THE END OF HELIUM REIONIZATION AT $z \simeq 2.7$ INFERRED FROM COSMIC VARIANCE IN $HST$/COS He$\upiota$ Ly$\alpha$ ABSORPTION SPECTRA

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ABSTRACT

We report on the detection of strongly varying intergalactic He$\upiota$ absorption in $HST$/COS spectra of two $z_{\text{em}} \simeq 3$ quasars. From our homogeneous analysis of the He$\upiota$ absorption in these and three archival sightlines, we find a marked increase in the mean He$\upiota$ effective optical depth from $\langle \tau_{\text{eff,Hei}} \rangle \simeq 1$ at $z \simeq 2.3$ to $\langle \tau_{\text{eff,Hei}} \rangle \gtrsim 5$ at $z \simeq 3.2$, but with a large scatter of $2 \lesssim \tau_{\text{eff,Hei}} \lesssim 5$ at $2.7 < z < 3$ on scales of $\sim 10$ proper Mpc. This scatter is primarily due to fluctuations in the He$\upiota$ fraction and the He$\upiota$-ionizing background, rather than density variations that are probed by the coeval H$\upiota$ forest. Semianalytic models of He$\upiota$ absorption require a strong decrease in the He$\upiota$-ionizing background to explain the strong increase of the absorption at $z \gtrsim 2.7$, probably indicating He$\upiota$ reionization was incomplete at $z_{\text{reion}} \gtrsim 2.7$. Likewise, recent three-dimensional numerical simulations of He$\upiota$ reionization qualitatively agree with the observed trend only if He$\upiota$ reionization completes at $z_{\text{reion}} \simeq 2.7$ or even below, as suggested by a large $\tau_{\text{eff,Hei}} \gtrsim 3$ in two of our five sightlines at $z < 2.8$. By doubling the sample size at $2.7 < z < 3$, our newly discovered He$\upiota$ sightlines for the first time probe the diversity of the second epoch of reionization when helium became fully ionized.

Key words: dark ages, reionization, first stars – diffuse radiation – intergalactic medium – quasars: absorption lines – quasars: individual (SDSS J092447.36+485242.8, SDSS J110155.74+105302.3)

1. INTRODUCTION

At redshifts $z \lesssim 6$, hydrogen in the intergalactic medium (IGM) is kept highly ionized by the UV background (e.g., Haardt & Madau 1996; Faucher-Giguère et al. 2009), as evidenced by the absence of strong H Ly$\alpha$ absorption in quasar sightlines (Gunn & Peterson 1965; Fan et al. 2006). In contrast, the full reionization of helium (He$\upiota$ → He$\upiota$ii) was likely delayed to $z_{\text{reion}} \sim 3$ when quasars were sufficiently abundant to supply the required hard $E > 54.4$ eV photons (Madau & Meiksin 1994; Miralda-Escudé et al. 2000).

The $z \sim 3$ H$\upiota$ Ly$\alpha$ forest provides at best indirect evidence of this last baryonic phase transition. The high IGM temperature measured at $z \sim 3$ likely requires photoheating due to He$\upiota$ reionization. While there is strong evidence for a gradual reionization event at $3 \lesssim z \lesssim 4$ (Becker et al. 2011), evidence for a temperature peak signaling rapid He$\upiota$ reionization is tenuous (e.g., Schaye et al. 2008; Lidz et al. 2010). The $z \simeq 3.2$ feature in the mean H$\upiota$ absorption (Theuns et al. 2002; Faucher-Giguère et al. 2008) is unlikely due to rapid heating of the IGM during He$\upiota$ reionization (Bolton et al. 2007; McQuinn et al. 2009, hereafter M09). Metal line systems might probe the spectral shape of the UV background during He$\upiota$ reionization (Agafonova et al. 2007; Madau & Haardt 2009), but easily accessible metal line ratios (Songaila 1998) are affected by metallicity variations (Bolton & Vieil 2011).

