Inhomogeneous He II reionization in Hydrodynamic Simulations

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ABSTRACT

The reionization of the second electron of helium shapes the physical state of intergalactic gas at redshifts between 2 ≤ z ≤ 5. Because performing full in situ radiative transfer in hydrodynamic simulations is computationally expensive for large volumes, the physics of He II reionization is often approximated by a uniform UV background model that does not capture the patchiness of reionization. We have devised a model that implements the thermal effects of He II reionization— a way to bypass a full radiative transfer simulation while still realizing the physics of He II reionization that affects observables such as the Lyman α forest. Here we present a publicly-available code that flexibly models inhomogeneous He II reionization in simulations at a negligible computational cost. Because many of the parameters of He II reionization are uncertain, our model is customizable from a set of free parameters. We show results from this code in MP-Gadget. We demonstrate the resulting temperature evolution and temperature-density relation of intergalactic gas—consistent with recent measurements and previous radiative transfer simulations. We show that the impact of He II reionization gives rise to subtle signatures in the one-dimensional statistics of the Lyman α forest at the level of several per cent, in agreement with previous findings. The flexible nature of these simulations are ideal for studies of He II reionization and future observations of the He II Lyman α forest.

Key words: intergalactic medium – quasars: absorption lines – cosmology: theory.

1 INTRODUCTION

The reionization of the second electron of helium is believed to be the last major heating event in the Universe’s baryonic matter, the intergalactic medium (IGM). While the reionization of hydrogen and the first electron of helium was likely seeded by the first galaxies and stars, helium was likely not fully ionized until photons of a higher energy regime (E ≥ 4 Rydberg) were produced in bulk (Madau & Meiksin 1994; Miralda-Escudé et al. 2000; McQuinn et al. 2009; Compostella et al. 2013, 2014).

This reionization of the second electron of helium, He II reionization, was likely driven by quasars. Firstly, the opacity in the He II Lyman α forest suggests the existence of ~ 10 comoving Mpc fluctuations that are most plausibly sourced by AGN. Secondly, the observed luminosity function and spectral energy distribution of quasars produces enough 4 Ryd photons to completely reionize He II by z ~ 3 (Madau et al. 1999; Miralda-Escudé et al. 2000; Haardt & Madau 2012; Khaire 2017; Puchwein et al. 2019; Kulkarni et al. 2019) and Gunn-Peterson troughs in the He II Lyman-α forest indicate that He II reionization ended around this time (McQuinn 2009; Shull et al. 2010; Worseck et al. 2011, 2019). While sources other than quasars emit 4 Rydberg photons (e.g. hot virialized gas, hot galactic and circumgalactic gas, and X-ray binaries), it is unlikely that any of these sources would produce a significant fraction of the extragalactic He II-ionizing radiation (Upton Sanderbeck et al. 2018).

He II reionization shapes the thermal state of the IGM at 2 ≤ z ≤ 5, photoheating the gas by up to tens of thousands of degrees Kelvin (Tittley & Meiksin 2007; McQuinn et al. 2009; Compostella et al. 2013, 2014; Puchwein et al. 2015; Upton Sanderbeck et al. 2016). Because He II reionization is a patchy process, with different regions becoming reionized at different times, it induces spatial fluctuations in temperature at correlated scales of tens of comoving Mpc, surviving for approximately a Hubble time (Hui & Haiman 2003). A secondary effect of the thermal impact of reionization, pressure smoothing, alters the spatial distribution of intergalactic gas as well as the subsequent thermal evolution. Both the thermal state of the gas and resulting pressure smoothing affect Lyman α forest absorption— the most widely used observable of the IGM at 2 ≤ z ≤ 5.

Furthermore, the thermal impact of He II reionization has a dramatic effect on the temperature-density relation of intergalactic gas. Following the end of photoheating from reionization, the temperature-density relation of the low-density IGM begins to evolve into an approximate single power-law relation (Hui & Gnedin 1997; McQuinn & Upton Sanderbeck 2016). Not only does He II reionization modulate the slope of the power law, but it also introduces a significant amount of scatter as a consequence of the patchiness He II reionization. Accurately characterizing the temperature-density relation of the IGM by implementing He II reionization...
into Lyman $\alpha$ forest simulations may reduce biases from cosmological parameters extracted from the Lyman $\alpha$ forest.

