Helium Reionization Simulations. III. The Helium Ly$\alpha$ Forest

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Received 2017 October 12; revised 2018 September 30; accepted 2018 October 4; published 2018 November 27

Abstract

In a previous paper we presented a new suite of hydrodynamic simulations with the aim of accurately capturing the process of helium II reionization. In this paper, we discuss the observational signatures present in the He II Ly$\alpha$ forest. We show that the effective optical depth of the volume-averaged $\tau_{\text{eff}}$ alone is not sufficient for capturing the ionization state of helium II, due to the large variance inherent in sightlines. However, the He II flux probability density function (PDF) can be used to determine the timing of helium II reionization. The amplitude of the one-dimensional flux power spectrum can also determine the ionization state of helium II. We show that, even given the currently limited number of observations ($\sim$50 sightlines), measurements of the flux PDF can yield information about helium II reionization. Further, measurements using the one-dimensional power spectrum can provide clear indications of the timing of reionization, as well as the relative bias of sources of ionizing radiation.

Key words: cosmology; theory – intergalactic medium – large-scale structure of universe – methods: numerical – quasars: general

1. Introduction

There has been much interest in understanding the reionization of helium II, using semi-analytic methods (Glezer et al. 2005; Furlanetto & Oh 2008a, 2008b, 2009; Dixon et al. 2014), numerical simulations (Croft et al. 1997; McQuinn et al. 2009, 2011; Compostella et al. 2013, 2014; Pachwein et al. 2015; Bolton et al. 2017), and observations (Jakobsen et al. 1994; Reimers et al. 1997; Zheng et al. 2008; Dixon & Furlanetto 2009; Syphers & Shull 2014; Worseck et al. 2016). Helium II reionization is thought to be driven by highly energetic photons emitted by quasars. Due to photoheating of gas in the intergalactic medium (IGM) from these high-energy photons, helium II reionization leaves an important signature on the thermal state of the IGM. Knowledge of the thermal state is important for making measurements of quantities related to the Ly$\alpha$ forest, such as the free-streaming length of warm dark matter (Viel et al. 2005; Iršič et al. 2017). However, such temperature measurements are difficult to make and have large systematic or statistical uncertainties (Schaye et al. 1999; McDonald et al. 2001; Becker et al. 2011; Boera et al. 2014). Further, these methods rely on correctly calibrating the state of the hydrogen Ly$\alpha$ forest with the gas temperature, which is fraught with difficulty.

A more appealing approach is to measure the ionization state of helium directly, without relying on calibration. Just as the Ly$\alpha$ transition for neutral hydrogen (H I) appears as absorption features in spectra of radiation from distant quasars, so too does the transition for singly ionized helium (He II). This feature appears at 304 Å in the rest-frame of the absorbing gas, a shift of a factor of four in frequency space compared to the hydrogen transition due to the additional proton in the helium nucleus. As with the H I Ly$\alpha$ forest, the very high transition strength means a very small amount of singly ionized helium can lead to total absorption of the incoming radiation. Typically, neutral fractions of $f_{\text{He II}} \gtrsim 10^{-3}$ can produce a Gunn–Peterson trough (Gunn & Peterson 1965), making detection of the early stages of helium II reionization difficult. Despite this difficulty, measuring the ionization status of helium from the He II Ly$\alpha$ forest provides a more direct probe than using temperature measurements or the H I Ly$\alpha$ forest.

Part of the difficulty in observing the He II Ly$\alpha$ forest lies in contamination of high-density systems at lower redshift. Lyman-limit systems (LLSs) and damped Ly$\alpha$ systems (DLAs) which are at intermediate redshift (say at $z_{\text{LLS}}$) between the comparatively high-redshift IGM gas we are interested in observing (say at $z_{\text{IGM}}$) and observers on Earth, can absorb much of the radiation above the ionization potential of hydrogen at 912 Å. Quantitatively, if $912(1 + z_{\text{LLS}}) \gtrsim 304(1 + z_{\text{IGM}})$, then the lower-redshift LLSs or DLAs will obscurce the He II Ly$\alpha$ forest of interest. Due to the relative abundance of LLSs and DLAs at low redshift, only a small number of quasar sightlines are suitable for measuring the He II Ly$\alpha$ forest (Møller & Jakobsen 1990; Zheng et al. 2005). Indeed, despite having more than 150,000 quasar sightlines from BOSS alone (Dawson et al. 2013), to date there have been only about 50 sightlines for which the He II Ly$\alpha$ forest has been measured (Syphers et al. 2009a, 2009b, 2012). These measurements have provided significant insight to the general picture of helium II reionization: at redshifts $z > 3$, a Gunn–Peterson trough has been detected (Jakobsen et al. 1994; Zheng et al. 2008; Syphers & Shull 2014); below this redshift, helium II reionization becomes patchy, showing extended regions of absorption and transmission corresponding to the ionization level of the gas (Reimers et al. 1997); finally, by redshift $z \sim 2.7$, helium appears to be totally reionized (Dixon & Furlanetto 2009; Worseck et al. 2011). However, information beyond this general picture is difficult to glean from the current limited set of He II spectra. To this end, measurements providing additional information about helium II reionization are an important application of current and ongoing research.

