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TOWARD ROBUST MAGNETOHYDRODYNAMIC SIMULATIONS OF GALAXY CLUSTER FORMATION

Allocation: GLCPC/450 Knh
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EXECUTIVE SUMMARY

Our goal is to understand the laws of physics that control the dynamics of ordinary, baryonic matter during the formation of galaxy clusters. Most of that matter is very hot, very dilute plasma. A key dynamical component that results from cluster formation is turbulence in the plasma that generates magnetic fields that control the microphysical processes essential to the physical state of the plasma. Much of the important action takes place on very small physical scales, which are quite challenging to capture in simulations, especially magnetic field behaviors. The work reported here was a vital component in developing a novel, exceedingly high-performance and exceptionally scalable MHD (magnetohydrodynamics) cosmology code named "WOMBAT" that we will apply to the problem detailed above on coming exascale systems. Here, we demonstrated that WOMBAT meets our design objectives when scaled to more than 16,000 Blue Waters nodes. Initial test simulations examined behaviors of astrophysical, hypersonic plasma jets in cluster settings.

RESEARCH CHALLENGE

Galaxy clusters are knots in the cosmic web with masses that can exceed 10^{15} M_{sun}, and sizes of several million light years. They are the largest and last structures to form by gravitational collapse from fluctuations in the Big Bang. Their formation is a critical diagnostic of cosmological theory. Galaxies are actually minor constituents of these clusters. Most of the matter is "dark matter," whose nature remains unclear. Most of the "ordinary" baryonic matter is very hot, very dilute plasma filling the cluster. Its properties trace the current cluster dynamical state and its history. A full understanding of the dynamics of this intracluster medium plasma, or ICM, is absolutely necessary to comprehend how clusters form. Much of the important ICM action, and especially action responsible for generation of the magnetic fields that control ICM physical properties, takes place on scales that are multiple orders of magnitude smaller than the size of a cluster. Until now, simulations that could capture those small-scale actions in cosmological-scale computations, especially including magnetic field generation (which depends on activating the small-scale, MHD dynamo), were beyond reach with existing software and high-performance computer systems. Even with petascale systems such as Blue Waters, no simulation codes existed until now with sufficient performance and scaling behavior to begin to address this research challenge. Our objective is to develop tools to resolve this problem on the coming generation of exascale systems, where the properties designed into WOMBAT will truly shine.

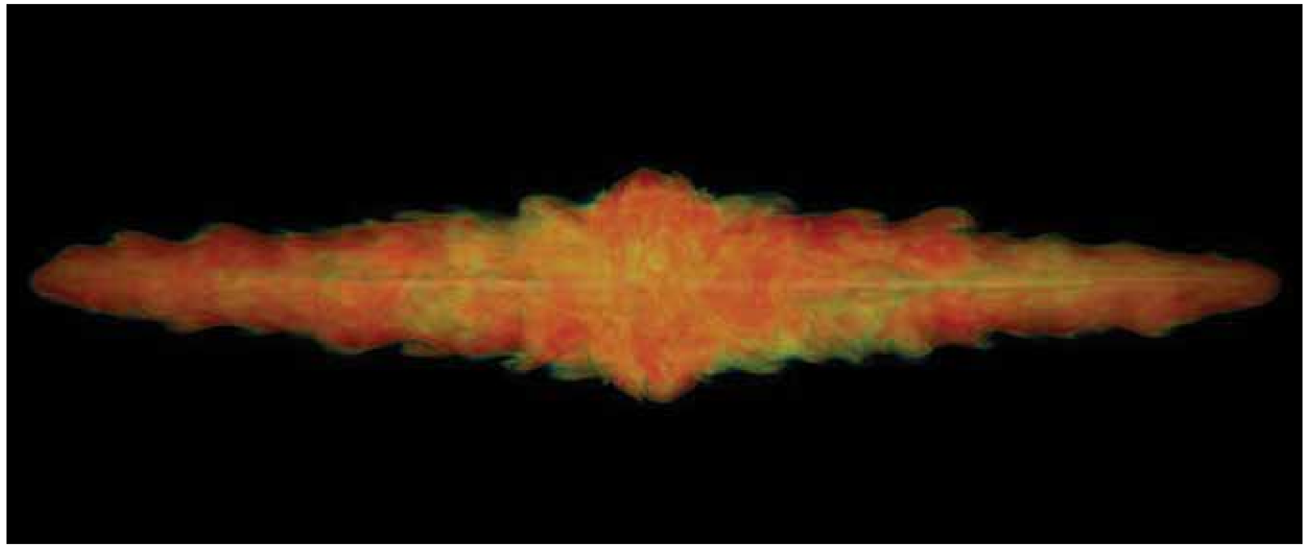

Figure 1: Volume rendering of the distribution of jet plasma resulting from 3D Mach 10, light, bipolar jets propagating through a galaxy cluster medium. The 1,728 x 576 x 576 cell MHD simulation was done with the WOMBAT MHD code on Blue Waters utilizing 2,196 MPI ranks. The volume shown spans approximately 280,000 light years, left to right.

METHODS & CODES

To address this important astrophysics problem we have built from the ground up a novel, exceedingly high-performance and highly scalable MHD cosmology code named "WOMBAT." The code optimizes local memory and vector performance and utilizes hybrid parallelization methods leveraging techniques pioneered at Cray that gain maximum "threading" performance within many-core nodes and MPI-RMA (message passing interface–remote-memory access) performance between nodes. The fast interconnect technology on Blue Waters is very important to our ability to test these designs. In addition, a novel strategy for decomposition of the computational domain minimizes inter-node communication and allows it to be highly asynchronous. Such features provide tremendous performance benefits that will allow WOMBAT to address exceedingly challenging problems, including cluster formation ICM dynamics down to the required physical scales.

RESULTS & IMPACT

Our primary objective on Blue Waters for this allocation was to test and tune the technologies built into WOMBAT in order to prepare to address the cosmological problems outlined above. We have succeeded very well in that. We demonstrated, for example, up to 75% weak scaling efficiency going from one Blue Waters XE6 node to 16,224 XE6 nodes with 16 floating point threads per node. As part of our team's collaboration with Cray, the Cray Programming Environments group developed a new MPICH release, based in part on our Blue Waters results, with enhanced performance for hybrid parallel applications. This will be the default MPICH model going forward, and will considerably benefit both the Blue Waters user community and the broader high-performance community. The N-body dark matter routines in WOMBAT were still in testing at the end of the allocation period. Those tests are very promising, but we were unable to carry out planned cosmological simulations before the allocation expired. We did, however, carry out very high-resolution WOMBAT MHD simulations of hypersonic plasma jets propagating in ICM environments in order to explore their propagation behavior. The distribution of jet plasma from one such simulation is volume rendered in Fig. 1. Instabilities forming along the boundary of the light plasma cocoon are evident.

WHY BLUE WATERS

Blue Waters was essential for this project because of the importance of using a system capable of sustained petaflop performance with very fast inter-node communications to allow proper WOMBAT performance testing. Blue Waters offers the unique opportunity to both test our strategy and to begin to carry out simulations that approach needed levels of physical fidelity.

PUBLICATIONS AND DATA SETS

Mendygral, P. J., et al., WOMBAT: A Scalable and High-performance Astrophysical Magnetohydrodynamic Code. *Astrophysical Journal Supplements*, 228:2 (2017), DOI: 10.3847/1538-4365/aa5b9c.