Cosmic Reionization on Computers: Evolution of the Flux Power Spectrum

Nishant Mishra1,2,3 and Nickolay V. Gnedin2,4,5

1 Department of Physics; The University of California; Berkeley, CA 94720, USA
2 Fermi National Accelerator Laboratory; Batavia, IL 60510, USA; gnedin@fnal.gov
3 Lawrence Berkeley National Laboratory; Berkeley, CA 94720, USA
4 Kavli Institute for Cosmological Physics; The University of Chicago; Chicago, IL 60637, USA
5 Department of Astronomy & Astrophysics; The University of Chicago; Chicago, IL 60637, USA

Received 2021 September 25; revised 2022 February 19; accepted 2022 March 1; published 2022 April 7

Abstract

We explore the evolution of the flux power spectrum in the Cosmic Reionization On Computers simulations. We find that, contrary to some previous studies, the shape of the flux power spectrum is rather insensitive to the timing of reionization. However, the amplitude of the flux power spectrum does strongly evolve with time, and that evolution is almost perfectly correlated with the timing of reionization. We show how such correlation can be used in a (futuristic) measurement to determine the redshift of overlap of ionized bubbles.

Unified Astronomy Thesaurus concepts: Lyman alpha forest (980); Reionization (1383)

1. Introduction

The Epoch of Reionization (EoR) is a critical period in the thermal history of our universe. This period is when radiation from the first light sources reionized the neutral hydrogen. The Lyα forest, created by the resonant scattering of redshifted Lyα photons from distant quasars by neutral hydrogen along a line of sight, has been used to successfully probe this period. While on large scales the Lyα forest can be well described by the large-scale structure in the Λ-cold-dark-matter cosmological model, on small scales it is dependent on the thermal history of the intergalactic medium (IGM). This allows it to be used as a probe of the EoR, as well as other astrophysical phenomena, such as the thermal nature of dark matter. In this paper we utilize the Cosmic Reionization on Computers (CROC) simulation suite to explore the evolution of one of the key statistical measures of the Lyα forest, its flux power spectrum (Croft et al. 2002) at redshifts 5 < z < 7.

Temperature fluctuations affect the Lyα flux power spectrum at a variety of scales. On small scales, Doppler broadening caused by thermal velocities of the neutral hydrogen along the line of sight results in the cutoff in the flux power spectrum at $k \gtrsim 0.1 \, \text{km s}^{-1} \, \text{s}$. There is also an additional effect of pressure smoothing that contributes to the small-scale cutoff and is dependent on the full prior thermal history (Gnedin & Hui 1998). At larger scales, inhomogeneous distribution of ionized bubbles during the EoR can affect the power spectrum by causing large-scale temperature fluctuations (Oñorbe et al. 2017; Montero-Camacho et al. 2019; Montero-Camacho & Mao 2020, 2021; Wu et al. 2019; Molaro et al. 2022). Finally, the flux power spectrum can also be used to probe the overall ionization fraction of the universe as a function of redshift, since at some sufficiently high redshifts during the EoR, all Lyα forest should become saturated and transmitted flux vanishes.

A number of measurements of the flux power spectrum at $z > 5$, approaching the EoR, currently exist (Viel et al. 2013; Walther et al. 2018; Boera et al. 2019; D’Aloisio et al. 2019; Walther et al. 2019). As the observational data on high-redshift quasars (and, hence, on the high-redshift Lyα forest) are bound to explode with the next generation of optical telescopes, it is useful to consider what potential constraints can be obtained from the observations of the flux power spectrum at $z \sim 6$.

2. Methodology

As a plausible model of cosmic reionization we use simulations from the CROC project (Gnedin 2014; Gnedin & Kaurow 2014). CROC simulations have two properties that make them highly suitable for this project. First, they provide a reasonable, albeit not perfect, match to the observed distributions of optical depths and dark gaps in the Lyα forest at 5 ≤ z ≤ 6 (Gnedin et al. 2017). Second, CROC simulations include several random realizations with variable DC modes (Gnedin et al. 2011) for each box size, and these random realizations can be used both as samples of different spatial locations in the universe (the primary, designed usage) and as models of different universes with somewhat different reionization histories (a secondary, serendipitous usage). It is the latter usage that is of a particular value for this work.

