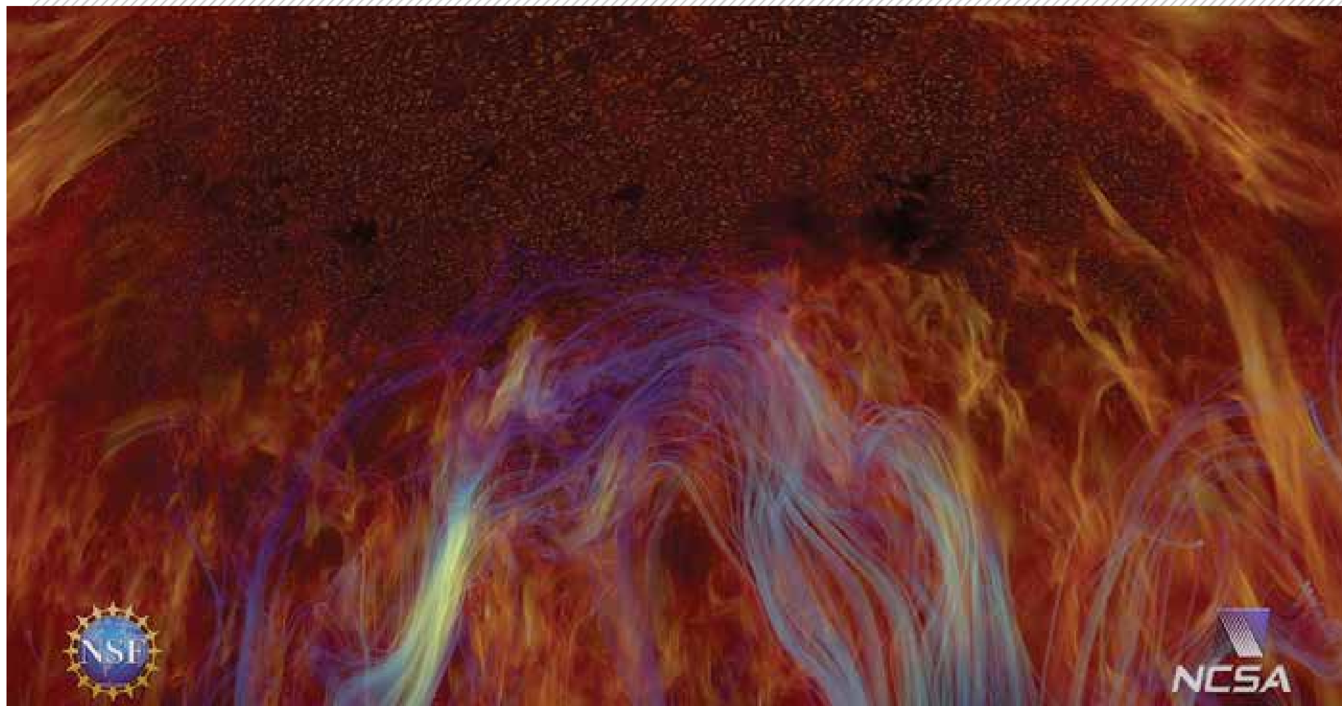


FIGURE 1: Image based on data from STAGGER calculations, from the planetarium show "Solar Superstorms" produced at NCSA showing the emergence of magnetic field lines through the solar surface.

METHODS & RESULTS

A finite-difference code is used to numerically solve the conservation equations for mass, momentum, internal energy. The induction equation for the magnetic field and the equation for non-gray radiation transport are used to model the magneto-convection and the behavior of the overlying chromosphere and corona.

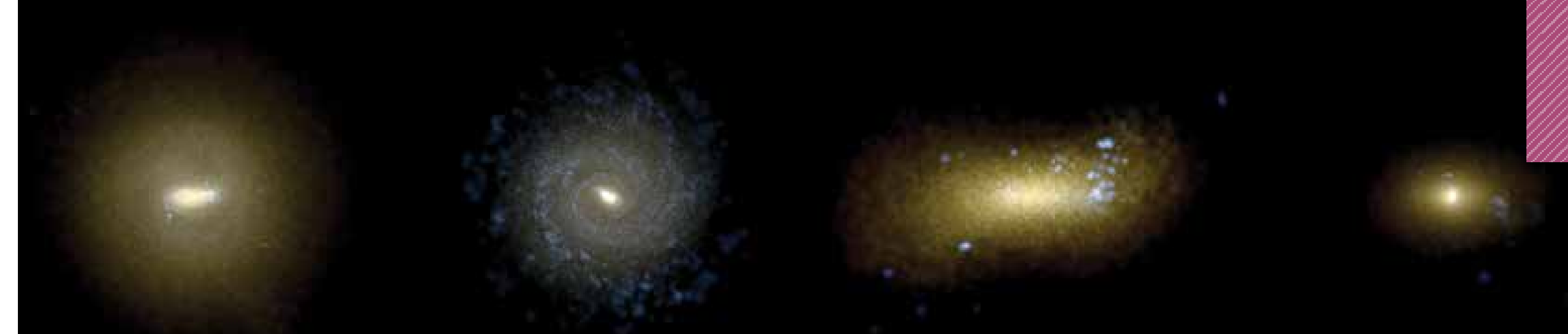
The bulk of this project year was spent finding and removing an incompatibility introduced between the interior calculation scheme and the bottom boundary conditions. It was finally possible to start the relaxation of a 192 Megameter (Mm)—one million meter—by 20 Mm deep model of the outer solar convection zone using a grid of 4,032 by 4,032 by 500. This large size make it possible to use data from interior dynamo simulations to control the bottom boundary conditions for the study of active region emergence.