Many have forecasted the impact of temperature fluctuations on several IGM statistics. Lai et al. (2006) calculated the effect of temperature fluctuations from a patchy and extended reionization on the Lyman $\alpha$ forest one-dimensional flux power spectrum. They found that models with order unity temperature fluctuations at scales of tens of comoving Mpc only had a few-per cent level effect on the flux power spectrum for small scales. Though McQuinn et al. (2011) reaffirmed the small effect of He II reionization on such one-dimensional Lyman $\alpha$ forest statistics, they show that the three-dimensional flux power spectrum could show order unity deviation from a model without temperature fluctuations.

Additionally, Meiksin (2000), Theuns & Zaroubi (2000), and Zaldarriaga (2002) argue that wavelet filters used on Lyman $\alpha$ forest spectra can effectively detect such spatial temperature fluctuations. Two- and three- point statistics from many Lyman $\alpha$ forest sightlines may also be sensitive to He II reionization temperature fluctuations (White et al. 2010), with a three-point function also being able to detect scatter in the temperature-density relation (Fang & White 2004).

Generally, models of He II reionization in simulations without in situ radiative transfer often use a spatially-uniform ionizing background model that can recreate the mean thermal history at the mean cosmic density owing to He II reionization (e.g. Haardt & Madau 2012; Puchwein et al. 2015, 2019; Faucher-Giguere & A. 2019). This approach neglects the patchiness and resulting fluctuations in temperature, ionization state, and pressure smoothing. This also leads to an artificially narrow temperature-density relation that does not capture the scatter that should result from the inhomogeneity of He II reionization.

In this paper, we present a method of implementing the thermal effects of He II reionization into hydrodynamic simulations without the need for an in situ radiative transfer treatment. While radiative transfer simulations can be an order of magnitude more computationally expensive than non-radiative simulations, our model incurs a negligible computational cost. We alter the thermal state of the gas to mimic the radiative transfer, modeling the impact of He II reionization with a small set of parameters.

Our method captures the patchiness of He II reionization—an important feature for cosmological simulations and for investigating large scales where it is measurable. The morphology of He II reionization in our simulations approximates that found in the radiative transfer He II reionization simulations of McQuinn et al. (2009) where large He III bubbles form rapidly—emerging faster than they grow—and overlap until they fill the entire volume.

In Section 2, we describe the physics of He II reionization and the free parameters of our model. Section 3 describes the details and results of our simulations. We conclude in Section 4.

## 2 He II REIONIZATION MODEL

### 2.1 Thermal physics model

The reionization of He II has a distinct morphology from hydrogen reionization, as it is accomplished by a different class of sources and photon energies. The higher energy photons produced by quasars have long mean free paths that do not collectively form ionization fronts (McQuinn et al. 2009). Approximately, He II ionizing photons can be categorized into two regimes—short mean free path photons that nearly instantaneously ionize the quasar’s surrounding medium and drive the production and growth of He III bubbles, and long mean free path photons that free stream through the Universe and uniformly heat the gas through their rare photoionizations. This multi-zone heating is found in detailed simulations of He II reionization (McQuinn et al. 2009) and serves as the basis of analytic models of the thermal history (Upton Sanderbeck et al. 2016).

The determination of whether any given photon will contribute to the formation and growth of a He III bubble, or free stream and ultimately uniformly heat the IGM can be roughly distinguished by considering the photon’s mean free path. The mean free path can be estimated by the following:

$$\lambda_{\text{MFP, HeII}} \approx 5 \bar{x}_{\text{HeII}} \left( \frac{E_\gamma}{100 \text{eV}} \right)^{3} \left( \frac{1 + z}{4} \right)^{-2} \text{cMpc},$$

(1)

where $E_\gamma$ is the energy of the photon. If the mean free path of the photon is greater than the typical size of a He II bubble, then this photon will contribute to a more uniform background of these higher energy photons.

We model the photoheating during He II reionization with a multi-zone model that distinguishes the heating from short mean free path photons that nearly instantaneously ionize the medium surrounding a quasar and the heating from long mean free path photons that uniformly heat the rest of the IGM.