Specifically, we use seven realizations of 40 h−1 cMpc ≈ 60 cMpc simulation volumes. The largest CROC simulations were performed in 80 h−1 cMpc volumes, but volumes of such size are so close to the mean universe that variations between different realizations do not lead to interesting variations in the reionization histories. In smaller 40 h−1 cMpc volumes such variations are larger, and hence these boxes are more useful for our purposes. The seven realizations include six random realizations (that we label A–F) and one variation of box E with the value for the fluctuation in the cosmic density on the scale of the simulation box (the so-called “DC mode”) manually set to 3σ (to produce a strongly overdense volume that can still be reasonably evolved to z ∼ 5). We label that simulation as “E. DC = 3.” Figure 1 shows reionization histories for these seven realizations. We note that these seven simulations span a wide range of reionization histories, with the strongly overdense run E.DC = 3D experiencing the earliest drop in the H1 fraction. These simulations can therefore serve as proxies for models with different cosmological parameters (a simulation with the nontrivial DC mode can also be interpreted as a simulation with

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https://doi.org/10.3847/1538-4357/ac5a50

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the zero DC mode, in which the values of cosmological parameters differ from the assumed ones; Sirko 2005).

For each simulation volume, 1000 genuinely random (i.e., starting at random positions and going along a random direction) lines of sight were produced at a number of redshifts and Lyα forest spectra were produced for each of them. The (one-dimensional) flux power spectrum \( P_F(k) \) was then computed at each redshift as

\[
P_F(k) = \left\langle \left| \frac{F_k}{\bar{F}} \right|^2 \right\rangle, \tag{1}
\]

where \( F_k \) is the Fourier transform of the simulated transmitted flux, \( \bar{F} \) is the mean flux at that redshift, and averaging is done over all 1000 lines of sight. The flux power spectrum quantifies information about the clustering of neutral gas, and hence contains information about both the reionization history of the universe and about the underlying cosmology.

### 3. Results

The Lyα flux power spectra from Realization A are shown in Figure 2 for multiple redshifts at \( 5 < z < 7 \). As can be expected, the flux power spectrum grows with redshift, as the higher neutral gas fraction at higher \( z \) results in more absorption, while at low \( z \) there is more ionized gas. The highest redshift value we show is \( z = 6.8 \). While there is some transmitted flux in some lines of sight at even higher redshifts, the number of lines of sight with any transmitted flux absorption across the velocity range is too low. This results in a power spectrum that is entirely determined by only a few transmitted spikes. Hence, we only show and analyze redshifts where at least 20% of the lines of sight contain some flux.

Comparison with the actual measurements of the flux power spectrum at \( z = 5 \) from Boera et al. (2019) shows that the flux power spectrum in the simulations falls down at small scales significantly faster than the data. This is the expected behavior, as CROC simulations use adaptive mesh refinement to achieve 100 pc resolution inside galaxies, but have only limited spatial resolution in the IGM. The finite numerical resolution affects modes with \( k \gtrsim 0.1 \text{ km} \cdot \text{s}^{-1} \).

It is clear from Figure 2 that the shape of the flux power spectrum does not change significantly, while the amplitude evolves rapidly with redshift. In order to illustrate the evolution in the shape (or lack thereof) quantitatively, we show in Figure 3 the flux power spectrum normalized by its value at the maximum. We also scale the x-axis by \( k_{\text{max}} \), the value of \( k \) at which the maximum \( P_F(k) \) is achieved. In order to measure the maximum value, the flux power spectrum is smoothed by a five-pixel-wide Gaussian filter to avoid measuring a noisier part of the spectrum as the true \( k_{\text{max}} \).