In La Plante & Trac (2016; hereafter Paper I), we provided a method by which simulation volumes can be populated with quasars in order to reproduce the quasar luminosity function.

\footnote{It should be noted, though, that a single sightline of, e.g., 100 physical Mpc, can yield multiple measurements of a given statistic by dividing the total sightline into multiple smaller segments of moderate size (e.g., 10 physical Mpc as in Worseck et al. 2016).}
(QLF) at various redshift epochs (Masters et al. 2012; McGreer et al. 2013; Ross et al. 2013) as well as quasar clustering (White et al. 2012). In La Plante et al. (2017; hereafter Paper II), we presented a new suite of large-scale simulations with the purpose of exploring helium II reionization. These simulations include N-body, hydrodynamics, and radiative transfer solved simultaneously, which allows us to capture the evolution of the IGM with newfound accuracy. Based on the output of these simulations, we are able to generate synthetic Lyα sightlines for H I and He II. In this paper, we present specific results about the He II spectra, and discuss ways to learn about the timing of helium II reionization.

We organize the rest of this paper as follows. In Section 2, we briefly discuss our suite of simulations. In Section 3, we discuss the He II Lyα forest, and various measurements that can be made using the spectra. In Section 4, we discuss prospects for detecting helium II reionization properties given the current measurements. In Section 5, we summarize our findings. Throughout this work, we assume a ΛCDM cosmology with Ωm = 0.27, ΩΛ = 0.73, Ωb = 0.045, h = 0.7, σ8 = 0.8, and YHe = 0.24. These values are consistent with the WMAP-9 year results (Hinshaw et al. 2013).

2. Radiation–Hydrodynamic Simulations

In Paper II, we presented a new suite of hydrodynamic simulations with radiative transfer, conducted with the goal of studying helium II reionization. Here, we summarize the properties of the simulations that are relevant to this paper’s results. Radiation–hydrodynamic simulations are run with the RadHydro code, which combines N-body and hydrodynamic algorithms (Trac & Pen 2004) with an adaptive ray-tracing algorithm (Trac & Cen 2007) to directly and simultaneously solve collisionless dark matter, collisional gas dynamics, and radiative transfer of ionizing photons. The simulations in Paper II employ 2048³ dark matter particles, and 2048³ hydrodynamic resolution elements in a fixed-grid Eulerian scheme. The grid for radiative transfer contains 512³ resolution elements. The simulation code has already been used to study hydrogen reionization (Trac & Cen 2007; Trac et al. 2008; Battaglia et al. 2013). For additional details about the simulations, see Paper II.

The simulations contain two features in particular that bear mentioning. First, they include a patchy model for hydrogen reionization developed in Battaglia et al. (2013). The midpoint of reionization has been set such that zgal = 8, but in general, regions of high-density undergo reionization before regions of low density. By incorporating an “inside-out” reionization scenario, we ensure that the thermal state of the IGM before helium II reionization accurately reflects the impact of hydrogen reionization. Second, the contribution of galaxies to the UV background Γgal is modified on-the-fly in order to reproduce the observed effective optical depth τeff of the H I Lyα forest. The quantity τeff is related to the flux of the Lyα forest $F_{\text{H I}}$, defined for every location in the volume as $F_{\text{H I}} = e^{-\tau}$. In this expression, $\tau$ is the optical depth of Lyα radiation. Note that $\tau = e^{-\tau}$. Values of $F \sim 0$ represent total absorption (typically the result of a high density of neutral hydrogen), and values of $F \sim 1$ represent total transmission. It is then possible to define the effective optical depth of the entire volume, namely as

$$\langle F_{\text{H I}} \rangle = e^{-\tau_{\text{eff, H I}}},$$

where $\langle F_{\text{H I}} \rangle$ is the average flux of the H I Lyα forest of the volume, with an analogous definition for He II. Specifically, we match τeff as parameterized in Lee et al. (2015). These results are based primarily on data from the seventh data release of the Sloan Digital Sky survey (SDSS DR7) presented in Becker et al. (2013). Modifying Γgal while the simulations are running means we do not need to renormalize the Lyα forest in post-processing, as previous studies of the Lyα forest have done (e.g., Bolton et al. 2009). This feature allows us to more easily compare the results between simulations and observations.

