The colors of galaxies at 4 z

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The Colors of Galaxies at $4 < z < 8$ and their Contribution to Reionization

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Abstract. We present recent results on the rest-frame ultraviolet (UV) colors of galaxies at high-redshift, and the contribution of these galaxies to the reionization of the intergalactic medium (IGM). Using a combination of deep and wide data from the CANDELS, HUDF09 and ERS programs, we find that galaxies at $z = 7$ appear to be dust free, and they become substantially dustier by $z = 4$. Faint galaxies at $z = 7$ appear very blue, but they are consistent with the colors of very blue local galaxies, thus there is no evidence for the presence of exotic stellar populations. We find that the observable galaxy population can sustain a fully ionized IGM at $z = 6$ if the escape fraction of ionizing photons (f_{esc}) is 30%. If the luminosity function extends much fainter, then the required f_{esc} is lowered to $\sim$10%. Examining the constraint on the emission rate of ionizing photons from Lyα forest measurements, we find that if the luminosity function extends to $M_{UV} = -13$, f_{esc} must be less than 13% at $z = 6$. This escape fraction can still sustain a reionized IGM at $z = 6$, and even at $z = 7$, but unless it rises substantially at $z > 6$, the IGM may be $\sim 20-50$% neutral by $z = 8$.

INTRODUCTION

The reionization of the intergalactic medium (IGM) is a hallmark event in the history of the universe, as it marks the first time bound objects, such as galaxies and/or black holes, were able to exert considerable influence on the environment around them. Learning when reionization occurred, and the nature of the sources that were responsible, can give us a unique glimpse into the cosmos at early times. Measuring the Thomson scattering optical depth to electrons from the *Wilkinson Microwave Anisotropy Probe* (*WMAP*), [1] were able to place contraints on the redshift for *instantaneous* reionization to be z_{reion} = 10.6 $\pm$ 1.2. However, reionization is likely more extended, particularly if galaxies dominated the process, as it would take time for their ionized bubbles to overlap and complete reionization, thus we can look for signatures of reionization at lower redshifts. While spectroscopic observations of quasars at $z \sim 6$ are consistent with a volume ionized fraction in the IGM of unity [e.g., 2], hints via studies of Lyα emission have been trickling in that this situation might change by $z = 7$. The luminosity function of Lyα emission from galaxies is remarkably constant from $z = 3$ to 6 [e.g., 3], but there is some evidence that it begins to decrease at $z > 6$ [e.g., 4], implying a rising IGM neutral fraction. Additionally, the fraction of galaxies which have detectable spectroscopic Lyα emission, which had been rising from $z = 4$ to 6 [5], appears to drop by $z \sim 7$ [6, 7, 8], though in the latter case the current samples are small, which highlights the need for better observations in the $z > 6$ universe. If galaxies are the main source of ionizing photons, by probing them at higher and higher redshift we can examine their contribution to the ionizing photon budget, and constrain when the universe was reionized.

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DISCOVERY AND PROPERTIES OF GALAXIES AT $6 < z < 8$

Until recently, the $z \geq 7$ universe was inaccesible, as galaxies at these great distances had their observable light shifted into the observed near-infrared (near-IR). This changed in 2009, with the installation of the Wide Field Camera 3 (WFC3) on board the *Hubble Space Telescope* (*HST*). The first science program executed with this sensitive instrument was the Hubble Ultra Deep Field 2009 (HUDF09; PI Illingworth). Very quickly, a number of groups published papers presenting the discovery of the first large samples of $z = 7$ and 8 galaxies [e.g, 9, 10, 11]. These studies showed via preliminary luminosity functions that the ultraviolet (UV) luminosity density from galaxies appears to continue its decrease, first noted from $z = 4 \rightarrow 6$ [e.g., 12], out to $z = 8$. However, as these observations were made in three filters, they also afforded the opportunity to measure the rest-frame UV colors of these galaxies, to diagnose their stellar populations.

Both [13] and [11] analyzed the UV colors, finding that faint galaxies at $z = 7$ had rather blue colors, with a UV spectral slope of $\beta = -3$ (β is a measure of the power-law slope of the rest-frame UV spectrum). This is bluer than can be obtained with a "normal" stellar population, with a Salpeter initial mass function (IMF) and a metallicity of at least 10% Solar. Thus, some speculated that these very blue colors might be indicative of very low metallicity star-formation, as one might expect in the earliest galaxies to form in the universe [13]. However, the uncertainties on these colors were very high, thus their colors were also consistent with local star-forming galaxies such as NGC 1705, which is thought to be dust-free, though with a substantial metal content [11].