The overall shape of the flux power spectrum is consistent across redshifts with only mild variation (25% at scales below \( k_{\text{max}} \) and 50% at smaller scales) at the highest redshifts. Even that variation may not be statistically insignificant due to the limited number of transmitted spikes in the simulated spectra. Figure 4 shows the normalized shape for the flux power spectra for all seven realizations we consider at a fixed redshift. Again, little variation in the shape is observed, although there exists a mild trend of more power at high \( k \) for realizations with larger DC modes.

In other words, the shape of the flux power spectrum is similar enough across redshifts and realizations that its peak value of \( P_F(k_{\text{max}}) \) is sufficient for the analysis of data from any conceivable survey in the near future. Figure 2 shows that the
power at $z \sim 7$ is about 3 orders of magnitude higher than power at $z \sim 5$, and the magnitude at high $k$ and high $z$ is lower still. Given the existing measurements of the quasar luminosity function (Onoue et al. 2017), there will be just several hundred around a thousand quasars available for high signal-to-noise spectroscopy at $z \gtrsim 5.5$ even with 30 m class telescopes. Thus, while one can, in principle, achieve a precision of several percent in measuring the flux power spectrum on large scales, such a measurement will require an observational sample that includes a significant fraction of all existing quasars. Such a sample will take many years to assemble, and hence we do not consider the small variations in the shape of the power spectrum we observe in Figures 3 and 4 any further.

If the full flux power spectrum can be characterized by only two values, $k_{\text{max}} \text{ and } P_{k}(k_{\text{max}})$, we only need to explore the evolution of these two quantities. The evolution of $k_{\text{max}}$ for Realization A is shown in Figure 5. It appears that $k_{\text{max}}$ also varies by less than 25% with redshift, and given the difficulty in measuring the exact location of such a broad maximum, we do not consider $k_{\text{max}}$ as a useful probe of reionization history hereafter. That leaves the amplitude of the flux power spectrum $P_{k}(k_{\text{max}})$ as the only quantity of interest.

The redshift evolution of $k_{\text{max}}P_{k}(k_{\text{max}})/\pi$ is shown in the left panel of Figure 6 for all seven independent realizations described in Section 2. While the evolution is similar for all seven simulation boxes, they do exhibit systematic offsets. Comparison with Figure 1 shows that models that reionize later tend to have higher flux power spectra at the same redshift or, equivalently, reach the same value for the flux power spectra at lower redshifts. We return to this trend below.

The rapid evolution in the amplitude of the flux power spectrum apparent from Figure 2 is, at least in part, due to the rapid evolution of the overall level of Ly$\alpha$ transmission in the quasar spectra. The evolution of the mean transmitted flux $F$ for our seven independent realizations calculated as the mean flux value for all 1000 lines of sight is shown in the right panel of Figure 6, and resembles, up to the flip in the direction, the corresponding evolution of the flux power spectrum from the left panel of that figure.

It is curious that the rate of the evolution in two quantities is similar (up to the opposite direction). That implies that the quantity $\bar{F}P_{k}(k_{\text{max}}) = (F^{2}/\bar{F})$ evolves little with redshift. We explored this quantity but found no obvious application for its use.

In order to quantify the redshift evolution of the flux power spectrum, we measure the "redshift offset" between each of the seven independent realizations and the "E.DC = 3" realization (including its own zero offset with itself) as the redshift offset that makes the two curves for $k_{\text{max}}P_{k}(k_{\text{max}})/\pi$ versus $z$ coincide on average. That is, if $P_{k}^{A}(k_{\text{max}}, z)$ and $P_{k}^{E.DC = 3}(k_{\text{max}}, z)$ are the flux power spectra for models A and E.DC = 3, the redshift offset $z_{A}$ between them is the value that minimizes the difference

$$\int dz(P_{k}^{A}(k_{\text{max}}, z - z_{A}) - P_{k}^{E.DC = 3}(k_{\text{max}}, z))^{2},$$