#### 2.1.1 Short mean free path photons

On average, the short mean free path He II ionizing photons that contribute to the formation of He III bubbles instantaneously heat the newly-ionized gas by,

$$\Delta Q_{\text{inst}} = n_{\text{HeII}} \left( \frac{\int_{h_{\text{HeII}}} E J_E(E(E-h_{\text{HeII}})/E)}{E_{\text{max}} \int_{h_{\text{HeII}}} E J_E(E(E-h_{\text{HeII}})/E)} \right) \Delta E,$$

(2)

where $J_E$ is the average specific intensity that ionized the gas, $h_{\text{HeII}}$ is the ionization potential of He II ($4 \text{ Ryd}/54.4 \text{ eV}$), and $E_{\text{max}}$ is the threshold photon energy that distinguishes photons that contribute to a He II bubble (short mean free path photons) from photons that free stream and uniformly heat the IGM (long mean free path photons). We approximate that the heat injection from these He II bubble-forming photons increases the temperature of the gas around a quasar by $\Delta T_{\text{inst}} = 2/(3k_{\text{Tot}}) \Delta Q_{\text{inst}}$ immediately once the quasar turns on and forms a He III bubble. While He II reionization is underway, the regions that have been exposed to these short mean free path photons are considered fully reionized and no longer experience non-equilibrium photoheating.

#### 2.1.2 Long mean free path photons

He II ionizing photons with energies greater than $E_{\text{max}}$ do not collectively contribute to ionization fronts during He II reionization, instead, they free stream for several tens or hundreds of Myr before absorption. Their impact on the global ionization state of the gas is negligible, but the photoionizations from the rare absorptions of these photons heat the IGM approximately homogeneously with a rate of

$$\frac{dQ_{\text{long MFP}}}{dt}(z) = n_{\text{HeII}}(z) \int_{E_{\text{max}}}^{\infty} \frac{dE}{E}(E-E_{\text{HeII}}) J_E(z) \sigma_{\text{HeII}}(E).$$
The specific intensity of these long mean free path photons at a redshift of $z_0$ is

$$J_E(z_0) = \frac{c}{4\pi} \int_{z_0}^\infty dz \left| \frac{dt}{dz} \right| \frac{(1 + z_0)^2}{(1 + z)^3} \tau_{HeII}(z, E) e^{-\tau_{HeII}(z_0, z, E)} ,$$

where the optical depth from photons emitted at redshift $z_{em}$ to redshift $z$ is defined by

$$\tau_{HeII}(z_{em}, z, E) = \int_{z_{em}}^{z} \frac{c dz}{H(z)(1 + z)} \sigma_{HeII} \left( \frac{1 + z}{1 + z_0} \right) n_{HeII}(z).$$

In Equation 4, we approximate the specific ionizing emissivity to hold the shape of a power-law, such that $\epsilon_E = AE^{-\alpha}$ (see § 2.3.1). The normalization factor, $A$, is determined by setting the ionizing emissivity equal to the total number of ionizations and recombinations, such that,

$$\int_{E_0}^{\infty} dE \epsilon_E = n_{He} \left( \frac{d\bar{x}_{HeII}}{dt} + C\bar{x}_{HeII} \tilde{\alpha} \bar{x}_{HeII} n_e \right),$$

where $\bar{x}_{HeII}$ is the model-dependent mean ionization fraction of He III, and $C\bar{x}_{HeII}$ the clumping factor (see § 2.3.5).

2.1.3 The patchiness of He II reionization

The multi-zone heating based on the two types of photoheating described in the previous subsections illustrates how we implement the thermal impact of He II reionization. Short mean free path photons form and heat He II bubbles, while long mean free path photons uniformly heat all intergalactic gas that is not yet part of a He II bubble. Gas particles will be reionized at different times—He II bubbles form around ionizing sources until the bubbles overlap completely and the whole volume ionized. As soon as a gas particle becomes part of a He II bubble, photoheating from the long mean free path photon background shuts off and this region experiences the instantaneous heating from the reionization of He II. This approach of heating and cooling local regions individually avoids artificial cooling rates— a consequence of using a UV background model to uniformly heat the IGM (e.g. Haardt & Madau 2012; Puchwein et al. 2019; Faucher-Giguere & A. 2019)— as recombination and collisional cooling rates are dependent on the local temperature.