As explained in detail in Paper I, the simulation volumes are populated with quasars such that the observed QLF is matched between redshifts $2 \leq z \leq 6$ (Masters et al. 2012; McGreer et al. 2013; Ross et al. 2013), as well as the clustering measurements at $z \sim 2.4$ (White et al. 2012). For individual quasar objects, we use the spectral energy density (SED) from Lusso et al. (2015), which has a spectral index of $\alpha = 1.7 (f_\nu \propto \nu^{-\alpha})$ for $\lambda \leq 912$ Å, and a spectral index of $\alpha = 0.61$ for $\lambda > 912$ Å.

In Paper II, we presented a suite of six simulations, with different quasar properties. We will now briefly summarize each of these simulations. Simulation H1 is the fiducial reionization model, which uses the QLF combining the various measurements at distinct redshift epochs and the SED of Lusso et al. (2015). Simulation H2 increases the amplitude of the QLF by a factor of 2, leading to an earlier reionization scenario. Simulation H3 decreases the amplitude of the QLF by a factor of 2, leading to a late reionization time. Simulation H4 increases the normalization of the SED by a factor of 2, so that a given quasar with a given magnitude $M$ will have a luminosity at 912 Å $L_{912}$ that is two times greater than that provided by the SED of Lusso et al. (2015). Simulation H5 uses a slightly different method for combining the QLF from distinct redshift epochs than Simulation H1, but uses the same SED. Simulation H6 does not have explicit quasar sources, but instead uses a uniform UV background with the photoionization and photoheating rates as specified by Haardt & Madau (2012). Rather than simply using the rates “as is,” we scale them to match the observed value of $\tau_{\text{eff, H I}}$, as with the other simulations. See Paper II for further details about each of the simulations. Figure 1 shows the ionization fraction of the various simulations as a function of redshift.

3. He II Lyα Forest Measurements

At each time step in the simulation, we generate synthetic Lyα sightlines on-the-fly for H I and He II. The measurements of $\tau_{\text{eff, H I}}$ for the H I sightlines allow for modifying Γgal to ensure that the value is matched at all times in the simulation. Determining He II from the synthetic sightlines allows for a more straightforward connection with the ionization state of helium in the volume. We will now turn to specific observables related to the He II Lyα forest.

3.1. Effective Optical Depth

The effective optical depth $\tau_{\text{eff}}$, as noted in Equation (1), is defined in terms of the average flux in the volume. As with the H I Lyα transition, the strength of the He II transition ensures that only a very small amount of singly ionized helium is
necessary to completely absorb incoming radiation. As a result, measurement of $\tau_{\text{eff,He II}}$ is most sensitive to the end of reionization. Further, due to the very large comoving size of He III regions (typically tens of Mpc in diameter), there is a large variation between different sightlines in the simulation volume, or even along a given sightline. One significant reason for this is that the correlation length $s_0$ of quasars, defined by the three-dimensional two-point correlation function $\xi(s) = (\xi_0 s_0)^{-2}$ (e.g., White et al. 2012), is comparable to, but slightly larger than, the mean free path of $h\nu = 54.4$ eV photons for $f_{\text{He II}} \sim 0.8$ at $z \sim 3$. Accordingly, until there is overlap of ionized regions, there are large contiguous regions of He II and He III. Ultimately, this results in large variation along a line of sight. Furthermore, these ionization regions typically do not overlap until the tail-end of reionization. This variation is especially prevalent while helium II reionization is proceeding. In other words, due to the large coherence of the doubly ionized regions, the observed optical depth can vary greatly from sightline to sightline, and so there should be a large variance in the measurements. This variation is in addition to any inherent variance in $\tau_{\text{eff,He II}}$ primarily due to density fluctuations.