with the integral taken over the redshift range for which we are able to measure $P_{k}(k_{\text{max}}, z; A)$. This redshift offset can then be compared with the "redshift of overlap" for each of the independent realizations. The concept of the "redshift of overlap" is intended to capture the crux of the reionization process, when isolated ionized bubbles merge and the ionization topology changes from isolated ionized regions in the continuous neutral medium to isolated neutral regions in the continuous ionized medium. While the formal definition of the redshift of overlap for cosmic reionization is the moment when the photon mean-free path grows at the highest rate (Gnedin 2000), that formal definition is not easy to use in practice. A good proxy for it is the moment when the volume-weighted neutral hydrogen fraction falls below $10^{-3}$ or so. In Figure 7 we show the relation between the so-defined redshift offset and the proxy for the redshift of overlap for three different values of the volume-weighted neutral hydrogen fraction.
In CROC simulations, the shape of the flux power spectrum at large scales \((k < 0.005 \text{ km}^{-1} \text{ s})\) varies little (at the level of 10\%) with the redshift of the measurement (except at highest redshifts) or the redshift of overlap (Figure 2), and that result is in surprising disagreement with the conclusions from AREPO-RT simulations in which Wu et al. (2019) found systematic deviations at large scales of the order of 40\%. The reason for such discrepancy is unclear, given that both sets of simulations have comparable box sizes, mass resolution, and radiation frequency coverage. Both simulations use the moments method for modeling radiative transfer, with the only difference that CROC employs OTVET approximation and AREPO-RT uses the M1 closure. There are no known numerical artifacts in either of the schemes, though, that could explain the difference between the two sets of simulations.

With this disagreement noted, we find that the amplitude of the flux power spectrum \(P_F(k_{\text{max}})\) evolves rapidly with redshift. That evolution reflects the rapid change in the ionization state of the IGM at the end of reionization and is similar (but not identical) to the evolution of the averaged transmitted flux, \(\langle F \rangle\).

The most interesting property of that evolution, however, is that it is correlated with the evolution of the mean neutral fraction. The latter, if volume averaged, serves as a good proxy for the redshift of overlap of ionized bubbles. Hence, measuring the rate of evolution of the flux power spectrum at \(z > 5\) allows one, at least in principle, to constrain the redshift of overlap. An example of how this can be done is shown in Figure 8. Given the observational measurements, one can determine the redshift offset needed to shift the reference model to match the measurements, in this case \(\Delta z = -0.55\). Comparison with Figure 7 shows that this value for the redshift offset corresponds to the redshift of overlap of about 6.7.

This measurement relies on the calibration from the simulations, and hence needs high fidelity simulations. CROC simulations can serve as an illustration of this procedure, but are not of high enough fidelity to be used for the actual measurement—they provide a close match to several observables, but are not close enough to match all the observational data within the observational uncertainties. Hence, we only present Figure 8 as an illustration.
The expectation that simulations become sufficiently good to allow such a measurement is not futuristic though. CROC simulations do not provide the exact match to the existing observational data on the quasar absorption spectra, but they are only off by a factor of 2 at most in all existing constraints (observed distributions of opacities in the IGM, the flux power spectrum, sizes of dark gaps, and cross-correlation between the absorption spectra and nearby galaxies; Gnedin et al. 2017; Garaldi et al. 2019), so the next generation of simulations can be expected to provide an improvement in order of magnitude over the existing ones in the precision with which they model the properties of the post-reionization IGM, and therefore match the observational measurements. Such simulations will offer a sufficiently accurate match to not only existing but future observational data as well allowing the direct measurement of the redshift of overlap from the measured evolution of the flux power spectrum.

This manuscript has been authored by Fermi Research Alliance, LLC under Contract No. DE-AC02-07CH11359 with the U.S. Department of Energy, Office of Science, Office of High Energy Physics. This work used resources of the Argonne Leadership Computing Facility, which is a DOE Office of Science User Facility supported under Contract DE-AC02-06CH11357. An award of computer time was provided by the Innovative and Novel Computational Impact on Theory and Experiment (INCITE) program. This research is also part of the Blue Waters sustained-petascale computing project, which is supported by the National Science Foundation (awards OCI-0725070 and ACI-1238993) and the state of Illinois. Blue Waters is a joint effort of the University of Illinois at Urbana-Champaign and its National Center for Supercomputing Applications. This work was supported in part by the U.S.

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