The gas in regions that are reionized last is exposed to the heating from the long mean free path photons longest and thus is heated more extremely than earlier-reionized regions. He II reionization ends with significant spatial fluctuations in the temperature of the intergalactic medium. Thus, the duration of He II reionization will affect the magnitude of these temperature fluctuations.

2.2 Model implementation

The morphology of He II reionization in the radiative transfer simulations of McQuinn et al. (2009) suggest that the emergence of He II bubbles happens rapidly and that these bubbles occur in a tight distribution of sizes. Our models emulate this process as follows:

(i) In the simulation, we identify halos of $M_{halo} \geq 10^{12}M_\odot$ and select one of these halos at random to host a quasar.

1 The mass range for potential quasar host halos is selectable by the user in our model.

(ii) We create a He II bubble centered around the quasar when the quasar “turns on”. The short-mean-free-path heating described in the previous section is applied to gas within the bubble—flash heating the region. Each ionized particle is marked so that particles are only ionized once.

(iii) We turn on additional quasars and form resulting bubbles in the box to match an ionization fraction that is pre-computed at each timestep in the simulation. Regions that have not been reionized are exposed to the long-mean-free-path photon background.

(iv) The He II bubbles eventually overlap and fill the entire volume. Once a particle is ionized, it stays ionized indefinitely regardless of whether it moves outside the spatial extent of the He II bubble at formation. Once the desired ionization fraction exceeds 0.95, all remaining gas in the simulation volume is ionized.

Because the uniform long mean free path heating is dependent only on the parameters of He II reionization selected prior to running the simulation, this heating is calculated ahead of time in tandem with the He II reionization evolution. These radiative transfer calculations are run in a separate (public) code that takes the user-selected parameters of He II reionization and produces an input file for the simulation.

2.3 Free parameters

We aim to capture the extent of the parameter space of He II reionization in these models. The following free parameters encapsulate the uncertainties in the sources of He II ionizing photons and the evolution of the thermal state of the IGM.

2.3.1 Quasar spectral index

The emissivity of quasars at 4 Ryd is uncertain. This owes to the difficult nature of observing any extragalactic radiation in the extreme ultraviolet and the uncertainty in the quasar SED at these energies. Observations in the nearer UV only reliably estimate the shape of this SED to a couple tens of electron volts (e.g. Telfer et al. 2002). The heating resulting from He II reionization is highly dependent on this emissivity. Most estimates of this emissivity model quasar SEDs as single power-laws fixed at 912 Å.

Quasar stacks in the UV are used to constrain the power-law index of the spectral energy distribution, $\alpha_{QSO}$. The analyses of these stacks find varying values of $\alpha_{QSO}$, between $\sim 1.0$ and 2.0 (Telfer et al. 2002; Shull et al. 2012; Stevans et al. 2014; Lusso et al. 2015). Uncertainty in the H I absorption from the IGM and the subsequent correction accounts for much of this discrepancy. Unlike H I reionization, collisional cooling is not effective in cooling the He II ionization fronts, and thus the value of $\alpha_{QSO}$ drives the magnitude of heating from He II reionization. Because $\alpha_{QSO}$ is the largest source of uncertainty for the temperature of a He II bubble immediately after it has undergone reionization, the value of $\alpha_{QSO}$ is crucial in determining the magnitude of peak of the temperature at $z \sim 3$.

2.3.2 Evolution and duration of HeII reionization

While the He II Lyman $\alpha$ forest provides a rough estimate in redshift for the finish of He II reionization, the duration and evolution is still uncertain. Large error bars on temperature measurements at high redshift and quasar luminosity functions do not reveal an obvious onset, though a very early start to He II reionization would
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2.3.3 He II bubble size

The size distribution of the He II bubbles will be dependent on the properties of their sourcing quasars—most importantly their luminosity and lifetime. In the radiative transfer simulations of McQuinn et al. (2009), the quasars are modeled with two different methods: (1) quasars have a constant lifetime and their luminosity is dependent on the host halo mass, and (2) the quasar lifetime is dependent on the luminosity. The distribution of resulting He II bubble sizes is centered around 20 comoving Mpc (for a quasar lifetime of 40 Myr) and 35 comoving Mpc respectively. The latter method has a much tighter distribution because the relation between quasar luminosity and lifetime results in brighter quasars having shorter lifetimes. Though these quasar models are extremely simple, they give a reasonable first order estimation. We leave both the mean bubble size and variance in the distribution as free parameters. The default bubble size is 30 Mpc/h with 0 variance.

