar sources, fesc ∼ 10% is likely required (e.g., Cen 2003). Moreover, detailed radiative transfer simulations indicate a porous ISM and a high escape fraction can also simultaneously explain the characteristic UV–optical colors of 198 simulated galaxies at z ∼ 7, given that a substantial fraction of starlight may originate from the late stage of stellar evolution (e.g., Draine 2009). Interestingly, observations of quasars at z ∼ 6–7 report the detection of large masses of dust (Bertoldi et al. 2003; Dwek et al. 2007; Wang et al. 2008; Venemans et al. 2012), supporting that a majority of dust is grown in the ISM (Draine 2003; for an alternative explanation, see also Bianchi & Schneider 2007). A most direct test of our model is by detection of strong IR emission from the UV selected galaxies and details will be presented in a companion paper (R. Cen & T. Kimm 2013, in preparation).

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