The most direct evidence for He$\upiota$ reionization completing at $z_{\text{reion}} \sim 3$ comes from observations of intergalactic He$\upiota$ Ly$\alpha$ absorption ($\lambda_{\text{rest}} = 303.78$ Å) toward the few $z_{\text{em}} \sim 3$ quasars whose far-UV emission is not extinguished by intervening H$\upiota$ Lyman limit systems (Picard & Jakobsen 1993; Worseck & Prochaska 2011). He$\upiota$ Gunn–Peterson absorption has been detected at $z \gtrsim 3$ (e.g., Jakobsen et al. 1994; Heap et al. 2000; Zheng et al. 2008), whereas the absorption becomes patchy at $z \lesssim 3$ (Reimers et al. 1997, 2005), and evolves into a He$\upiota$ Ly$\alpha$ forest at $z < 2.7$ (e.g., Zheng et al. 2004; Fechner et al. 2006).

Semi-analytic (Gleser et al. 2005; Furlanetto & Oh 2008; Furlanetto & Dixon 2010) and numerical radiative transfer simulations (Sokasian et al. 2002; M09) predict that He$\upiota$ reionization is inhomogeneous and extended. Akin to H$\upiota$ at $z > 6$ (Gnedin 2000), He$\upiota$ reionization is characterized by three phases: (1) He$\upiota$ii “bubble” growth around $z_{\text{em}} \gtrsim 4$ quasars, (2) overlap of He$\upiota$ii zones around the more abundant quasars at $z_{\text{reion}} \sim 3$, and (3) gradual reionization of remaining dense He$\upiota$ regions. The large fluctuations in the He$\upiota$ absorption suggest that the overlap phase occurs at $z \sim 3$ (Reimers et al. 1997; Smette et al. 2002; Jakobsen et al. 2003), but current constraints on the physics and morphology of He$\upiota$ reionization are limited by cosmic variance among the handful of sightlines studied in detail.

The Cosmic Origins Spectrograph (COS; Osterman et al. 2010) on the Hubble Space Telescope ($HST$) has the sensitivity to obtain He$\upiota$ absorption spectra of unprecedented quality (Shull et al. 2010). Although efficient pre-selection of likely...
transparent sightlines with UV photometry from the Galaxy Evolution Explorer (GALEX) resulted in the discovery of 22 He\textsuperscript{II}-transparent quasars (Syphers et al. 2009a, 2009b), most of them are too faint for detailed studies with COS. In this Letter, we report the discovery of two UV-bright quasars with detected He\textsuperscript{II} absorption selected from our survey of the GALEX data set (Worseck & Prochaska 2011): SDSS J0924+4852 (\(z_{\text{em}} = 3.027\)) and SDSS J1101+1053 (\(z_{\text{em}} = 3.029\)). Hereafter SDSS J0924+4852 and SDSS J1101+1053, respectively. Together with archival data, their diverse COS spectra constrain the completion of He\textsuperscript{II} reionization to \(z_{\text{reion}} \lesssim 2.7\). We adopt a flat cosmology with \(H_0 = 70\) km s\(^{-1}\) Mpc\(^{-1}\) and \((\Omega_m, \Omega_{\Lambda}) = (0.27, 0.73)\) (Komatsu et al. 2011).

2. OBSERVATIONS AND DATA REDUCTION

2.1. HST Far-ultraviolet Spectra

We obtained HST/COS FUV spectra of SDSS J0924+4852 and SDSS J1101+1053 in course of a survey for He\textsuperscript{II}-transparent sightlines among the few UV-bright quasars detected by GALEX (Worseck & Prochaska 2011, G. Worseck et al. 2011, in preparation). We employed the grating G140L in the 1105 Å setup (\(\lambda, \lambda_{1110} - 2150\) Å, \(\lambda, \Delta\lambda \sim 2000\) at 1150 Å) at two detector settings to reduce fixed-pattern noise.