2.3.4 Threshold energy of He II bubble photons

Equation 1 estimates the photon energy which would give a mean free path longer than the size of the He II bubbles. Though Upton Sanderbeck et al. (2016) found that the mean thermal history was highly insensitive to the value of this threshold photon energy that separates the short mean free path photons that contribute to He II bubbles from the uniform long mean free path photon background, it is dependent on the size of the mean He II bubble size. Because the He II bubbles are likely on the order of tens of Mpc, the value of this threshold energy, $E_{\text{max}}$, should fall roughly between 100-200 eV.

$$\frac{\langle \alpha_{B} \rho_{\text{HeIII}} n_{e} \rangle}{\langle \alpha_{B} \rangle \langle n_{\text{HeIII}} \rangle / \langle n_{e} \rangle} = \frac{\langle \alpha_{B} \rho_{\text{HeIII}} n_{e} \rangle}{\langle \alpha_{B} \rangle \langle n_{\text{HeIII}} \rangle / \langle n_{e} \rangle}$$

where $\alpha_{B}$ is the Case B recombination rate for He II, and $n_{e}$ and $n_{\text{HeIII}}$ are the number densities of electrons and He III respectively. The clumping factor is found on the right side of Equation 6, and modulates the normalization of the emissivity of ionizing sources and heating from the long mean free path photon background. $C_{\text{HeIII}}$ is typically in the range of $\sim 1 - 5$, near unity at high redshift and increasing with decreasing redshift. During the span of He II reionization, the clumping factor in our simulations grows between $2 \lesssim C_{\text{HeIII}} \lesssim 3.5$. Despite this evolution, in these simulations, we use a constant value—selectable by the user.

3 SIMULATIONS AND RESULTS

The code described in this paper is integrated into the cosmological simulation code MP-Gadget Feng et al. (2018). MP-Gadget is descended from Gadget-2 Springel (2005), with heavy modifications for scalability7. We recommend using this code with simulations that exceed a box size of $\sim 100$ Mpc in order to fully capture the scales of He II reionization effects. We use a fiducial UV background model from Puchwein et al. (2019), modified to have zero He II photoheating during He II reionization. The simulations shown in § 3 are run with a box size of 100 Mpc/h and 1024$^3$ particles. Cooling, star formation, a black hole accretion model, and feedback from supernovae and black holes are included following Feng et al. (2016).

In this section, we present the results of our simulations, demonstrate the impact of He II reionization on various gas statistics, and compare these results with historical He II reionization radiative transfer simulations. Figure 2 shows snapshots of our simulation with fiducial parameters at a redshift prior to He II reionization ($z = 4$), during He II reionization ($z = 3.25$), and after He II reionization has completed ($z = 2.5$). The left panels show the density distribution with shaded He II-ionized regions. The right panel shows the corresponding temperature field. Our fiducial model sets $\alpha_{\text{QSO}} = 1.7$, $C_{\text{HeIII}} = 3$, $E_{\text{max}} = 150$ eV, and $z_{\text{reion,HeII}} = 2.8 - 4$. 

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3.1 Evolution of the thermal history of the IGM at the mean density

The evolution of the thermal state of intergalactic gas has been studied extensively over the past couple decades in response to the emergence of high-resolution, high signal-to-noise Lyman α forest spectra data. These spectra allowed for measurements of the temperature of the low density IGM through quantification of the small-scale structure in the absorption features. A bump found in the temperature at \( z \sim 3 \) hinted at additional photoheating from He II reionization, though variations in temperature measurements amongst different studies have disputed the amplitude and timing of this peak (Schaye et al. 2000; Lidz et al. 2010; Becker et al. 2011; Garzilli et al. 2012; Boera et al. 2014; Bolton et al. 2014; Hiss et al. 2018; Walther et al. 2019; Boera et al. 2019; Gaikwad et al. 2020).