Figure 2 shows two sample sightlines of the He II Ly$\alpha$ forest for all of the simulations at $z \sim 2.7$. As shown in Figure 1, this redshift corresponds to a He II ionization fraction of $x_{\text{He II}} \gtrsim 0.95$ for all simulations except for H3. Accordingly, for most simulations there are regions of both high and low flux, though typically few fully transparent regions at this redshift. In the regions of high flux, though, Simulation H3 shows much lower flux. Also worth noting is the fact that, for a given pixel, there is no consistent trend as to which simulation has the highest flux value. This fact reflects the complex interplay between the low-density IGM gas and the radiation field, as well as the redshift-space distortions inherent in computing the Ly$\alpha$ forest. A similar feature can be seen in Figure 8 of Paper II, which shows sample sightlines of the H I Ly$\alpha$ forest. Nevertheless, as shown below, there are significant statistical differences between the simulations at a given redshift, and measurements with sufficient resolution may be able to distinguish among them.

Figure 3 shows $\tau_{\text{eff,He II}}$ as a function of redshift. The value of $\tau_{\text{eff,He II}}$ is computed for every available sightline in the volume using 10 proper Mpc segments, and the median and central 95% of the resulting values are determined. The lines in the figure correspond to the median for each simulation, and the shaded region shows the central 95% for Simulation H1. The other simulations show a similar trend (relatively low dispersion at low redshifts, becoming broader at $z \gtrsim 2.7$), and are omitted for clarity. Figure 3 also includes observational data from Worseck et al. (2016), also showing the median and central 95% of values. These quasar spectra were taken using the Cosmic Origins Spectrograph (COS) on the Hubble Space Telescope (HST). These spectra measure $\tau_{\text{eff,He II}}$ for segments of about 10 proper Mpc. The large sightline-to-sightline variation is evident in the observational data, which show very different values of $\tau_{\text{eff,He II}}$ at the same redshift. The results from most of the simulations are largely consistent with the data at the redshifts for which data are available ($2.5 \lesssim z \lesssim 3.5$).

The gray shaded regions in Figure 3 show the central 95% of $\tau_{\text{eff,He II}}$ values. Computing the median and central 95% of $\tau_{\text{eff,He II}}$ values is consistent with previous studies of the He II Ly$\alpha$ forest (McQuinn et al. 2009; Compostella et al. 2013). The various reionization scenarios overlap to a significant degree at most redshifts. Significantly, the data from Worseck et al. (2016) are also broadly consistent with all reionization scenarios, with the already noted exception of Simulation H3. Thus, the median value of $\tau_{\text{eff,He II}}$ alone is not sufficient to constrain the reionization scenarios presented in the simulation suite.

Figure 4 shows the full distribution of $\tau_{\text{eff,He II}}$ at $z \sim 2.7$. When the He III ionization fraction of the volume is still relatively high for a given simulation, there is a broad distribution of $\tau_{\text{eff,He II}}$ values. This can be seen specifically for Simulations H1, H3, and H4. As reionization proceeds, a more well-defined peak emerges, as in Simulations H2, H5, and H6. The distributions for these latter simulations are comparable, but using a statistic such as the Kolmogorov–Smirnov test or Anderson–Darling test would likely be capable of distinguishing them. There are visible differences present, such as the comparatively broader high-$\tau$ tail of Simulation H2. The broadness of the peak also decreases as the volume becomes more ionized, which is reflected by the narrower dispersion seen at lower redshifts in Figure 3.

3.2. Flux Probability Density Function

As discussed in Paper II, another tool for analyzing the ionization state of the medium is the flux probability density function (PDF). This measurement captures the distribution of flux for all pixels. As with $\tau_{\text{eff,He II}}$, this statistic is most sensitive to the tail-end of reionization. Due to the low number of He II pixels with high transmission ($F \gtrsim 0.5$) before the end of reionization ($x_{\text{He II}} \gtrsim 0.99$), the flux PDF cannot provide detailed information while reionization is underway. However,
it can still provide valuable information about the timing of reionization. Figure 5 shows the He II flux PDF for the different simulations. The panels show the volume at redshifts \(z \sim 2.7\) (top), \(z \sim 2.5\) (bottom left), and \(z \sim 2.3\) (bottom right). Note that at redshift \(z \sim 2.7\), most of the simulations are 99% reionized. Despite this fact, there are comparatively few pixels with high transmission: for the fiducial case of Simulation H1, 90% of the pixels have flux of \(F \leq 0.5\). This relatively strong absorption is related to the strength of the Ly\(\alpha\) transition, where only a small amount of He II is necessary to absorb most of the incoming radiation. Note, though, that measurement of the flux PDF can still be an important marker of the timing of reionization. As noted above, Simulation H3 reaches 99% reionization significantly later at \(z_\text{reion} \sim 2.23\), which is evident in the distinct shape of the flux PDF. In particular, there are far fewer pixels with \(F \geq 0.5\) at all redshifts, indicative of its relatively late completion of reionization. The flux PDF of H3 at \(z \sim 2.3\) is comparable to that of, e.g., Simulation H1 at \(z \sim 2.7\). Thus, by measuring the redshift when the central portion of the flux PDF is relatively flat (e.g., when PDF \((F = 0.25) \approx PDF(F = 0.75)\)), one can determine the timing of when the volume is \(\sim 99.9\%\) ionized. This point is addressed more directly in Figure 6 (discussed below).