The spectra were extracted using CALCOS v2.12 and recalibrated with custom software. Because the diffuse background is dominated by COS detector dark current, it is well approximated by a constant over the cosmetically better detector segment A on which the G140L spectra were recorded. A wavelength-dependent background estimate gives very similar results, so that any systematic background subtraction error is likely small (\(<10\%\)), Geocoronal H\textsuperscript{I} Ly\alpha emission was subtracted. The raw counts of individual exposures were co-added before flux calibration, thereby preserving integer counts of our faint targets obtained in the Poisson regime. The spectra were rebinned by a factor of three to yield approximate Nyquist sampling (\(\geq 0.24\) Å pixel\(^{-1}\)) at a signal-to-noise ratio (S/N) of \(\geq 2\) (\(\geq 3\)) per pixel for SDSS J1101+1053 (SDSS J0924+4852) in the quasar continuum (Figure 1).

The HST/COS G130M and G140L data of HE 2347–4342 (Shull et al. 2010) were retrieved from the HST archive and reduced accordingly. For the G140L spectrum on detector segment B, we adopted the wavelength solution by Shull et al. (2010) and aligned it with the archival FUSE spectrum and the G130M spectrum on their overlapping wavelength range. The spectra both have an S/N \(\geq 10\) per 0.24 Å (G140L) and 0.03 Å (G130M) pixel.

We also reanalyzed the archival HST/STIS G140L \(\lambda/\Delta\lambda \sim 1000\) spectra of Q 0302–003 (Heap et al. 2000) and HS 1157+3143 (Reimers et al. 2005). The individual exposures were extracted using CALSTIS v2.30 and co-added, yielding a continuum S/N \(\approx 5\) per 0.6 Å pixel.

Each extinction-corrected spectrum was normalized by fitting a power law \(f_\lambda \propto \lambda^\alpha\) on selected regions redward of He\textsuperscript{II} Ly\alpha in the quasar rest frame, and free of obvious emission and absorption lines. We accounted for low-redshift Lyman limit breaks by adopting the power law only blueward of the lowest-redshift break redward of He\textsuperscript{II} Ly\alpha. The continuum fit was performed by maximizing the likelihood function for the Poisson gross counts, modeling the signal part as a power law in flux. Continuum errors were estimated by a Monte Carlo routine, drawing Poisson deviates of the inferred continuum. The 1σ statistical continuum error in the extrapolation region blueward of He\textsuperscript{II} Ly\alpha is \(<2\%\) for the high-quality spectrum of HE 2347–4342 and 5%–10% for the remaining quasars. Weak Lyman limit breaks of low-redshift H\textsuperscript{I} absorbers present a systematic uncertainty in the continuum in the He\textsuperscript{II} absorption region, although no such absorber could be identified by its Lyman series in the low S/N data.

2.2. Optical High-resolution H\textsuperscript{I} Forest Spectra

We observed SDSS J0924+4852 with the Keck I High-Resolution Echelle Spectrometer (HIRES; Vogt et al. 1994) for 3 hr with the 0′′86 slit (\(R \sim 45,000\)) covering the range
3300 Å \lessapprox \lambda < 5930 Å. The HIRedux\(^7\)-reduced spectrum has an S/N \simeq 20 per 2.6 km s\(^{-1}\) pixel in the H\(\text{I}\) Ly\(\alpha\) forest. The echelle orders were normalized by low-order polynomials and weighted by inverse variance in their overlapping regions.

SDSS J1101+1053 was observed with the Very Large Telescope (VLT) UV-Visual Echelle Spectrograph (UVES; Dekker et al. 2000) for 12.1 hr with the 1\(''\) slit (\(R \sim 45,000\)) covering the range \(\lambda \lambda 3750-4980\) Å. The spectra were reduced and normalized using the ESO Common Pipeline Library,\(^8\) yielding an S/N \simeq 30 per 1.85 km s\(^{-1}\) pixel in the Ly\(\alpha\) forest.

We complement this data set with an archival S/N \sim 100 VLT/UVES spectrum of HE 2347−4342 (e.g., Worseck et al. 2007).