Recent UV background models (e.g. Haardt & Madau 2012; Puchwein et al. 2019) are able to emulate the evolution of the temperature of the IGM at the mean cosmic density, \( T_0(z) \), which includes a bump in temperature from He II reionization. However, modeling the impact of He II reionization with a single, spatially uniform UVB model will result in heating and cooling rates that differ from those found in an inhomogeneous reionization. Not only do these models miss the impulsive heating during the creation of He III bubbles, but many of the cooling processes of intergalactic gas are dependent on temperature, such as from recombinations and collisional cooling.

Figure 3 shows the temperature evolution at the mean cosmic density for a selection of our He II reionization models and a single case with only the Puchwein et al. (2019) UV background model. The solid purple curve shows our fiducial model with a linear reion-
Figure 3. Average temperature evolution of the IGM at the cosmic mean density for a selection of He II reionization models. The solid purple curve shows our fiducial model with $\alpha_{\text{QSO}} = 1.7$, $C_{\text{HeII}} = 3$, $E_{\text{max}} = 150$ eV, and $\tau_{\text{reion,HeII}} = 2.8 - 4$. The dashed turquoise curve and black curves vary $\alpha_{\text{QSO}}$ to 1.3 and 2.0 respectively. The dotted pink curve shows a thermal history based on the quasar emissivity function of Kulkarni et al. (2019). The dashed green curve shows the temperature evolution without an inhomogeneous He II reionization model, but that recreates the mean thermal history with the Puchwein et al. (2019) UV background model.

The evolution of the temperature-density relation of the IGM is shown in Figure 4 for our fiducial He II reionization model. The dispersion seen in the bottom panels of Figure 4 is marked by several distinct power-laws that represent each independently-evolving He II bubble. The scatter in the temperature-density relation will peak at the conclusion of He II reionization. Following the end of the photoheating associated with reionization, the temperature-density relation will gradually settle back down into a single power-law.

Many of the temperature measurements aim to simultaneously constrain the temperature at the mean cosmic density and $\gamma$, with the assumption that the temperature-density relation follows a single power-law relation, but this does not reflect the nature of the independently-evolving regions that are ionized at different epochs. However, the dispersion in the temperature-density relation is highest at the lowest densities, and thus the observability of these fluctuations is diminished (McQuinn et al. 2011).

3.3 The Lyman $\alpha$ forest, flux PDF, and flux power spectrum

The flux probability distribution function (PDF) and the one-dimensional flux power spectrum of the Lyman $\alpha$ forest are the most frequently used statistics of this observable. On one end (small $k$), it is sensitive to the large-scale density distribution of matter and at large $k$, it is more sensitive to astrophysical processes such as ionizing backgrounds and thermal fluctuations in intergalactic gas. Because the Lyman $\alpha$ forest flux power spectrum quantifies fluctuations at both cosmological and astrophysical scales, it is a potential tool to constrain cosmological parameters.

In the following figures, we compare (1) a simulation that has our He II reionization model turned off, but with the Puchwein et al. (2019) UVB model uniformly heating the IGM during the redshifts of He II reionization and (2) a simulation with our He II reionization model that roughly matches the temperature evolution at mean cosmic density of the former. Recalling Figure 3, the closest match to the Puchwein et al. (2019) UVB model is our fiducial model with $\alpha_{\text{QSO}}$ modified to 2.0—thus this the He II reionization model we use for the remainder of the figures. Because we are approximately controlling for the temperature evolution of intergalactic gas at the mean density during He II reionization, the following comparisons highlight the effect of patchy reionization on the Lyman $\alpha$ forest. Figure 5 shows simulated Lyman $\alpha$ forest spectra with and without inhomogeneous He II reionization. Because the individual lines in the Lyman $\alpha$ forest are sensitive to the local thermal state of intergalactic gas, spectra from models with patchy He II reionization show more dispersion in the small scale structure of temperature and will not conform to a tight power law temperature-density relation before the onset of He II reionization.  

