MODELING OF GALAXY POPULATIONS

Allocation: NSF PRAC/9,000 Knh
PI: Thomas Quinn[1]
Co-Pi: Fabio Governato[1]
Collaborators: Michael Tremmel[2], Arif Babul[3], Iryna Butsky[1]

[1]University of Washington
[2]Yale University
[3]University of Victoria

EXECUTIVE SUMMARY

Clusters of galaxies are both a useful probe of cosmology and a laboratory for understanding galactic feedback processes. However, modeling galactic-scale feedback processes in the context of a cluster presents a computational challenge because of the large dynamic range involved. Through the use of a highly scalable N-body/smooth-particle hydrodynamics code running on Blue Waters, the research team is tackling this challenging problem. The results show that models that have successfully reproduced the morphology and number densities of field galaxies can also produce realistic models of cluster galaxies. Large computational resources with high-performance networks are necessary for these calculations, however.

RESEARCH CHALLENGE

Groups and clusters of galaxies are the largest bound objects in the Universe, containing more than a third of its warm–hot diffuse gas and a significant fraction of all galaxies. Consequently, understanding the physical processes that occur in group and cluster environments, including the interactions among the dark matter, hot diffuse gas, stars, and active galactic nuclei (AGN), is key to gaining insights into the evolution of baryons and galaxies across the age of the Universe. Furthermore, galaxy clusters are one of the few places where the majority of the baryons are visible via X-ray and microwave. In contrast to field galaxies, where feedback from supernovae and AGN puts gas into a mostly invisible circumgalactic medium, feedback from cluster galaxies will impact the state of the intracluster medium (ICM). Hence, clusters will provide very tight constraints on our understanding of galactic feedback processes.

Clusters of galaxies are also key probes of cosmology and large-scale structure. Their size makes them visible across a wide range of redshifts and their population statistics are sensitive to cosmological parameters such as the amplitude of the initial power spectrum and the evolution of the cosmic expansion rate. However, using clusters as cosmological probes requires understanding of the relationship between observables and the total mass of the cluster, which in turn requires the detailed modeling of the gravitational/hydrodynamic processes using large simulations.

METHODS & CODES

The research team used the highly scalable N-body/hydrodynamics code ChaNGa to model the formation and evolution of a population of galaxies in a Coma-sized galaxy cluster, including their contribution to and interaction with the ICM. This code is built on the Charm++ [1] parallel programming infrastructure. It leverages the object-based virtualization and data-driven style of computation inherent in Charm++ to adaptively overlap communication and computation and achieve high levels of resource utilization on large systems. The code has been shown to scale well to 500,000 cores on Blue Waters [2].

The code includes a well-constrained model for star formation and feedback, with improved implementation of supermassive black hole formation, growth, mergers, and feedback [3,4]. In a previous Blue Waters allocation, the team demonstrated that these models can reproduce populations of field galaxies at intermediate-to-high redshift [5] and can reproduce the observed stellar mass–halo mass relationship of galaxies from dwarfs up to galaxy groups [4].

These simulations are being compared to observations of cluster galaxies to understand the physical and temporal origin of their morphologies. The model ICM will be compared to X-ray and microwave data via the Sunyaev–Zeldovich effect to understand the relationship among these observables and the underlying gas properties. Finally, the overall mass distribution will be used to better understand how these clusters gravitationally amplify the light from background galaxies.

RESULTS & IMPACT

The team's simulations are advancing the state of the art in simulations of galaxy clusters, particularly in the relationship among galactic processes and the cluster environment. The research has shown that the supermassive black holes (SMBHs) at the center of galaxies can effectively regulate the star formation rate in cluster galaxies just as they do in field galaxies. Furthermore, the process that establishes the observed relationship between the SMBH mass and the stellar mass of the galaxy is independent of the galactic environment and is determined by the correlation between SMBH accretion rate and the star formation rate. On the other hand, the state of the gas in the core of the cluster is not determined by the SMBH feedback but, rather, is set by the mergers of larger substructures. The team's high-resolution simulations allow them to make predictions about the multiphase structure of the cluster gas and how it can be observed with the Hubble Space Telescope and future UV-capable space telescopes (Fig. 1).

