

DI

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

Allocation: NSF PRAC/2,500 Knh

PI: Michael L. Norman^{1,2,3}

Co-PI: James Bordner^{1,3}

Collaborators: David Tytler^{1,2}, Pengfei Chen^{1,2}, Dan Reynolds⁴

¹University of California, San Diego

²Center for Astrophysics and Space Sciences

³San Diego Supercomputer Center

⁴Southern Methodist University

BW

MP

EXECUTIVE SUMMARY

We have performed state-of-the-art simulations of the intergalactic medium (IGM) during the epoch of helium reionization. UV radiation from quasars ionizes the intergalactic helium over a period of several billion years beginning about 1 billion years after the Big Bang. 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. 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. We

have discovered that helium reionization completes significantly later compared to models that treat the quasar radiation as a homogeneous background. This modifies the heating history of the IGM substantially, with a maximum mean temperature of 14,000°K being achieved at a redshift of 3, consistent with observations.

RESEARCH CHALLENGE

In the past decade, 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 that 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 where the U.S. 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.

METHODS & CODES

We have used an enhanced version of the hydrodynamic cosmology code ENZO to examine the possibility that inhomogeneous photoheating of the IGM by quasars is the missing physics. In the standard model of the Lyman alpha forest, 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 (Fig. 1).

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. We have used the multigroup flux-limited diffusion (MGFLD) branch of ENZO developed by Dan Reynolds to perform the simulations. Simulations with grids sizes and particle counts of 1,0243 and 2,0483 were performed on 64/1,024 and 256/4,096 nodes/cores, respectively. Using MGFLD, we accurately transport the hard UV radiation from quasars covering photon energies 54.4 eV to 500 eV and calculate its effects on the IGM self-consistently. Results are analyzed using the open source yt toolkit.

RESULTS & IMPACT

We find that the IGM photoheating is inhomogeneous and time-dependent due to multiple quasar point sources turning on and off over the 2 billion year interval we simulate between redshifts 5 and 2. Fig. 1 shows slices through the 80 Mpc volume for five quantities related to the ionization of helium, for four different redshift snapshots. Bubbles of doubly ionized helium grow and merge in the first row of images so that by the last column, the IGM is completely ionized. The temperature of the IGM is boosted to about 14,000°K in roughly spherical shells surrounding each quasar, as shown in the third row of images.

The time evolution of the IGM temperature at mean density is depicted in Fig. 2 for several simulations, overlaid on observational data. The data points show that IGM temperature peaks around redshift 3. The standard optically thin model shown with the blue line peaks at a redshift of 3.5—earlier than observed. However, the MGFLD simulations, shown in other colored lines, peak around redshift 3, in agreement with observations.

the MGFLD simulations, shown in other colored lines, peaks around redshift 3, which is in agreement with observations. The reason for the difference has to do with the finite time it takes for an ionization front to propagate across the vast distances of intergalactic space. This discovery helps resolve one, but not all, of the above-mentioned discrepancies among observations and our earlier models. The impact of these results is that all future models of the IGM must be revised to include this finite time propagation effect.

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 2,000³ 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 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.

PUBLICATIONS AND DATA SETS

Chen, P., The Effect of Inhomogeneous He II Reionization on the Lyman Alpha Forest. Ph.D. Dissertation, University of California, San Diego (2016).

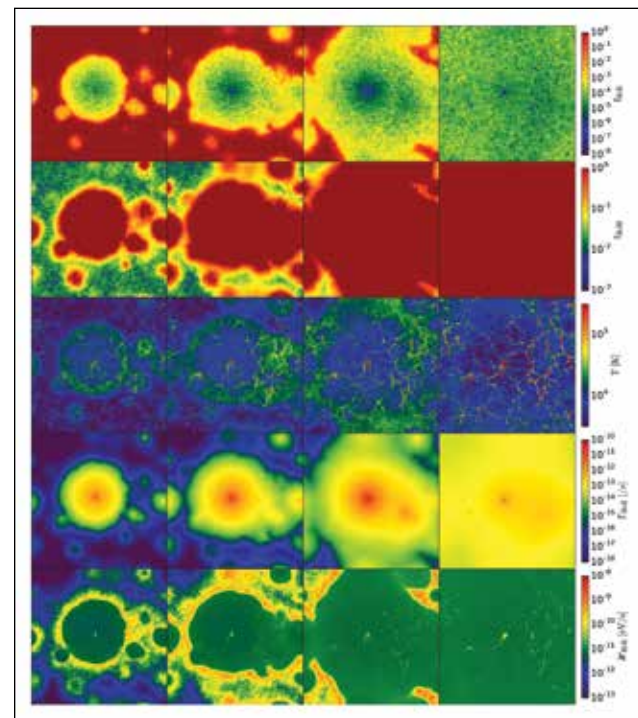


Figure 1: Redshift evolution of the thermal and ionization state of the intergalactic medium on a slice through the 80 Mpc simulation volume. Left to right: redshift snapshots at $z=4, 3.5, 3,$ and 2 . Top to bottom: He II fraction, He III fraction, gas temperature, He II photoionization rate, He II photoheating rate.

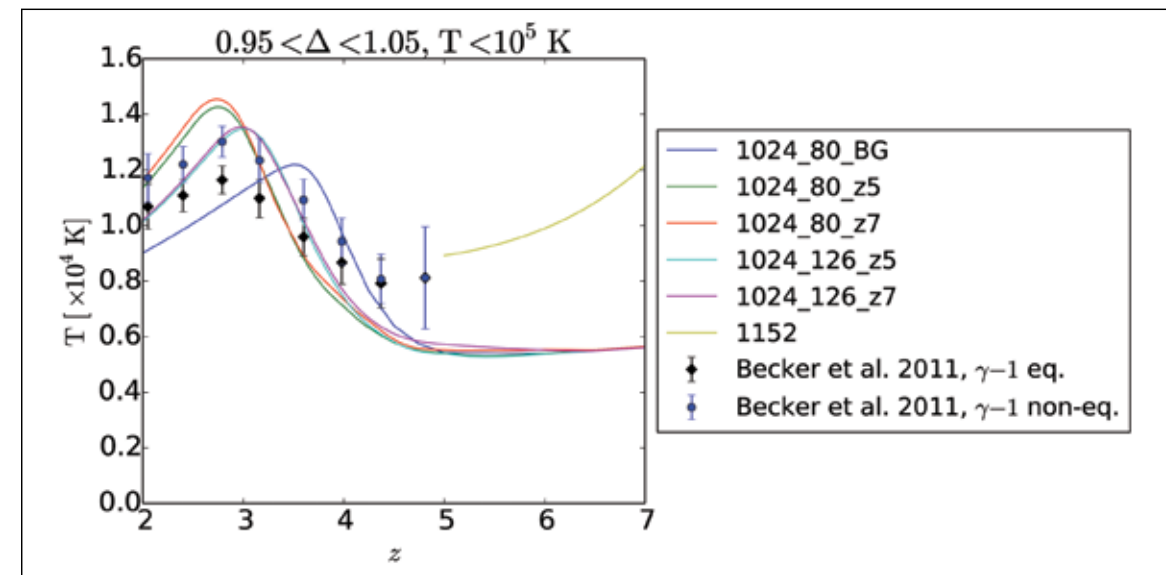


Figure 2: The time evolution of the IGM temperature for several simulations, overlaid on observational data that show that IGM temperature peaks around redshift 3. The standard model (blue line) peaks at $z=3.5$ —earlier than observed. However the MGFLD simulations, shown in other colored lines, peak around redshift 3, in agreement with observations.

CI