3. RESULTS

3.1. Detection of Intergalactic He II Ly\(\alpha\) Absorption

Figure 2 shows the cospatial H\(\text{I}\) and He II Ly\(\alpha\) absorption spectra of SDSS J1101+1053 and SDSS J0924+4852 as a function of redshift. The H\(\text{I}\) spectra have been corrected for metal line absorption. At \(z > 2.98\) the He II spectra are contaminated by residuals of geocoronal Ly\(\alpha\) emission, so that the proximity zones of the quasars cannot be covered. Both sightlines present strong unresolved He II absorption compared with the optically thin H\(\text{I}\) forest, yet at different levels. While we see almost completely saturated Gunn–Peterson-like absorption toward SDSS J1101+1053, the absorption toward SDSS J0924+4852 is patchy over the whole covered redshift range. Comparing H\(\text{I}\) and He II absorption, we find that H\(\text{I}\) and He II do not track each other very well. Toward SDSS J0924+4852, a small H\(\text{I}\) void at \(z \simeq 2.71\) shows corresponding He II transmission, but there is stronger He II transmission at \(z \simeq 2.86\) and \(z \simeq 2.92\) where H\(\text{I}\) absorption is stronger and should have caused almost complete saturation in He II. The small H\(\text{I}\) void at \(z \simeq 2.94\) toward SDSS J1101+1053 does not show obvious He II transmission. Near \(z \simeq 2.83\), the He II absorption spectrum of SDSS J1101+1053 is contaminated by H\(\text{I}\) Ly\(\beta\) absorption of a serendipitously discovered damped H\(\text{I}\) absorber (\(z = 0.1358\), log(N\(\text{HeII}\)) = 21.09). Strong residuals after profile division render the spectral region unusable for assessing He II absorption. Neither the damped system nor the interstellar medium causes significant metal line absorption at our low spectral resolution.

3.2. The Redshift Evolution of the He II Effective Optical Depth

To quantify the He II absorption we computed the He II effective optical depth, \(\tau_{\text{eff,HeII}}\), in our newly discovered sightlines and the three archival ones. We employed a novel maximum-likelihood technique to measure \(\tau_{\text{eff,HeII}}\) in the Poisson limit in the low-count regime of our data. The Poisson nature of the COS detector counts becomes prominent in Figure 2 at \(z < 2.7\), where single counts are registered at a decreasing instrument response. Naive subtraction of a mean background from these integer counts results in unphysical negative fluxes.

For a spectral segment with \(n\) pixels we maximized the Poisson likelihood function

\[
L = \frac{n!}{\prod_{j=1}^{n} (S_j + B_j)!} N_j! \, e^{-(S_j + B_j)N_j} \, \prod_{j=1}^{n} (S_j + B_j)^{S_j} e^{-S_j - B_j},
\]

with the integer number of counts per pixel \(N_j\), the average background \(B_j = \text{constant}\), and the unknown signal \(S_j\). The signal was modeled as a constant in transmission, \(S_j = t_j C_j P_j e^{-\tau_{\text{HeII},\text{var}}}\) converted to non-integer counts via the exposure time \(t_j\), the flux calibration curve \(C_j\), and the power-law continuum \(P_j\). Error bars (68.26% confidence) were calculated via integrating \(L\). In case of no maximum in \(L\) (\(\tau_{\text{eff,HeII}} \rightarrow \infty\)), we obtained the 1\(\sigma\) lower limits on \(\tau_{\text{eff,HeII}}\) by refitting \(\tau_{\text{eff,HeII}}\) on mock data generated from Poisson fluctuations of the background.