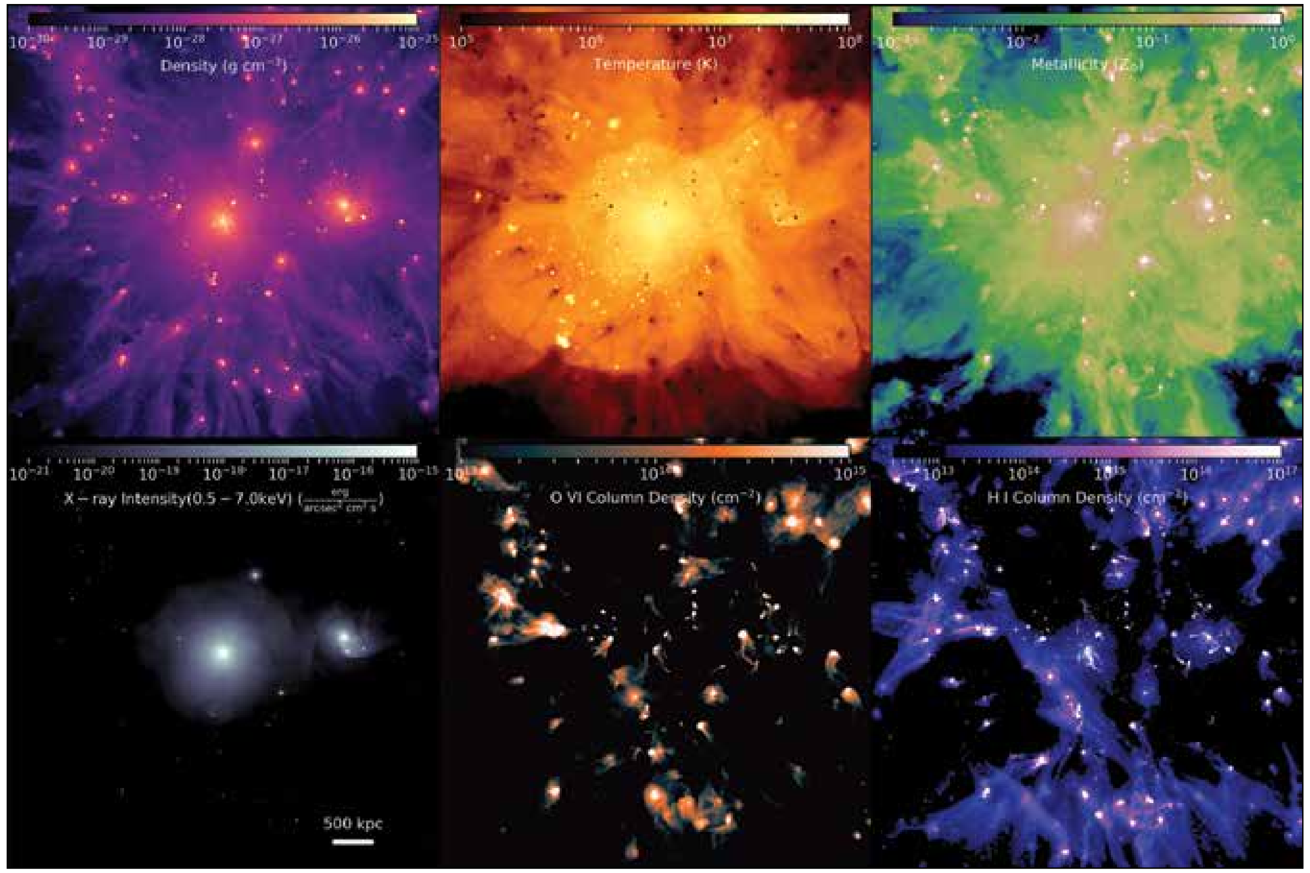

Figure 1: The state of the intracluster gas in the cluster simulation. The top row shows the intrinsic state of the gas: density temperature and metal content. The bottom row shows observable properties: X-ray intensity, column density of oxygen VI, and column density of neutral hydrogen.

WHY BLUE WATERS

Our scientific goals require modeling over a large dynamic range in mass and space. We have demonstrated that mass resolutions on the order of 10^5 solar masses are needed to accurately follow star formation and galaxy morphology. Likewise, we need to model a galaxy cluster on the order of 10^{15} solar masses that is comparable to those observed over a range of redshifts. Hence, simulations require approximately 10 billion particles. Such simulations can only be run on the largest computers available. Furthermore, the long-range nature of gravity requires a high-performance, low-latency network to perform the calculations.

PUBLICATIONS & DATA SETS

M. Tremmel *et al.*, "Dancing to ChaNGa: A self-consistent prediction for close SMBH pair formation time-scales following galaxy mergers," *Mon. Notices Royal Astron. Soc.*, vol. 475, no. 4, pp. 4967–4977, 2018, doi: 10.1093/mnras/sty139.

M. Tremmel *et al.*, "Wandering supermassive black holes in Milky-Way-mass halos," *Astrophys. J. Letters*, vol. 857, no. 2, pp. L22–27, 2018, doi: 10.3847/2041-8213/aabc0a.

E. Lentz *et al.*, "A new signal model for axion cavity searches from N-body simulations," *Astrophys. J.*, vol. 845, no. 2, pp. 121-125, 2017, doi: 10.3847/1538-4357/aa80dd.

M. Tremmel *et al.*, "Dancing to ChaNGa: The formation of close pairs of supermassive black holes in cosmological simulations and implications for LISA," presented at the 233rd Meeting of the American Astronomical Society, Seattle, WA, U.S.A., Jan. 7, 2019, Paper id.141.10.

M. Tremmel *et al.*, "Nature versus nurture: unraveling the mystery of ultra diffuse galaxy formation with the RomulusC galaxy cluster simulation," presented at the 233rd Meeting of the American Astronomical Society, Seattle, WA, U.S.A., Jan. 10, 2019, Paper id.416.04.

M. Tremmel *et al.*, "Introducing RomulusC: A cosmological simulation of a galaxy cluster with unprecedented resolution," *Mon. Notices Royal Astron. Soc.*, vol. 483, no. 3, pp. 3336–3362, 2019, doi: 10.1093/mnras/sty3336.