The shaded error regions in Figure 5 show 1\(\sigma\) uncertainties, and are calculated using bootstrap resampling of 10 sightlines of length 40 proper Mpc and computing the variance within each flux bin. These values were chosen to reflect the limited number of quasar sightlines at a given redshift (for example, compare with Appendix C of Worseck et al. 2016), but a relatively larger distance can be treated as “coeval” (effectively at the same redshift) than the 10 physical Mpc used in Worseck et al. (2016).
Figure 3. Effective optical depth of singly ionized helium $\tau_{\text{eff,He }^+}$ as a function of redshift for the suite of simulations. The black dots represent the binned observational data from Worseck et al. (2016), which are taken from HST/COS data. Color and line styles for the simulations are the same as in Figure 1. The top panel shows the results for the simulations presented in Paper II, and the bottom panel shows the relative difference to the fiducial simulation. As can be seen, there is a large degree of scatter in the measurements. By extension, none of the simulations is clearly disfavored. See Section 3.1 for additional discussion.

Figure 4. Probability density function of $\tau_{\text{eff,He }^+}$ for each simulation. Although the distributions for some simulations are similar, there are significant differences between them. It may be possible to discriminate between the different distributions using the Kolmogorov-Smirnov test or Anderson-Darling test. See Section 3.1 for additional discussion.

In contrast to the shaded regions in Figure 3, these error regions are generally quite small, and do not significantly overlap with other simulations. This result demonstrates that only a few sightlines are necessary to determine the shape of the flux PDF. It should be noted that, analogously to the H I flux PDF (and further discussed in Appendix B of Paper II), the continuum level of the measured spectra can have a dramatic effect on the shape of the flux PDF. Accordingly, uncertainty in this level can lead to systematic shifts in the calculated flux PDF. Nevertheless, Figure 5 shows that, given low systematic uncertainties, the flux PDF of the He II Ly$\alpha$ forest can be a powerful tool for determining the ionization state of helium in the IGM.

Figure 6 shows the derivative of the flux PDF, dPDF($F$)/d$F$ at a value of $F = 0.5$ as a function of the complement of He III ionization fraction $1 - x_{\text{He III}}$. This quantity is used instead of simply the ionization fraction to emphasize the behavior at high ionization levels. All of the reionization scenarios have been converted from redshift to ionization fraction in order to demonstrate uniformity across realizations. As discussed above, the transition from most pixels with values of $F \sim 0$ to $F \sim 1$ occurs relatively late in the ionization process. This transition can be captured in the change of the slope of the PDF at a value of $F = 0.5$; at early times and low ionization levels, the slope is negative with increasing flux values. Once the volume becomes $\sim 99\%$ ionized, the flux PDF flattens out. At even higher ionization levels, the slope becomes positive. As shown in Figure 6, the timing for these transitions is closely tied to the ionization fraction, rather than a specific redshift. Furthermore, as demonstrated with the relatively small statistical error bars in Figure 5, the flux PDF can be determined to high fidelity with relatively few He II sightlines. Assuming systematic uncertainties of observations can be sufficiently mitigated, this quantity represents a robust method for determining the endpoint of helium II reionization, to a much greater degree than the effective optical depth $\tau_{\text{eff,He }^+}$.

To provide a realistic comparison with HST/COS data, we decreased the resolution of the sightlines in the simulations, and added noise to the spectra. The fundamental resolution of the simulations is $\Delta v = 10.3 \text{ km s}^{-1}$ at $z \sim 3$, whereas the majority of HST/COS spectra have a FWHM of $\Delta v \sim 150 \text{ km s}^{-1}$ ($R = 2000$, Worseck et al. 2016). We applied a Gaussian convolution to the spectra with a FWHM corresponding to $150 \text{ km s}^{-1}$, and reduced the number of pixels accordingly. After obtaining these lower-resolution spectra, we added Gaussian noise to achieve a mock signal-to-noise ratio (S/N) of 10, again to match the typical S/N of HST/COS data (Worseck et al. 2016). We computed the resulting flux PDF, and again computed bootstrap errors for the different simulations using 10 sightlines of 40 physical Mpc in length.

