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COSMIC REIONIZATION ON COMPUTERS

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EXECUTIVE SUMMARY

Cosmic reionization—the process of ionization of the bulk of cosmic gas by ultraviolet radiation from the first galaxies and quasars—is the last frontier of modern cosmology. The Cosmic Reionization on Computers (CROC) project produced several numerical simulations of reionization that self-consistently modeled all relevant physics from radiative transfer to gas dynamics and star formation in simulation volumes of over 100 comoving megaparsecs (Mpc). This was necessary to model a representative sample of high-mass galaxies, and a spatial resolution approaching 100 parsecs in physical units was necessary to reliably model star formation in galaxies. CROC simulations, therefore, cover the full range of spatial, temporal, and mass scales important for studying reionization. The largest CROC simulations required Blue Waters'-class machines to complete.

RESEARCH CHALLENGE

Study of cosmic reionization has been highlighted by the last Decadal Survey as one of the most promising areas of astrophysical research. Because of the observational constraints on reionization, theoretical modeling, including numerical simulations, plays a relatively larger part in reionization studies than in many other fields of modern astrophysics. While the first simulations of reionization were attempted nearly 20 years ago, major breakthroughs in this field are only possible with modern petascale supercomputing platforms.

Taking advantage of this technological progress, the research team initiated a CROC project. This aims, over the course of several years, to produce numerical simulations of reionization that model self-consistently all relevant physics, ranging from radiative transfer to gas dynamics and star formation, in simulation volumes of over 100 comoving Mpc, which is necessary to model a representative sample of high-mass galaxies, and with a spatial resolution approaching 100 parsecs in physical units, which is necessary to reliably model star formation in galaxies. These simulations, therefore, cover the full range of spatial, temporal, and mass scales important for studying reionization.

The primary motivation for focusing on reionization now is the expected major advance in observational capabilities: The James Webb Space Telescope (the next flagship NASA mission) is scheduled to launch in 2021, and studying galaxies responsible for cosmic reionization is one of its primary goals. Studies of intergalactic gas will be propelled forward by the deployment of 30-meter telescopes, several of which will become operational in the first half of the next decade. Other novel observational tools will follow in the second half of the next decade.

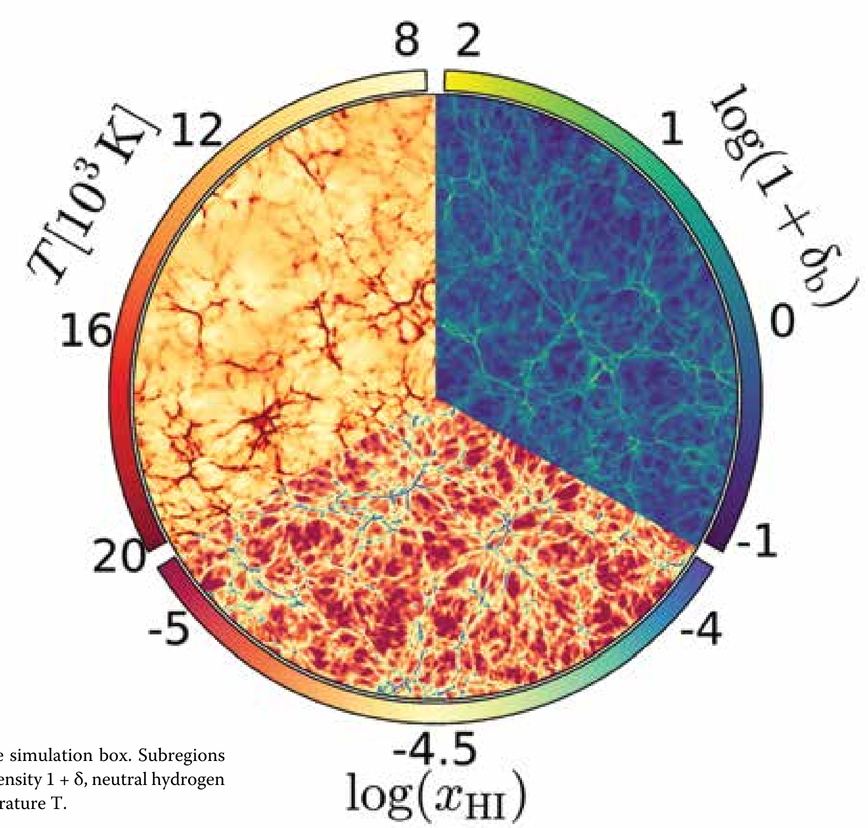

Figure 1: Slice through the simulation box. Subregions show the cosmic gas overdensity $1 + \delta$, neutral hydrogen fraction x_{HI}, and gas temperature T.

METHODS & CODES

In order to reach the required dynamic range, the research team relied on the adaptive mesh refinement technique. The simulations are run with the adaptive refinement tree code, a publicly available cosmological simulation code developed and supported by the research group. The code includes all necessary physical modules for simulating cosmic reionization (dynamics of dark matter and gas, atomic processes, interstellar chemistry, star formation and stellar feedback, radiative transfer of ionizing and UV radiation). ART is MPI+OpenMP parallel and scales perfectly on this type of simulation to about 50,000 cores, with parallel scaling remaining acceptable to about 100,000 cores.

RESULTS & IMPACT

CROC simulations are defining the state of the art in this field. By virtue of including all the relevant physics and extending to volumes that are required to properly capture the process of reionization, they are creating a physically plausible model of cosmic reionization that can be matched against any existing observational data. Such comparisons have been made by the research group in the last several years in a series of papers. However, the most constraining observational data set that exists today is the distribution of optical depth in the spectra of distant quasars. Over 100 quasars during the reionization epoch have been discovered so far, and for almost 70 of them, high-resolution and high-quality spectra exist. These data probe the largest spatial scales relevant for reionization of about 70 comoving Mpc.

During the second year of this project, the team focused on two separate scientific questions: (1) how galaxies influence and shape the distribution of ionized gas on large scales; and (2) how the brightest known quasars affect galaxies and gas in their vicinity. Both of these questions are at the frontier of modern research and promise to develop into new, independent areas of study in the next several years. An example of cosmic gas distribution from one of the team's simulations is shown in Fig. 1.

WHY BLUE WATERS

Only two supercomputers in the United States were available for these simulations, which are both memory- and communication-intensive. The largest simulations use 8 billion particles and around 50 billion cells in the adaptively refined mesh. Thus, they require petascale computing capabilities. Blue Waters was much faster than the other available machine and had better I/O support. Hence, it was the platform of choice.

PUBLICATIONS & DATA SETS

H. Chen and N. Y. Gnedin, "Constraints on the duty cycles of quasars at z ~ 6," *Astrophys. J.*, vol. 868, no. 2, p. 126, Nov. 2018.

E. Garaldi, N. Y. Gnedin, and P. Madau, "Constraining the tail end of reionization using Lyα Transmission Spikes," *Astrophys. J.*, vol. 876, no. 1, p. 31, April 2019.

H. Zhu, C. Avestruz, and N. Y. Gnedin, "Cosmic reionization on computers: Reionization histories of present-day galaxies," *Astrophys. J.*, vol. 882, no. 2, p. 152, Sept. 2019.

H. Chen, "The role of quasar radiative feedback on galaxy formation during cosmic reionization," in preparation, 2019.