To make progress on the issue of stellar populations thus requires a higher fidelity sample, composing more than just a few faint $z = 7$ galaxies. This has now been accomplished by combining the data in the HUDF with new, deep and wide-area data from the *HST* Multicycle Treasury program CANDELS (Cosmic Assembly Near-Infrared Deep Extragalactic Legacy Survey; PIs Faber & Ferguson) and the WFC3 Early Release Science dataset (ERS). Combining these surveys, we have now discovered ~150 galaxies at $z > 7$, compared with only ~20-30 in the original HUDF WFC3 studies [14, 15]. We have selected these samples via photometric redshifts, comparing the observed photometry to a series of spectral templates to determine a redshift probability distribution function. Combining these samples with similarly selected galaxy samples at $z = 4$, 5 and 6, we have compiled a sample of ~ 2800 $z = 4 - 8$ galaxies, with which we can use to examine the evolution of the UV colors of galaxies over this ~1 Gyr period.

Figure 1 shows the evolution of the UV spectral slope β from this sample of galaxies, taken from [14]. The points here show a strong evolution in the median value of β at each redshift. This color evolution is likely dominated by an increase in dust extinction, as just a little bit of dust can redden a galaxy much more than a substantial increase in age or metallicity (see Figure 7 of [16]). Thus $z \sim 7$ galaxies appear to have little-to-no dust, while by $z = 4$ galaxies typically have ~ 0.4 magnitudes of visual dust attenuation. The timescales involved are intriguing, as this substantial build-up in dust does not appear to begin until ~600-800 Myr after the Big Bang. Assuming galaxies have a formation redshift of $z \sim 15 - 20$, it is surprising that dust does not appear until $z < 7$. Dust forms via both supernovae (SNe), and in evolved stars when they pass through their asymptotic giant branch (AGB) phase. As massive stars likely existed at early times, there should have been SNe at $z > 8$, thus dust should have existed as well. However, it takes 3-4 $M_{\odot}$

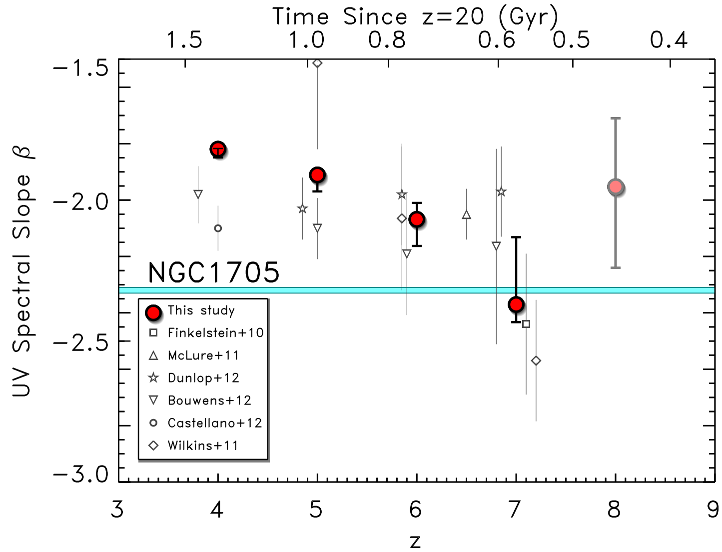

FIGURE 1. Evolution of the median value of the UV spectral slope β with redshift for all galaxies in our sample (circles). The smaller symbols represent recent results from the literature. We find that significant evolution in β takes place from $z = 7$ to 4, likely due to increased dust extinction. The point at $z = 8$ is preliminary, due to the large scatter inherent in measuring β for faint galaxies from a single color. We have faded this point in the figure to caution the reader about these uncertainties [figure from [14]].

stars $\sim$ 500 Myr to evolve off the main sequence, and pass through the AGB phase. This is very similar to the amount of time between the inferred formation redshift of galaxies, and the epoch when we see the dust content begin to rise. Thus, perhaps the dust we observed in the $z < 7$ galaxies forms predominantly in AGB stars.

To investigate this further, we examined the evolution of β with redshift as a function of stellar mass. We found that while lower mass galaxies exhibited a trend similar to the median as shown in Figure 1, the highest mass galaxies (log $M = 9 - 10$) appeared red at every redshift, with $\beta = \sim 1.8$. Thus, some galaxies at $z = 7$ possess dust, and they just happen to be the most massive ones. At $z = 7$ this dust must have formed in SN. Why then do we not see dust in lower mass galaxies? The answer likely is related to feedback. At $z \leq 3$, a relationship between stellar mass and gas-phase metallicity has been observed, where lower-mass galaxies have lower metallicities [e.g., 17]. This has been interpreted as outflows (driven by SNe from ongoing star-formation), preferentially removing gas (including metals and dust) from lower-mass galaxies. The mass-dependent trend in β we observe indicates that a similar effect is taking place at very high redshift.

