SIMULATING GALAXY FORMATION ACROSS COSMIC TIME

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EXECUTIVE SUMMARY

This research project addresses several critical questions about galaxy formation and evolution via a suite of physics-rich, high-dynamic-range adaptive mesh refinement simulations of cosmological structure formation. The two main goals 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 elucidate 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 our 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. Each of these telescopes is 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 extremely high dynamic range in space and time, complex physics (including radiation transport and nonequilibrium gas chemistry), and large simulation volumes.

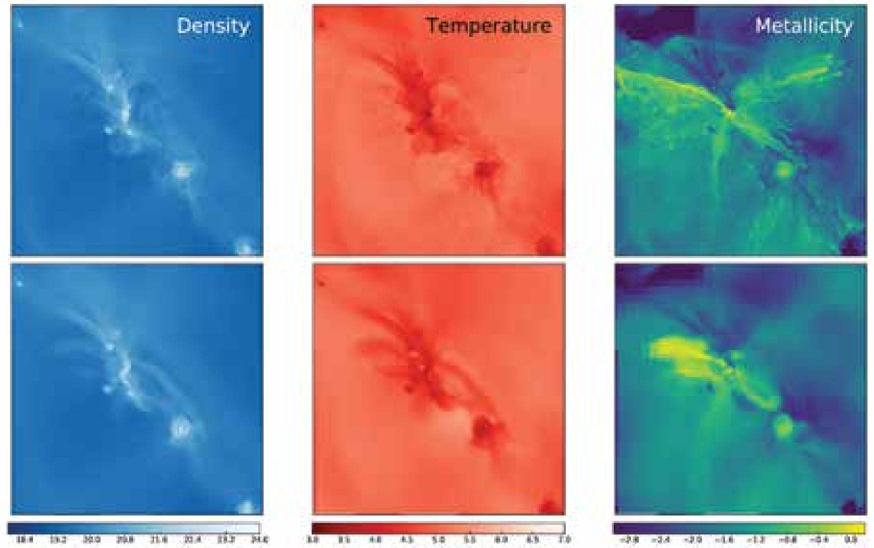

Figure 1: This figure shows a projection of (left to right) gas density, temperature, and metal content for two simulations: one with an enhanced spatial refinement in the circumgalactic gas (top row), and one using standard refinement methods (bottom row).

METHODS & CODES

Our simulation tool of choice is the Enzo code [1], an open-source and community-developed software platform for studying cosmological structure formation. Enzo allows us to include all of 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].

RESULTS & IMPACT

The two main results thus far involve the growth of supermassive black hole candidates in the early universe, and the cycling of gas into and out of galaxies. The former result involves analysis and resimulation of work done in an earlier PRAC allocation, and shows that, while stellar-mass black holes are not capable of growing into billion-solar-mass objects by the time that they can be observed (a billion years after the Big Bang), it is possible for massive gas clouds to directly collapse into much more massive objects that can easily seed black holes [3,4].

Our second important result involves the cycling of gas into and out of galaxies. Simulations 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. We found that increasing the resolution by more than an order of magnitude beyond previous state-of-the-art calculations resulted in the appearance of both spatial and chemical features that are seen in observations but not in previous models. This work is revolutionizing our understanding of the interface between the stellar component of galaxies and the diffuse corona of gas that surrounds them.

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 in order to model the many early galaxies that merged together to create a Milky Way-like galaxy at the present day. Further, 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 data set sizes and large computational resources, as well as an extremely high bandwidth and 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.

PUBLICATIONS & DATA SETS

Smith, B., et al., The Growth of Black Holes from Population III Remnants in the Renaissance Simulations. *The Astrophysical Journal*, accepted (2018), arXiv:1804.06477.

Wise, J., et al., Ubiquitous massive black hole formation in rapidly growing pre-galactic gas clouds. *Nature Astronomy*, under review (2018).