REALISTIC SIMULATIONS OF THE INTERGALACTIC MEDIUM: THE SEARCH FOR MISSING PHYSICS

Allocation: NSF PRAC/5.00 Mnh
PI: Michael L. Norman[1]
Co-PI: James Bordner[1]

[1]University of California, San Diego

EXECUTIVE SUMMARY

We have performed state-of-the-art simulations of the intergalactic medium (IGM) during the epoch of helium reionization. It is believed that the UV radiation emitted from quasars ionized the intergalactic helium over a period of several billion years beginning at a redshift of 4. We have carried out a suite of the first fully coupled radiation hydrodynamic cosmological simulations that treat the quasars as a time varying population of point sources. For **the first time** we have performed multigroup radiative transfer self-consistently coupled to the cosmological hydrodynamics of the IGM at sufficient resolution and domain size to examine the photoionization and photoheating processes in detail. This is being done to determine whether this is the "missing physics" that will improve the agreement between models and high-precision observations of the IGM, specifically the Lyman-alpha forest observations of distant quasars.

INTRODUCTION

In the past decade, new, more precise observations of the intergalactic medium (IGM)—the hydrogen and helium gas between the galaxies produced in the Big Bang—have revealed a discrepancy with the well-established predictions of our computational models. In particular, precision observations of the IGM using the Keck telescopes in Hawaii show that the temperature and ionization state of the IGM is not what our standard cosmological simulations predict: The IGM is either somewhat hotter than ultraviolet radiation from stars in galaxies can make it, or the IGM is distributed differently in space than the simulations predict, or both. There could be missing sources of heat in our models, such as energy injection by decaying dark matter particles. The discrepancy is perplexing since the standard model predicts the galaxy distribution exceedingly well. The discrepancy suggests that the standard model lacks some essential ingredient, which we refer to simply as "missing physics." The significance of this project to the nation is that it promotes the progress of science in the fundamental field of cosmology, in which the United States is a world leader. The project is addressing the issue of whether we are overlooking a key component of the mass-energy content of the universe. Precise answers require powerful tools, and the Blue Waters supercomputer is the tool for the job.

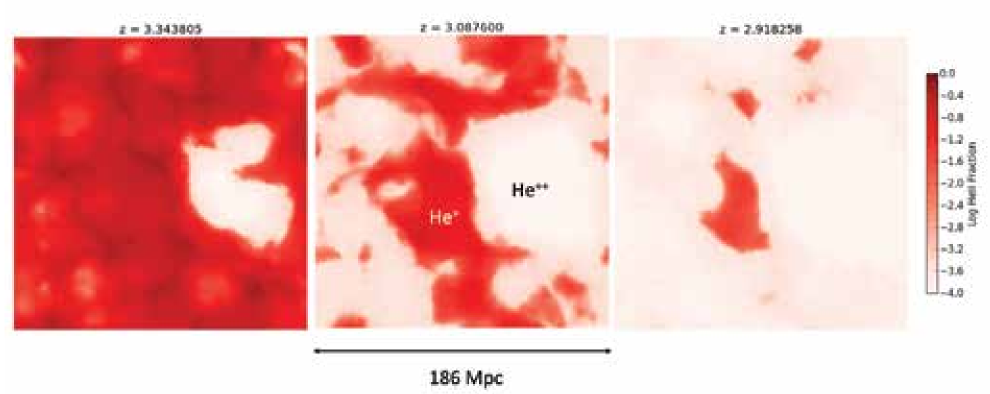

FIGURE 1 : Photoionization of helium in the intergalactic medium by UV radiation from time-dependent quasars. Shown is the projection of the He^{+} fraction, which steadily diminishes as He^{+} is converted to He^{++}. Simulation is carried out in a 186 Mpc volume using the Enzo hydrodynamic cosmology code coupled to a 5-group radiation diffusion solver. Credit: M. Norman, UCSD.

METHODS & RESULTS

In the first year of this project, we have examined the possibility that late photoheating of the IGM by quasars is the missing physics. In the standard model of the Lyman-alpha forest (which subtly disagrees with observations), quasar ionization is modeled as a homogeneous but time-varying radiation background. Photoheating is treated in the optically thin limit, which underestimates the heating behind optically thick ionization fronts. In reality, quasars are radiating point sources that ionize the helium in the IGM in their vicinity; it is the growth and eventual overlap of these growing spheres of ionization, each centered on a luminous quasar, that ionize the IGM. This is the situation we have simulated on Blue Waters (see Figure 1).

We have carried out a suite of the **first** fully coupled radiation hydrodynamic cosmological simulations that treat the quasars as a time-varying statistical population of point sources. For the **first** time, we perform multigroup flux limited diffusion radiative transfer self-consistently coupled to the cosmological hydrodynamics of the IGM at sufficient resolution and domain size to examine the photoionization and photoheating processes in detail. This is being done to determine whether this is the "missing physics" that will improve the agreement between models and high-precision observations of the IGM, specifically the Lyman-alpha forest observations of distant quasars. We now are analyzing the spectroscopic properties of our simulated Lyman-alpha forest, including these effects.

WHY BLUE WATERS

Blue Waters is required because the simulation is extremely computationally intensive. Large spatial volumes need to be simulated at high resolution, to simultaneously resolve the Lyman-alpha forest absorbers, and at the same time encompass a representative sample of quasars. The ratio of the outer and inner scales is about 2,000, meaning that simulations require $2{,}000^3$ grids. Additionally, a multifrequency treatment of radiative transfer is essential to accurately model the transport of the hard UV spectrum of quasars, including the phenomena of ionization front pre-ionization and spectral hardening of the radiation field.

The ability to do a suite of exploratory runs of this new type of simulation with **excellent throughput**, each run of which is quite computationally intensive, is **only possible** on a Blue Waters-scale system. In this way we are able to "home in" on the model that best agrees with the high-precision observations.

NEXT GENERATION WORK

In the 2019-2020 timeframe the post-petascale version of the Enzo adaptive mesh refinement (AMR) simulation code will be fully operational. Called Enzo-P, it will permit AMR radiation hydrodynamic cosmological simulations to be performed of a size and dynamic range equaling or surpassing the largest pure dark matter N-body simulations carried out today. Enzo-P is an application built on top of the extreme scale AMR framework called Cello, developed at the University of California, San Deigo. Cello, in turn, is based on the Charm++ parallel objects framework that underpins the highly scalable molecular dynamics code NAMD. We will use Enzo-P to simulate the combined effects of galaxies and quasars on the intergalactic medium, including radiative, chemical, and kinetic feedback. We will use the improved knowledge of high redshift galaxies obtained by the James Webb Space Telescope, to be launched in 2018, to create the most physically detailed model of the co-evolving population of galaxies and active galactic nuclei that reionize the universe at z=6-7. We will explore the post reionization evolution of the IGM in the redshift interval 4-6, which is relatively poorly understood at this time.