The distribution of \(\tau_{\text{eff,HeII}}\) depends on the averaging scale in the forest. We chose a constant bin size of \(\Delta z = 0.04\) (\(\approx 10\) proper Mpc at \(z \sim 3\)) as a compromise to capture small-scale variations in the absorption, while retaining enough sensitivity to measure high effective optical depths against the Poisson detector background. Small bin size variations do not change our results. For all five sightlines, we adopted identical redshift bins without focusing on particular features. Proximity zones, geocoronal emission, and the damped H\(\text{I}\) absorber toward SDSS J1101+1053 were omitted from our analysis. For HE

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\(^7\) http://www.ucolick.org/~xavier/HIRedux/

\(^8\) http://www.eso.org/sci/software/cpl/
2347–4342, we adopted $\tau_{\text{eff}, \text{He} \text{II}}$ from the G130M spectrum for completely covered redshift bins.

Figure 3 and Table 1 present $\tau_{\text{eff}, \text{He} \text{II}}(z)$ for the five sightlines in the redshift range $2.32 \leq z \leq 3.20$. The He II effective optical depth evolves strongly from $\tau_{\text{eff}, \text{He} \text{II}} \approx$ 1 at $z \approx 2.3$ to $\tau_{\text{eff}, \text{He} \text{II}} \gtrsim$ 5 at $z \approx 3.2$, although cosmic variance might play a role at the lowest and highest redshifts (probed by one sightline each). The effective optical depth in the HE 2347–4342 sightline rather smoothly increases with redshift until $z \approx 2.7$. Between $z \approx 2.7$ and $z \approx 3$, we observe a large scatter in $\tau_{\text{eff}, \text{He} \text{II}}$. In four of our five sightlines, approximately half of the data points continue the smooth trend from lower redshifts, whereas the remaining ones are significantly higher. For example, the high-quality spectrum of HE 2347–4342 shows $\tau_{\text{eff}, \text{He} \text{II}} \approx$ 5.1 at $z = 2.76$. In the sightline toward SDSS J1101+1053, strong absorption with $\tau_{\text{eff}, \text{He} \text{II}} \gtrsim$ 5 occurs almost everywhere, whereas $\tau_{\text{eff}, \text{He} \text{II}}$ mostly fluctuates around $\tau_{\text{eff}, \text{He} \text{II}} \approx$ 2 toward SDSS J0924+4852. Apart from the known He II void at $z = 3.05$ (e.g., Jakobsen et al. 2003), the Q 0302–003 sightline shows $\tau_{\text{eff}, \text{He} \text{II}} \gtrsim$ 5 at $z > 3$.

Small-scale density variations might contribute to the effective optical depth variations. We investigated this by comparing the He II absorption with the cospatial H I Lyα absorption on a small scale $\Delta z = 0.01$ (≈ 2.8 proper Mpc at $z = 2.8$). We focused on the redshift range $2.7 < z < 2.97$ where the scatter and the data coverage is largest. Figure 4 presents our measurements toward the three quasars with H I and He II data. From the absence of a clear correlation between the measured H I and He II absorption we conclude that the $\tau_{\text{eff}, \text{He} \text{II}}$ fluctuations cannot be due to IGM density variations alone.

4. DISCUSSION

4.1. Comparison to Models

To further explore the results in Figure 3 we constructed a simple semianalytic model for He II absorption in a reionized IGM. For an IGM highly photoionized in H and He that follows the temperature–density relation $T(\Delta = \rho/\bar{\rho}) = T_0\Delta^{-1}$ (Hui & Gnedin 1997), the H I optical depth is

$$\tau_{\text{HI}} \simeq 0.612 \left( \frac{T_0}{20,000 \text{ K}} \right)^{-0.724} \left( \frac{\Gamma_{\text{HI}}}{10^{-12} \text{ s}^{-1}} \right)^{-1} \times \Delta^2 \frac{\gamma - 1}{4} \left( \frac{1 + z}{4} \right)^{4.5},$$

(2)

also known as the fluctuating Gunn–Peterson approximation (e.g., Weinberg et al. 1997). H I and He II trace the same cosmic densities, so

$$\tau_{\text{He} \text{II}} \simeq 0.112 \frac{\Gamma_{\text{HI}}}{\Gamma_{\text{He} \text{II}}} \tau_{\text{HI}} \simeq \eta \frac{\gamma}{4} \tau_{\text{HI}},$$