4 Realistically, He II bubbles are not instantaneously ionized, so dispersion in the temperature-density should be smoother than our simulations suggest.

If hydrogen reionization ends lower than $z \approx 3$, it is sensitive to the large-scale density distribution of matter and at large $k$, it is more sensitive to astrophysical processes such as ionizing backgrounds and thermal fluctuations in intergalactic gas. Because the Lyman $\alpha$ forest flux power spectrum quantifies fluctuations at both cosmological and astrophysical scales, it is a potential tool to constrain cosmological parameters.

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\[ T = T_0 \Delta \gamma^{-1} \]

where $T_0$ is the temperature of the IGM at the mean cosmic density, $\Delta$ is the fractional gas overdensity, and $\gamma - 1$ is the power-law index shaped by the heating and cooling processes of the gas. This parameterization holds generally true after He II reionization and possibly after hydrogen reionization, settling approximately into a single power-law with $\gamma$ typically holding a value of $\approx 1.6$ (Hui & Gnedin 1997; McQuinn & Upton Sanderbeck 2016). Once He II reionization begins, the regions undergoing reionization are flash heated by thousands of degrees, while the newly He III -ionized regions begin to cool. Regions where He II has not yet been ionized are exposed to the long mean free path photons that gradually heat the gas. The spatially-varying heating and cooling introduces scatter in the temperature-density relation that peaks around the end of He II reionization.

The evolution of the temperature-density relation of the IGM is shown in Figure 4 for our fiducial He II reionization model. The dispersion seen in the bottom panels of Figure 4 is marked by several distinct power-laws that represent each independently-evolving He II bubble. The scatter in the temperature-density relation will peak at the conclusion of He II reionization. Following the end of the photoheating associated with reionization, the temperature-density relation will gradually settle back down into a single power-law.

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the absorption features. This can be more clearly represented in the following statistics of the forest.

From our simulated Lyman α forest spectra, we calculate the flux PDF for our simulations shown in Figure 5. Because the patchiness of reionization will result in multiple temperatures at the same gas density, the flux PDF will reflect more bimodality after He II reionization is underway. The left panel of Figure 6 shows the flux PDF for a redshift at the onset of He II reionization (z = 4) and towards the end of reionization in the right panel (z = 3). The solid curve shows our model with inhomogeneous reionization and the dashed curve shows the effect of a homogeneous UVB. Indeed, in the midst of He II reionization, we find a more bimodal distribution in comparison to our simulation without inhomogeneous He II reionization.

From these same simulations, we show the one dimensional flux power spectrum in Figure 7. The left panel presents the flux power spectrum for a redshift at the onset of He II reionization (z = 4) and the right panel shows how the two models deviate after He II reionization is well underway (z = 3). The bottom panels show the fractional difference between our model with inhomogeneous reionization and a homogeneous UVB. The inclusion of He II reionization changes the amplitude of the flux power spectrum at the several per cent level: ~ 10% at scales approximately greater than the He II bubble scale, and at tens of per cent at scales ≲ 0.2 [Mpc/h]^{-1}. Though we approximately controlled for the temperature at the mean cosmic density between these two simulations, we acknowledge that some of the deviation may owe to small differences in the evolution of \( T_0 \).

McQuinn et al. (2011) predicted that the effect of temperature fluctuations from He II reionization on these one-dimensional statistics would be exceedingly small. However, their model does not include the dynamical response of intergalactic gas to the thermal impact of He II reionization such as self-consistent pressure smoothing of the gas. This pressure smoothing is a natural outcome of our model and potentially contributes to the impact of our He II reionization model. Despite the small effect on the one-dimensional statistics of the forest, precision cosmological searches now push constraints to the per cent-level– benefitting from even small improvements in such statistics.

3.4 He II Lyman α forest

Though more observationally elusive than the H I Lyman α forest, the He II Lyman α forest is an ideal diagnostic for the timing and duration of He II reionization. The He II Lyman α line falls at 303.8 Å, within the extreme ultraviolet, and thus its forest is only possible to observe above \( z > 2 \) – at lower redshifts, our own galaxy’s high column density systems absorb any He II Lyman α transmission. Even more limiting, quasar sightlines that intersect systems with \( N_{HI} \gtrsim 10^{17} \text{ cm}^{-2} \) have absorbed He II Lyman α...
sufficient transmission (Worseck et al. 2011; Worseck et al. 2016, 2019).

