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SIMULATING GALAXY FORMATION ACROSS COSMIC TIME

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EXECUTIVE SUMMARY

This simulation campaign addresses several pressing questions about galaxy formation and evolution by using a suite of physics-rich, high dynamic range adaptive mesh refinement simulations of cosmological structure formation. The two main thrusts of these simulations are: (1) to understand the connection of the first generations of galaxy formation with the Milky Way and its satellites, and (2) to understand the cycling of metal-enriched, magnetized plasma into and out of galaxies like the Milky Way and the regulation of star formation in these galaxies. All of these problems require simulations with extremely high dynamic range in space and time, complex physics (including radiation transport and nonequilibrium gas chemistry), and large simulation volumes. We use the Enzo code (enzo-project.org), which has been modified to scale to large core counts on Blue Waters—the only machine available where the heavy data and communication needs can be satisfied.

RESEARCH CHALLENGE

Our goals are to understand two critical issues in galaxy formation: the formation of the earliest generations of galaxies and their connections to the Milky Way through hierarchical structure formation, and the "baryon cycle" in galaxies like the Milky Way—in other words, how gas gets into and out of galaxies, and what it does while it is there. Both of these questions are important to understanding observations of galaxies over the age of the universe using telescopes such as the 10-meter Keck telescope on Mauna Kea and the Hubble Space Telescope, which are both used to observe light from very distant galaxies as well as the absorption of light by the intergalactic and circumgalactic medium. All of the calculations needed to study these problems require simulations with an extremely high dynamic range in space and time, complex physics (including radiation transport and nonequilibrium gas chemistry), and large simulation volumes.

METHODS & CODES

Our simulation tool of choice is the Enzo code [1; also see http://enzo-project.org], an open-source and community-developed software platform for studying cosmological structure formation. Enzo allows us to include all the critical physical components needed to study galaxy formation—gravity, dark matter dynamics, fluid dynamics, the microphysics of plasmas, and prescriptions for star formation and feedback—and to do so using a tool that can scale to large numbers of CPUs. All analysis was done with the yt code [2; also see http://yt-project.org].

RESULTS & IMPACT

The analysis of the simulation performed as part of this campaign has only recently begun. However, our most important results thus far involve the cycling of gas into and out of galaxies. Both cosmological simulations of galaxy formation as well as more idealized calculations demonstrate that massively increased physical resolution in the "circumgalactic medium"—the gas outside the stellar disk of a galaxy but which is bound to the galaxy by gravity, and composes almost half of the mass of the baryons in the galaxy—is incredibly important. In particular, we find that increasing the resolution by more than an order of magnitude beyond previous state-of-the-art calculations results in the appearance of both spatial and chemical features that are seen in observations but not in previous models. Similarly, we find in our idealized simulations that galaxies can attain a dynamic equilibrium between cold gas condensing and falling into the galaxy (and thus fueling star formation), and the ejection of hot, metal-enriched gas into the circumgalactic medium. This work is changing our understanding of the interface between the stellar component of galaxies and the diffuse plasma component.

WHY BLUE WATERS

The simulations used to properly model galaxies in both the early universe and the present day require extremely high spatial and temporal dynamic range, and also require complex physics—most importantly, radiation transport, magnetohydrodynamics, and nonequilibrium gas chemistry. Furthermore, large simulation volumes (and thus many resolution elements) are needed to model the many early galaxies that will merge together to create a Milky Way-like galaxy at the present day. Additionally, in our present-day galaxy simulations, huge numbers of cells are required to accurately resolve the circumgalactic gas. Taken together, this requires the use of a supercomputer with large memory and disk space (to accommodate the tremendous dataset sizes), large computational resources, and an extremely high bandwidth, low-latency communication network to enable significant scaling of the radiation transport code. Blue Waters is the only machine available to the academic community that fits all of these requirements.