(3)

in a reionized IGM with an H I (He II) photoionization rate $\Gamma_{\text{HI}}$ ($\Gamma_{\text{He} \text{II}}$). We have approximated number densities as column densities with the column density ratio $\eta = N_{\text{He} \text{II}}/N_{\text{HI}}$, commonly measured in He II forest spectra. The He II effective optical depth can be written as

$$\tau_{\text{eff}, \text{He} \text{II}} = -\ln \left[ \int_0^\infty e^{-\frac{\tau_{\text{HI}}}{\gamma}} \frac{\rho}{\bar{\rho}} P(\tau_{\text{HI}}) \, d\tau_{\text{HI}} \right],$$

(4)

with the H I optical depth probability distribution function $P(\tau_{\text{HI}}) = P(\Delta)|d\Delta/d\tau_{\text{HI}}|$. With Equation (2) and the overdensity probability distribution $P(\Delta)$ from simulations by Bolton & Becker (2009), $\tau_{\text{eff}, \text{He} \text{II}}$ is a function of the temperature–density relation $(T_0, \gamma)$ and the ionization conditions $(\Gamma_{\text{HI}}, \eta)$. We adopt $T_0 = 15,000 \text{ K}$ and the post-reionization asymptotic value $\gamma = 1.5$ (Hui & Gnedin 1997), $\Gamma_{\text{HI}} = 10^{-12} \text{ s}^{-1}$ (Bolton et al. 2005) and $\eta = 80$ (Fechner & Reimers 2007).

The lower solid curve in Figure 3 shows the resulting $\tau_{\text{eff}, \text{He} \text{II}}(z)$ model. It matches surprisingly well to the measured
values at \( z \sim 3 \). Part of the data follows this relation until \( z \sim 3 \), whereas the rest significantly departs from it to larger \( \tau_{\text{eff}, \text{He} \, ii} \) values. The amplitude of \( \tau_{\text{eff}, \text{He} \, ii}(z) \) mostly depends on the ionization conditions, indicated in Figure 3 by a higher \( \Gamma_{\text{H} \, i} \) (Dall’Aglio et al. 2008) or a softer UV background (higher \( \eta \)). However, the steep evolution of \( \tau_{\text{eff}, \text{He} \, ii} \) cannot be matched unless there is significant redshift evolution in the model parameters. A change in the temperature–density relation seems implausible, since a flattening would cause \( \tau_{\text{eff}, \text{He} \, ii} \) to decrease, and a rise in \( \tau_{\text{eff}, \text{He} \, ii} \) would require unreasonably low

IGM temperatures. Since \( \Gamma_{\text{H} \, i} \) and \( \eta \) are tied, the steep increase of \( \tau_{\text{eff}, \text{He} \, ii} \) might suggest a strong decrease of \( \Gamma_{\text{He} \, ii} \) at \( z > 2.7 \) related to a drop in the mean free path of He \( \tau_{\text{He} \, ii} \) reionizing photons if the quasar emissivity is constant. While this alone likely indicates that He \( \tau_{\text{He} \, ii} \) reionization is occurring, the breakdown of the high-ionization limit of helium could simply invalidate our semianalytic approach at \( z > 2.7 \).