We also re-examined the issue of faint galaxies at $z = 7$. Using our updated sample, we measured $\beta = -2.7 \pm 0.35$ (-2.4 correcting for observational bias). Not only is this redder than previously measured, but the uncertainty has shrunk as well (σ_β was previously 0.5 [11]). We confirm our earlier conclusion that galaxies at $z \sim 7$ are not harboring very low metallicity stellar populations.

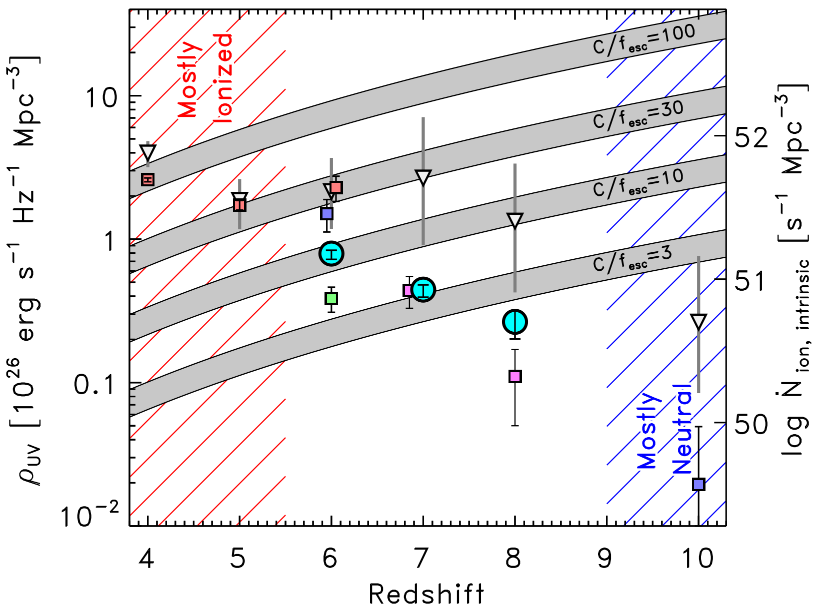

FIGURE 2. The specific luminosity density versus redshift, where our incompleteness-corrected samples are plotted as the cyan circles. Results from the literature are shown as squares at $z = 4$, 5 and 6 from GOODS [red; 22], $z = 6$ from the HUDF [green; 23], $z = 7$ and 8 from the HUDF [purple; 11] and $z = 6$ from GOODS+HUDF and $z = 10$ from the HUDF [blue; 24, 25]. The inverted triangles denote the integrated luminosity functions down to $M_{UV} = -13$ from [12], [19], [20] and [25]. The wide gray curves denote the value of ρ_{UV} needed to sustain a fully reionized IGM at a given redshift, for a given ratio of the clumping factor C over the escape fraction of ionizing photons f_{esc} [figure from [18]].

REIONIZING THE UNIVERSE WITH GALAXIES

Using an updated version of the galaxy sample from [14], we can now examine the contribution of galaxies to the reionization of the universe, which we have presented in [18]. Previous studies have looked at the contribution from galaxies to reionization by fitting a Schechter function to the observed galaxy luminosity distribution, and integrating that function down to a magnitude far below the observational limit [e.g., 9]. This is however reliant on the assumption of a Schechter function parameterization. As we push closer to the Big Bang, galaxies are changing rapidly, thus at some point we may encounter an epoch where the Schechter function is no longer an accurate representation. Also, when integrating the luminosity function one needs to choose a limiting magnitude, as only gas above a certain mass limit can cool and form stars. However, we have no observational evidence for this value, and theoretical results from the literature yield values of $-15 < M_{UV} < -10$ [e.g., 21]. With a steep faint-end slope, this range can result in a difference in the integrated luminosity density by more than a factor of two. To avoid these uncertainties, we examine the contribution from galaxies above the detection limit of *HST*. The results of our analysis are shown in Figure 2, which shows the rest-frame UV specific luminosity density from galaxies in our sample (at $M_{UV} < -18$) at $z = 6$, 7 and 8. We use the model of [26], which is shown as the gray