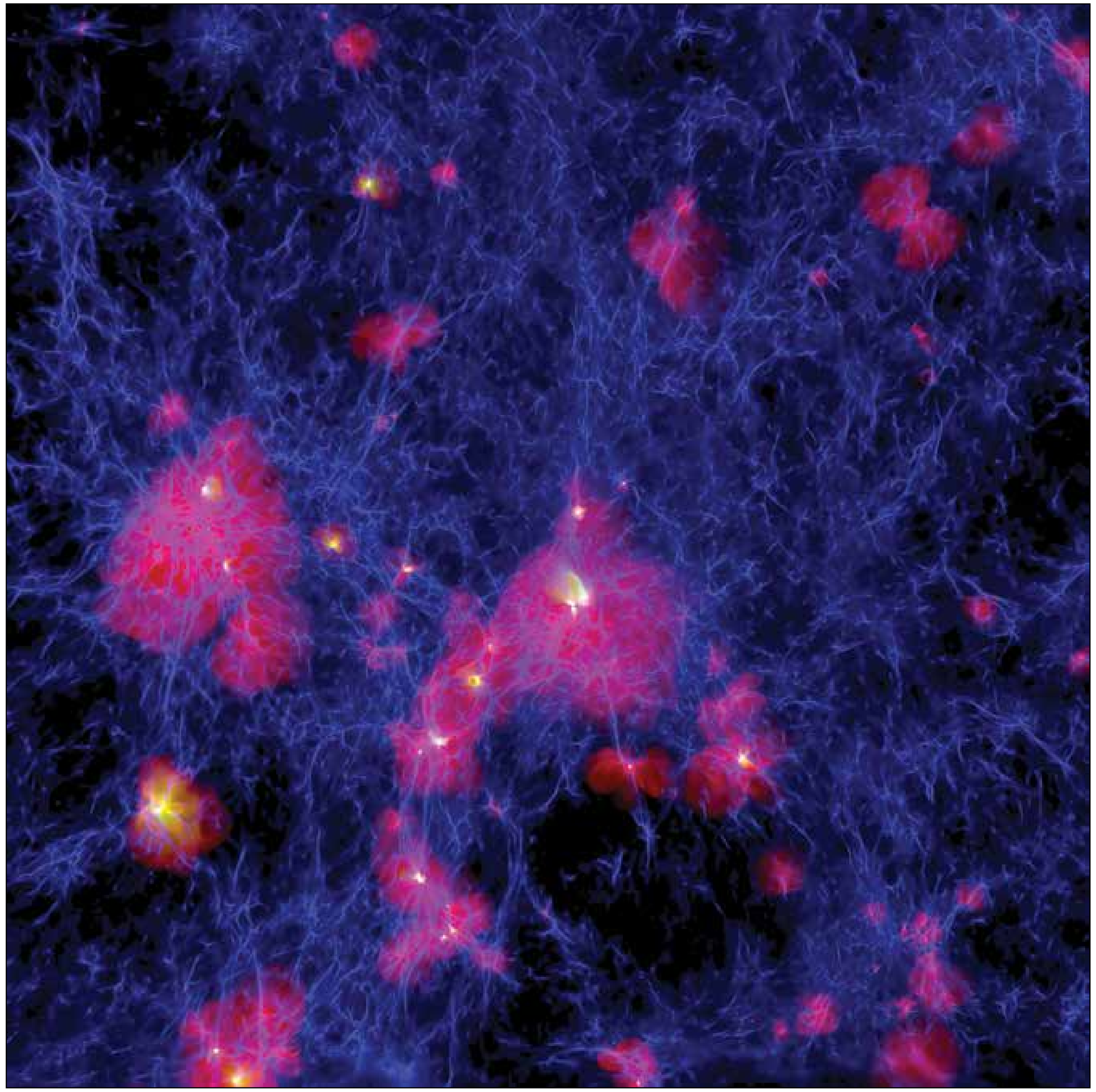

Figure 1: Composite volume rendering of several galaxies at z=8.6, approximately 590 million years after the Big Bang. The field of view is 250 kpc (approximately 800,000 light years) across. The blue color table shows density, red shows temperature, and green shows ionizing radiation.

PUBLICATIONS AND DATA SETS

No publications, reports, or datasets have resulted from this simulation campaign yet. Several improvements to the open-source Enzo code have been made, and can be found at http://enzo-project.org.