Figure 7 shows the resulting flux PDF, at the same redshifts as those presented in Figure 5. Note that the shape of the PDF has changed at a given redshift: there are slightly fewer high-flux pixels, and more low-flux pixels. The notable exception is the highest-flux bin, where $F \sim 1$. This is due to the addition of positive noise to pixels containing an already high flux value (say, $F \sim 0.95$), and resulting in values of $F \approx 1$. Also, once noise has been added, values of pixels with $F < 0$ have been collapsed into the $F = 0$ bin, and pixels with $F > 1$ have been collapsed into the $F = 1$ bin. The relative difference between high-flux and low-flux values can also be explained by the addition of noise: positive noise added to a low-flux pixel can appear to be high-flux, and negative noise added to a high-flux pixel can appear to be low-flux. As Figure 5 shows, at most redshifts, there are significantly more low-flux than high-flux pixels, so there are more low-flux pixels to scatter to high-flux than vice versa. Also worth noting is that the pixel smoothing and additional noise increase the bootstrap error bars (the gray shaded regions in the figure). The result is that the resulting PDFs are no longer distinguishable in all simulations. The late reionization scenario in Simulation H3 is still sufficiently different at a given redshift, though differences among other scenarios are more subtle. Nevertheless, the flux PDF in principle contains much more information about the He III...
reionization history, which higher-resolution measurements may be able to constrain.

3.3. One-dimensional Flux Power Spectra

In addition to the flux PDF, the one-dimensional power spectrum of the He II Lyα forest can be used to learn important information about the ionization state of the IGM. The overall amplitude of the power spectrum as well as the shape as a function of Fourier mode \(k\) will change as the ionization state and the size of ionized regions change. As with the one-dimensional power spectrum for H I, the amplitude on large scales is related to the optical depth \(\tau_{\text{eff,He II}}\) with higher amplitudes corresponding to higher values of \(\tau_{\text{eff,He II}}\) (see Figure 3).

Figure 8 shows the one-dimensional power spectrum of the He II Lyα forest. The primary difference between the simulations is in the amplitude of the power spectra. At a given redshift, the amplitude of the power spectrum is directly related to the value of \(\tau_{\text{eff}}\). Note that Simulation H3 has the largest value of \(\tau_{\text{eff}}\) at a given redshift (as shown in Figure 3), and also has the largest amplitude in Figure 8. This can be understood in terms of the amplitude of fluctuations in the flux field: when the IGM has a relatively low value of \(\tau_{\text{eff}}\), then all points in the volume have a similarly (high) value of flux. These differences in flux are driven primarily by correlations with the radiation field. Not only is the fraction of He III higher in regions of high radiation intensity, but the temperature is also greater. Both of these effects contribute to a lower value of \(\tau_{\text{eff,He II}}\) or a higher value of flux \(F\). The combination leads to highly correlated regions of high and low flux, increasing the amplitude of the power spectrum. At the same time, it is not solely the radiation field that controls the amplitude of the power spectrum, as Simulation H6 has a uniform radiation field. In this simulation, the differences are driven primarily by the local gas density, and so there is no corresponding correlation between regions of high and low flux.

At \(z \sim 2.7\), the difference in the power spectrum amplitude of Simulation H3 at all scales is an order of magnitude larger than that of the other simulations. Such a dramatic difference should be detectable, and would allow for a straightforward determination of the helium ionization state of the IGM. Most
importantly, the amplitude of the flux power spectrum as a function of redshift is clear and pronounced, even for reionization histories that are not fully reionized. Hence, the one-dimensional power spectrum can be a window into helium II reionization at times prior to 99% ionization.

