UNIFIED MODELING OF GALAXY POPULATIONS IN CLUSTERS

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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 galaxy 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, our project is tackling this challenging problem. Preliminary results show that models that have successfully reproduced the morphology and number densities of isolated field galaxies can also produce realistic models of cluster galaxies. Large computational resources with high-performance networks are necessary for these calculations.

RESEARCH CHALLENGE

Groups and clusters of galaxies are the largest bound objects in the universe, containing more than a third of the warm–hot diffuse gas and a significant fraction of the galaxies in the universe. Consequently, understanding the physical processes that occur in group and cluster galaxy 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 radiation. In contrast to field galaxies, where feedback from supernovae and AGN puts gas into a mostly invisible circumgalactic medium (ICM), feedback from cluster galaxies will impact the state of the 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.

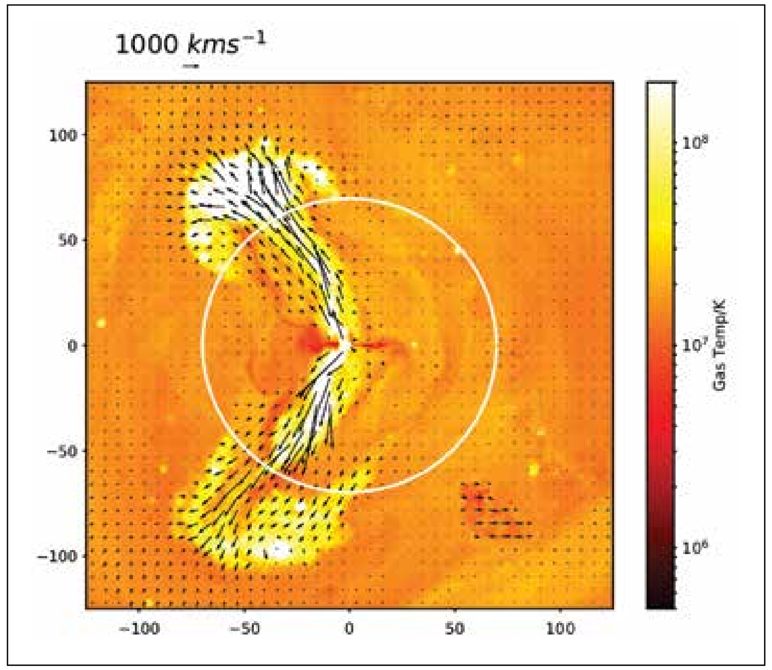

Figure 1: Outflows from the active galactic nucleus (AGN) of the central cluster galaxy. The columnation of the flow is emergent from the simulation: the energy from the AGN is injected isotropically. This outflow counteracts the cooling of the intracluster gas and suppresses star formation.

METHODS & CODES

This project uses 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. ChaNGa 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 one-half million cores on Blue Waters [2].

ChaNGa includes a well-constrained model for star formation and feedback, and improved implementations of supermassive black hole formation, growth, mergers, and feedback [3,4]. In our previous Blue Waters allocation, we have 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].

Our simulations will be 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 (via the Sunyaev–Zeldovich effect) to understand the relation between these observables and the underlying gas properties. Finally, the overall mass distribution will be used to better understand how these clusters gravitationally lens background galaxies.

RESULTS & IMPACT

We have completed the simulation of several smaller galaxy clusters in preparation for our flagship simulation. Even the completed smaller simulations are advancing the state of the art in the simulation of galaxy clusters. Of particular significance is that models based on energy injected from supernovae and active galactic nuclei in field galaxies are able to naturally explain the properties of clusters and the galaxies within them. In this way, the models become predictive of the growth of galaxies and the black holes that power the active galactic nuclei.

WHY BLUE WATERS

Our scientific goals require modeling over a large dynamic range in mass and space. We have demonstrated that we need mass resolutions of order 10^5 solar masses to accurately follow star formation and galaxy morphology. Likewise, we need to model a galaxy cluster of order 10^{15} solar masses that is comparable to those observed over a range of redshifts. Hence, 10 billion particles are needed. Such a simulation 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 calculation.

PUBLICATIONS & DATA SETS

Tremmel, M., et al., Dancing to CHANGA: a self-consistent prediction for close SMBH pair formation time-scales following galaxy mergers. *MNRAS*, 475:4 (2018), DOI:10.1093/mnras/sty139.

Tremmel, M., et al., Wandering Supermassive Black Holes in Milky-Way-mass Halos. *Ap. J.*, 857:2 (2018), DOI:10.3847/2041-8213/aabc0a.

Lentz, E., et al., A New Signal Model for Axion Cavity Searches from N-body Simulations. *Ap. J.*, 845:2, DOI:10.3847/1538-4357/aa80dd.