To describe the redshift evolution of the effective optical depth during reionization, we calculated \( \tau_{\text{eff}, \text{He} \, ii}(z) \) from numerical models of He \( \tau_{\text{He} \, ii} \) reionization (M09). We focused on their D1 and L3 simulations, which have different reionization histories due to the filtering of UV radiation by dense absorbers. Run L3 supplements the D1 simulation with absorbers that may not be resolved and which delay completion of reionization slightly from \( z_{\text{reion}} \), (Dall’Aglio et al. 2008) or a softer UV background, He \( \tau_{\text{He} \, ii} \) cannot be contained large amounts of He \( \tau_{\text{He} \, ii} \) fraction rises, in contrast to our optically thin models. On our chosen scale \( \Delta z = 0.04 \), the models exhibit large fluctuations in \( \tau_{\text{eff}, \text{He} \, ii} \) due to cosmic variance in the He \( \tau_{\text{He} \, ii} \) reionization histories. At the end of He \( \tau_{\text{He} \, ii} \) reionization, both models show a characteristic turnover in \( \tau_{\text{eff}, \text{He} \, ii} \) to approximately our favored optically thin model of the post-reionization IGM. The data are largely inconsistent with the predictions from model D1 of M09 due to the large excess toward high \( \tau_{\text{eff}, \text{He} \, ii} \) at \( z < 3 \). Model L3, meanwhile, also does not reproduce the data perfectly, since the largest \( \tau_{\text{eff}, \text{He} \, ii} \) values at \( z \simeq 2.7–2.8 \) and the lowest values at \( z \simeq 2.9–3 \) cannot be easily accommodated.

In Figure 4, we compare the measured H \( \tau_{\text{H} \, i} \) and He \( \tau_{\text{He} \, ii} \) effective optical depths to ~20,000 mock samples of two snapshots of the L3 simulation by M09, obtained on the same scale \( \Delta z = 0.01 \) and rescaled to a common redshift \( z \simeq 2.8 \). With respective volume-averaged He \( \tau_{\text{He} \, ii} \) fractions of \( \tau_{\text{He} \, ii} = 1.8\% \) and \( \tau_{\text{He} \, ii} = 0.3\% \), the simulation outputs trace the end stages of He \( \tau_{\text{He} \, ii} \) reionization. In the mock spectra, helium and hydrogen absorptions are correlated due to the underlying density field and the emerging He \( \tau_{\text{He} \, ii} \) ionizing background. The scatter in this relation is primarily due to fluctuations in the He \( \tau_{\text{He} \, ii} \) fraction and the UV background, which delay as He \( \tau_{\text{He} \, ii} \) reionization proceeds. H \( \tau_{\text{H} \, i} \) voids (low \( \tau_{\text{eff}, \text{H} \, i} \)) without nearby UV sources contain large amounts of He \( \tau_{\text{He} \, ii} \) if reionization is still ongoing. The largest inferred effective optical depths \( \tau_{\text{eff}, \text{He} \, ii}(z) \geq 7 \) toward HE 2347–4342 indicate that the He \( \tau_{\text{He} \, ii} \) fraction is still >2%. The SDSS J1101+1053 sightline is mostly consistent with the scenario of still incomplete He \( \tau_{\text{He} \, i} \) reionization, whereas parts of the SDSS J0924+4842 sightline are better matched with a reionized IGM, which, however, does not contain the strong fluctuations seen in the data. Thus, while data and the M09 models suggest that we see the end stages of He \( \tau_{\text{He} \, ii} \) reionization, the coexistence of patches with both large and small He \( \tau_{\text{He} \, ii} \) fractions at moderate densities is difficult to explain. A more rapid increase in the quasar emissivity, a short quasar lifetime or quasar anisotropy (e.g., Hennawi & Prochaska 2007) might amplify the modeled fluctuations to the required level.

### 4.2. Implications

Our newly discovered quasar sightlines with detected He \( \tau_{\text{He} \, ii} \) Ly\( \alpha \) absorption highlight the diversity in He \( \tau_{\text{He} \, ii} \) absorption near the epoch of He \( \tau_{\text{He} \, ii} \) reionization, irrespective of the gas density
probed by the coeval H I Lyα forest. The alternating voids and troughs toward SDSS J0924+4852 are expected at the very end of He ii reionization, in agreement with current numerical modeling (McQuinn et al. 2009). In contrast, the two long troughs toward HE 2347–4342 indicate that He ii reionization is still incomplete. In agreement with Furlanetto & Dixon (2010) and Shull et al. (2010) we find that the large troughs toward SDSS J0924+4852 are expected at the very end of He ii reionization. The steep increase in the He ii density, spectral energy distribution, lifetime, anisotropy). Thus, He ii reionization might yield unique insight into the quasar phenomenon.

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