Because our simulations track the different ionization states of helium and capture the patchiness of the He II field, we are able to extract mock He II Lyman α forest spectra. Figure 8 shows the He II Lyman α forest from a simulation with our fiducial He II reionization model at multiple redshifts—toward the conclusion of He II reionization (z = 2.9) and following the completion (z = 2.7). These spectra are qualitatively consistent with the existing He II Lyman α forest sightlines, showing a limited number of transmission spikes at redshifts where He II reionization is still ongoing that likely correspond to very underdense regions that have already undergone He II reionization. The sightlines shown in Figure 8 serve primarily to demonstrate the functionality of our code, with constraints on the evolution of He II reionization possible with the advent of future He II Lyman α programs.

4 CONCLUSIONS

We have constructed a model for He II reionization in cosmological simulations without the need for in situ radiative transfer. This method includes the thermal impact of the reionization of He II - capturing the patchiness— and thus temperature fluctuations and secondary effects such as pressure smoothing of the intergalactic gas. It also includes patchiness in the He III field, reflecting the fact that these bubbles develop around biased tracers of the density field. This model is now publicly available as a feature of MP-Gadget.

This tool can be used to investigate the parameter space of He II reionization and frees future simulations from the rigid He II parameters in UVB models. Because of its flexibility and efficiency, our model can perform a Bayesian analysis of He II reionization, something previously unattainable with He II reionization simulations that required radiative transfer.

Our simulations show thermal histories consistent with historical temperature measurements of the IGM—though uniform UVB models also are able to reproduce the thermal evolution at mean cosmic density. However, the thermal evolution of the gas in our simulations more accurately reflects the physics of He II reionization than simulations that use a uniform UVB to model the He II reionization photoheating and captures the spatial variance in temperature from a patchy reionization. We show the evolution in the dispersion of the temperature-density relation with patchy reionization, finding that the scatter at redshifts near the conclusion of He II reionization is consistent with previous radiative transfer simulations (McQuinn et al. 2009; Compostella et al. 2013, 2014).

Though the one-dimensional statistics of the Lyman α forest, specifically the one-dimensional flux power spectrum, do not reflect a dramatic change between models with and without patchy He II reionization as previously shown in McQuinn et al. (2011), we find signatures of inhomogeneous He II reionization at the level of several per cent. With precision cosmology requiring percent-level accuracy for models of the flux power spectrum, it may be necessary to marginalize over the parameters of He II reionization to improve constraints.

The recent debut of new He II Lyman α forest sightlines require large He II reionization simulations for future progress in observationally constraining He II reionization. The He II Lyman α forest extracted from our simulations can eventually serve as a theoretical tool to better constrain the evolution and conclusion of He II reionization. While the small number of sightlines limit this progress, flexible He II reionization simulations will be crucial for future He II Lyman α programs.

Until now, including He II reionization in hydrodynamic simulations required computationally expensive radiative transfer. Going forward, hydrodynamic simulations can include He II reionization with a minimal increase in simulation time. The addition of the long-neglected physics of He II reionization and the ability to customize the He II reionization parameters should incentivize future work on He II reionization from both the observational and theoretical perspective.

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Figure 6. Flux probability distribution function from a simulation with inhomogeneous He II reionization model (solid) and from a simulation with a uniform UVB (dashed). The left panel shows a redshift at the onset of He II reionization ($z = 4$) and the right panel shows a redshift just before its completion ($z = 3$).

Figure 7. One dimensional flux power spectrum from a simulation with inhomogeneous He II reionization model (solid) and from a simulation with a uniform UVB (dashed). The lower panels show the fractional change between these two models. The left panel shows a redshift at the onset of He II reionization ($z = 4$) and the right panel shows a redshift just before its completion ($z = 3$).

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Figure 8. Simulated He II Lyman α forest spectra from our fiducial He II reionization. The top panel shows ten different sightlines at $z = 2.9$ (before the completion of He II reionization) and the bottom panel shows ten sightlines from $z = 2.7$ (after the completion of He II reionization).