The shaded regions show 1σ uncertainty in the measurements using 10 sightlines and bootstrap resampling, with the same rationale as that discussed regarding Figure 5 in Section 3.2. Unlike the approach taken there, though, the entire sightline is used rather than a 10 Mpc segment. By using the entire sightline, there are no issues related to broken periodicity when performing the Fourier transform for the power spectrum calculation. Note that for redshifts $z \geq 3$, the bootstrap estimation of uncertainty has not converged using only 10 sightlines. For comparison, the same bootstrap estimation of errors was performed with 50 sightlines, and the resulting uncertainty was much more tightly constrained. This is likely largely due to the decrease in the scatter of $1/\sqrt{N}$ for a random variable as the number of samples $N$ in the sample increases. At the earliest redshift ($z \sim 3.2$), there is a relatively large uncertainty, so that at most scales, several of the reionization histories are expected to lie within 1σ of each other. However, simulations with vastly different values of $\tau_{\text{eff}}$ (as in Simulations H2 and H3 in Figure 3) still show a distinct change in amplitude of the power spectrum. Thus, the one-dimensional power spectrum can serve as another measurement of the overall opacity of the volume.

Note that the feature in the power spectrum at $k \sim 0.2$ (km/s)$^{-1}$ seen most prominently in Simulation H6 is likely a reflection of structure in the baryon distribution in high-density regions. By construction, there are no fluctuations in the radiation field for this simulation, whereas other simulations feature a strong radiation field (and hence a highly ionized state) in high-density regions near quasar sources. At lower redshifts, when $x_{\text{He III}} \gtrsim 0.99$, even the high-density gas is highly ionized, and so the feature is not as pronounced. As a point of comparison, this feature is not present in Simulation H3, because while the global ionization fraction is lower than in Simulation H6, the gas in high-density regions is still ionized.

At lower redshift, the uncertainty of the power spectra decreases noticeably. As a result, in principle it becomes easier to distinguish the histories. At the same time, there is significant overlap in several of the histories, which is due to having a comparable value of $\tau_{\text{eff}}$. Some of the largest differences that remain are at large scales. As with the H I Lyα forest (and discussed in Paper II), these differences might be attributable to the large-scale radiation field. Because the radiation field is highly non-uniform He II-ionizing radiation originating from quasars (as opposed to the H I forest that has a largely uniform background component from galactic radiation), the large-scale power may reflect the degree of bias in the sources. Note in particular that Simulation H6, which has only a uniform UV background and no explicit sources, has consistently the lowest large-scale power, despite having one of the earliest reionization times. At all redshifts considered, this simulation shows a lack of power compared to the simulations with explicit sources. Thus, the large-scale power may be a way to learn about the bias of sources of helium II reionization.

As in Section 3.2, we have also computed the one-dimensional power spectrum using sightlines that have been convolved down to the typical HST/COS resolution, and with noise added as well. These mock observational changes to the one-dimensional power spectrum are significantly more detrimental than for the flux PDF. Figure 9 shows the resulting one-dimensional power spectrum at $z \sim 3$ for the different simulations. Note that the extent of $k$-modes on the $x$-axis is significantly reduced compared to Figure 8. This reflects the coarsening of the resolution of the different pixels, by more than an order of magnitude. The turnover seen in Figure 8 at $k \sim 0.03$ (km/s)$^{-1}$ is also absent from the scales probed, and so only the large-scale rise is seen. As in Figure 7, the bootstrap errors now show significant overlap between the different simulations, somewhat reducing the constraining power on the reionization history. Nevertheless, the primary results shown in Figure 8 demonstrate that, when measured using sufficient resolution, the differences in the reionization history are apparent in the one-dimensional power spectrum.

4. Discussion

One very pertinent question with these measurements is the degree to which the reionization history can be determined with a limited number of observations. As discussed in Section 1, to date there have been only about 50 observations of the He II Lyα forest (Sypniers et al. 2012). We have shown in Sections 3.2 and 3.3 that the flux PDF and one-dimensional power spectrum provide significant information about the ionization state of helium. However, it is reasonable to wonder to what extent current observations are able to determine the ionization state of the IGM.

To this end, we have used bootstrap resampling using 10 sightlines to estimate the standard deviation for our different
scenarios. Figures 5 and 8 show the 1σ dispersion as measured for the 10 sightlines. As noted in the earlier discussion, the ionization state of helium may be readily detectable in the flux PDF measurement. Even accounting for uncertainty in the continuum level of the forest, the shape of the flux PDF varies strongly as a function of ionization fraction. This variation in shape is significantly larger than the inherent variation of the flux PDF, and so even with comparatively few sightlines, a meaningful determination of the ionization level of helium maybe possible given the current data. Figure 6 shows that the slope of the flux PDF is capable of well-characterizing the timing of the end of reionization, since the slope is highly correlated with the ionization fraction rather than a particular redshift. Accordingly, the flux PDF should be a powerful tool for learning more about helium II reionization.