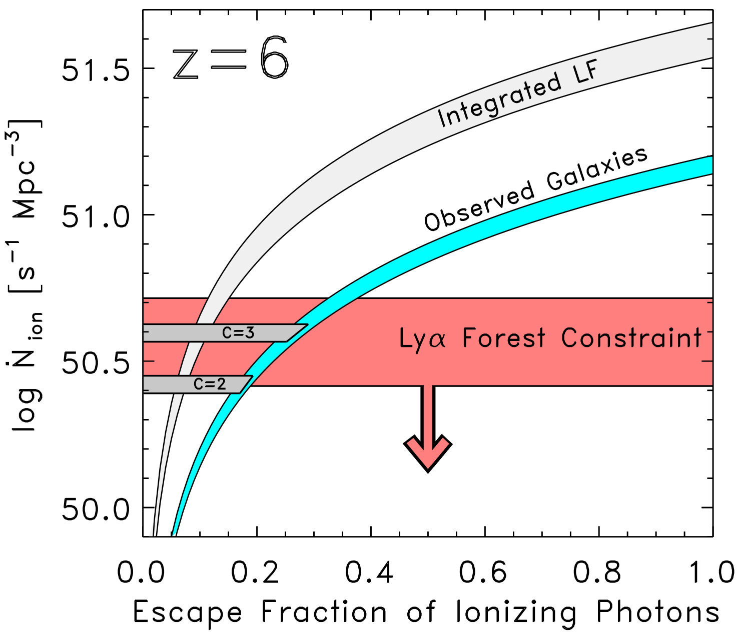

FIGURE 3. The inferred emission rate of ionizing photons from our incompleteness-corrected sample of $z = 6$ galaxies (cyan; the width denotes the 68% confidence range), as well as from the $z = 6$ luminosity function of [12] integrated down to $M_{UV} = -10$ (left side of light-gray curve) and -15 (right side). Both quantities are plotted as a function of the escape fraction of ionizing photons. The red region denotes the constraints on this quantity at $z = 6$ from the Lyα forest, with the lower and upper edges representing the 1 and 2σ constraints from [27], respectively. The dark gray bands denote the emission rate of ionizing photons necessary to sustain reionization for a given value of the clumping factor [figure from [18]].

curves in Figure 2 for different ratios of the clumping factor of ionized gas in the IGM (C) and the escape fraction (f_{esc}), to examine whether our observed luminosity density can maintain a fully reionized universe. C is estimated theoretically, and likely lies in the range $1 < C < 5$, while f_{esc} is only directly measured at $z < 3$, and is found to be <2% at $z < 1$, and up to 20% at $z = 3$, thus it may be rising with redshift. For our discussion, we thus assume $C = 3$, and $f_{esc} = 30\%$ (see [18] for a full discussion).

We focus first at $z = 6$, as previous results at this redshift differed by more than a factor of five (in part due to the lack of deep near-IR imaging at that time). We measure the specific luminosity density for galaxies at $z = 6$ with $M_{UV} < -18$ to be in the middle of the previous values, with a much smaller uncertainty. As shown in Figure 3, this value is sufficient to maintain a fully ionized IGM for our canonical case of $C/f_{esc} = 10$. Thus, one need not assume that galaxies exist much fainter than our detection limit to complete reionization by $z = 6$. However, the luminosity densities at $z = 7$ and 8 lie below this curve, thus the observed galaxies cannot sustain a reionized IGM unless the escape fraction is near unity, which is unlikely. However, the luminosity function likely extends fainter than the *HST* limit, thus in Figure 2 we also show the luminosity density derived by integrating the current UV luminosity functions to $M_{UV} = -13$. If this represents reality, it implies that galaxies can sustain a fully reionized IGM by $z = 6$ if the escape fraction is only ~10% (again assuming $C = 3$), as can galaxies at $z = 7$.

Galaxies may be able to complete reionization by $z = 8$ *if* the escape fraction is ~30%.

However, we have not yet considered the photoionization rate from Lyα forest measurements in the spectra of quasars. [27] studied this, combining simulations with high-resolution spectroscopic observations of $z > 6$ quasars, calculating a limit on the emission rate of ionizing photons at $z = 6$. In Figure 3, we compare this constraint to our observations for a variety of escape fractions, converting our observed ρ_{UV} into a rate of ionizing photons using the same assumptions in Figure 2. If only the galaxies we can observe are leaking ionizing photons, the escape fraction must be $< 34\%$ to avoid violating the 2σ constraints from the Lyα forest. This is consistent with our canonical case defined above, and is sufficient to reionize the universe by $z = 6$. However, if the luminosity function extends to $M_{UV} = -13$, the average escape fraction must be $< 13\%$, which can complete reionization by both $z = 7$. Unless the average escape fraction rises steeply from $z = 6$ to $z = 8$, which is unlikely, galaxies cannot sustain a fully reionized IGM at $z = 8$. Unless some other significant source of ionizing photons are present, the volume neutral fraction in the IGM must rise significantly above zero at $z > 7$.

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