SIMULATING GALAXY FORMATION ACROSS COSMIC TIME

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EXECUTIVE SUMMARY

This project addresses two fundamental questions in galaxy formation: How do the first stars and galaxies influence the rest of cosmological structure formation over the following 13 billion years? And how does the cycling of gas into and out of galaxies through cosmic inflows and supernova-driven winds regulate the behavior of these galaxies?

The research team addresses these questions via a suite of physics-rich, high-dynamic-range adaptive mesh refinement simulations done with the Enzo code (enzo-project.org), which has been modified to scale to large core counts on Blue Waters. Through these simulations, the researchers have gained key insights into the formation of the first supermassive black holes and into the ways in which the circumgalactic gas around galaxies acts as a "thermostat" that regulates star formation.

RESEARCH CHALLENGE

The primary goals of this research are to understand two fundamental issues in galaxy formation: the birth and growth of the first generations of galaxies and their connections to present-day galaxies like the Milky Way, and the "baryon cycle" in galaxies like the Milky Way; in other words, the movement of gas into and out of galaxies, and how this regulates the behavior of star formation in galaxies. Both of these questions are critical to interpreting observations of galaxies over the age of the Universe through both current observatories (such as the Hubble Space Telescope and the 10-meter Keck telescope on Mauna Kea) and future observatories (such as the James Webb Space Telescope and the Large Synoptic Survey Telescope). All of the calculations needed to study these problems require simulations with extremely high dynamic range in space and time, complex physics (often including radiation transport and nonequilibrium gas chemistry), and large simulation volumes.

METHODS & CODES

The researchers' simulation tool of choice is the Enzo code [1,2; http://enzo-project.org], an open source and community-developed software platform for studying cosmological structure formation. Enzo allows the inclusion of 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 can scale to large numbers of CPUs. All analysis was done with the yt code [3; http://yt-project.org].

RESULTS & IMPACT

The main results involve the growth of supermassive black holes in the early Universe and the cycling of gas into and out of galaxies. The former result [4,5] demonstrates a novel "direct collapse" mechanism for gas clouds to turn into intermediate-mass black holes (with masses of thousands or tens of thousands of solar masses) rather than first turning into stars. This is important because it provides the first plausible formation mechanism for the extremely massive (hundreds of millions to billions of solar masses) black holes seen in the early Universe. The project has also demonstrated that the frequency with which these black holes form is consistent with the frequency that early-Universe supermassive black holes are observed.

The second set of important results involves the exploration of gas cycling into and out of galaxies [6–8]. Simulations demonstrate that massively increased physical resolution in the "circumgalactic medium"—the gas outside of the stellar disk of a galaxy but is bound to the galaxy by gravity, and composes almost half of the mass of the baryons in the galaxy—is incredibly important. The work suggests 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 simulations. This research is revolutionizing the understanding of the interface between the stellar component of galaxies and the diffuse corona of gas that surrounds them and provides predictions of observational quantities relating to quasar absorption line spectra and to the direct emission of radiation from the circumgalactic medium, as observed by Keck's KCWI instrument.

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 ranges and also require complex physics—most importantly, radiation transport 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, and in the research team's present-day galaxy simulations, huge numbers of cells are required to accurately resolve the circumgalactic gas. Taken together, this project requires the use of a supercomputer with large memory and disk space to accommodate the tremendous data set 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.

PUBLICATIONS & DATA SETS

J. Wise *et al.*, "Formation of massive black holes in rapidly growing pre-galactic gas clouds," *Nature*, vol. 566, pp. 85–88, 2019.

[5] J. Regan *et al.*, "The emergence of the first star-free atomic cooling haloes in the Universe," *MNRAS*, submitted, 2019, arXiv:1908.02823.

[6] M. Peeples *et al.*, "Figuring out gas and galaxies in Enzo (FOGGIE), I. Resolving simulated circumgalactic absorption at $2 \leq z \leq 2.5$," *Astrophys. J.*, vol. 873, p. 129, 2019.

[7] L. Corlies *et al.*, "Figuring out gas & galaxies in Enzo (FOGGIE), II. Emission from the z=3 circumgalactic medium," *Astrophys. J.*, submitted, 2019, arXiv:1811.05060.

[8] C. Hummels *et al.*, "The impact of enhanced halo resolution on the simulated circumgalactic medium," *Astrophys. J.*, vol. 882, p. 156, 2019.