To provide a better comparison with the available HST/COS data, we have decreased the resolution of the sightlines using a Gaussian convolution to a FWHM of $\Delta v = 150$ km s$^{-1}$, which corresponds to the resolution of most available measurements. A handful of higher-resolution spectra are available (Syphers & Shull 2014), though the small number of spectra may not be able to distinguish between the different models. Note the large size of the uncertainty in Figure 7, which is the bootstrap errors on the 10 sightlines. We have also added noise to the pixels to achieve an S/N of 10, and computed the flux PDF as done previously. This process produced results which were more similar among simulations, though there were individual simulations (such as H3) which were still sufficiently different from the others to be distinguished. Nevertheless, the flux PDF still has a characteristic shape change that marks the transition from an ionization fraction of 99% to 99.9%.

Furthermore, the He II one-dimensional power spectrum on large scales could help determine the bias of sources driving helium II reionization. Note that there is more than an order of magnitude difference in the amplitudes at large scales (e.g., $k = 3 \times 10^{-3}$ (km/s)$^{-1}$), which should be detectable. In addition to the overall amplitude, the shape of the power spectrum on large scales is greatly influenced by the relative bias of the sources: note that all simulations with explicit sources (H1–H5) have a relatively flat power spectrum at large scales, but the uniform UV background featured in Simulation H6 shows decreasing amplitude with decreasing $k$. This is likely related to the radiation field properties; the differences in the helium II ionization fraction in Simulation H6 are driven
primarily by gas density fluctuations, since the same ionization field is seen at all points in the volume. Accordingly, there is less correlation between regions of high and low flux in terms of helium ionization level as well as temperature, and thus less power. In principle, the different source populations for the remaining simulations should have differences reflected in the large-scale power, such as the bias of typical sources. For instance, one might expect the amplitude of the power spectrum from Simulation H4 to be greater than that of Simulation H1 for fixed small-scale amplitudes, reflecting the larger size of ionized regions given the same sources. Although this is reflected in the data somewhat, the trends are not perfect. Much more information could be gained from the full three-dimensional flux power spectrum, where the bias of sources is more straightforward to interpret.

As with the flux PDF results, the introduction of lower resolution and instrumental noise mitigates the differences between the simulations. The scale available to probe the one-dimensional power spectrum is reduced due to the lower resolution of the sightlines, and the amplitude of the power spectrum has been reduced due to the convolution with neighboring pixels. The size of the bootstrap uncertainties has also increased with the introduction of noise, and so the difference between simulations is not as great. However, the main results presented in Sections 3.2 and 3.3 show that there is much information present in the He II Lyα forest at high resolution. Probing the forest with higher-resolution measurements would be very beneficial for understanding the state of the IGM at these redshifts, and having a direct probe of the ionization state of helium.

5. Conclusion

To date, the He II Lyα forest has largely only been used to determine the value of \( \tau_{\text{He II}} \). As can be seen from Figure 3, there is a very large dispersion in this measurement, owing to the large sightline-to-sightline variations. Thus, determining the reionization history from this quantity alone is very difficult, and leads to large uncertainties in the determination of the redshift of reionization. Additionally, as discussed in Section 3.1, this measurement is largely sensitive to the tail-end of reionization, and does not yield much information about the intermediate stages of the reionization process. Accordingly, new applications of the He II Lyα forest would be
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cial for learning more about the timing and duration of reionization.

To this end, we have presented the flux PDF and the one-
dimensional power spectrum as ways to break the degeneracy
present in $\tau_{\text{eff}}$. These differences are generally quite large
between different simulations, in some cases being larger than
an order of magnitude. Further surveys will hopefully be able
to take advantage of these pronounced differences, and begin to
measure the timing and duration of helium II reionization.

This work was supported in part by NASA grants NNX14AB57G, NNX12AF91G, and NNX17AK56G, NSF grants AST15-15389, AST-1615940, and AST-1614853.

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Figure 9. One-dimensional He III flux power spectrum at $z \sim 3$, incorporating the effects of low-resolution spectra and instrumental noise. Due to the lower resolution, the $k$-range probed is drastically reduced compared to Figure 8. The $y$-axis has been kept the same as in Figure 8 to emphasize that the overall amplitude has been reduced by the convolution to lower resolution. The introduction of noise also increases the width of the bootstrap uncertainties, shown in shaded gray in the figure. See the text in Section 3.3 for additional discussion.