WHY BLUE WATERS

Blue Waters was particularly well suited for this task. Although it is up to four times slower on a per core basis than the newer Pleiades supercomputer, it was possible to run efficiently on 2,016 nodes or 64,512 integer cores on Blue Waters, whereas only 4,032 cores can be used on Pleiades because of excessive queue wait times for larger jobs.

NEXT GENERATION WORK

A new code, DISPATCH, is being developed which uses task based scheduling of small Cartesian patches that evolve with local time stepping. This type of code is ideal for obtaining **unprecedented** performance and scaling the current petascale and the near-future exascale computing eras, and with its large number of nodes and emphasis on a small number of large-scale projects, the Blue Waters system is particularly well suited for DISPATCH.



EVOLUTION OF THE SMALL GALAXY POPULATION FROM HIGH REDSHIFT TO THE PRESENT

Allocation: NSF PRAC/11.9 mnh
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Co-PI: Fabio Governato[1]
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FIGURE 1: A large galaxy from our cosmological simulations is modeled with different active galactic nucleus (AGN) feedback and dynamics. The morphology of the galaxy is significantly different depending on whether we use (from left to right) our new AGN model, no AGN feedback, poor black hole dynamics or a less sophisticated accretion model.

EXECUTIVE SUMMARY

Creating robust models of the formation and the evolution of galaxies requires the simulation of a cosmologically significant volume with sufficient resolution and subgrid physics to model individual star-forming regions within galaxies. This project aims to perform such modeling with the specific goal of interpreting Hubble Space Telescope observations of high redshift galaxies. We are using the highly scalable N-body/Smooth Particle Hydrodynamics code, ChaNGa, based on the Charm++ runtime system on Blue Waters to perform a simulation of a 25 Mpc cubed volume of the universe with a physically motivated star formation/supernovae feedback model. This past year's accomplishments include incorporating realistic black hole formation, dynamics, and feedback into our model which allows us to create and advance more realistic modeling of the knee in the galaxy luminosity function at high redshift. Comparisons with Hubble data show that we can reproduce the high redshift galaxy population with models that also reproduce the morphologies of present-day galaxies.

INTRODUCTION

The cold dark matter (CDM) paradigm for structure formation has had many successes over a large range of scales, from cosmic microwave background fluctuations on the scale of the horizon to the formation and clustering of individual galaxies. However, at the low end of the galaxy luminosity function, the CDM theory and observations are somewhat at odds. In particular, the existence of bulgeless, cored small galaxies is not a natural prediction of CDM. However, these are the scales where the baryonic physics of gas cooling, star formation, and feedback can significantly impact the overall mass of the galaxy. Furthermore, accurately modeling the star formation process requires a spatial resolution of order 100 parsecs to resolve the molecular star-forming regions of the interstellar medium. On the other hand, survey volumes addressing small galaxies, including recently approved Hubble Space Telescope (HST) programs, are over 10,000 cubic Mpc. Only with large simulations can we perform proper comparisons with these programs to address the following basic issues of the CDM model:

- Does the standard ΛCDM model produce the correct number densities of galaxies as a function of mass or luminosity?
- What role to these galaxies play in the evolution of the baryons in the Universe?
- How do these galaxies relate to the galaxies we can study in detail in the local universe?

METHODS & RESULTS

We used the highly scalable N-body/smooth particle hydrodynamics code ChaNGa to simulate the volumes surveyed by HST with sufficient resolution to make robust predictions of the luminosity function, star formation rate, and morphologies appropriate for these surveys. The results of the simulations were processed by our parallel data reduction pipeline that creates simulated observations. These results can be directly compared with results from observational programs.

Results from our simulations indicate that we can reproduce the high-redshift galaxy luminosity functions observed by Hubble. The simulations also predicted the numbers of galaxies fainter than those observed so far. Depending on how much UV radiation can escape from these low-mass galaxies, these galaxies can produce enough stellar radiation to completely reionize the intergalactic medium. This reionization occurs on a timescale that is consistent with observations of absorption in high redshift quasars and polarization of the cosmic microwave background.

We also made significant improvements in the algorithms used for the treatment of Black Hole formation, dynamics, and feedback. With this new treatment, we can reproduce observed star formation and black hole accretion histories, star formation histories and supermassive black hole masses in Milky Way-sized galaxies over the age of the universe.

WHY BLUE WATERS

We used the same mass and resolution requirements from our previous resolution tests to reliably model galaxy form and structure. Therefore, the size of the simulations we performed are set by the sub-volume of the universe we wish to model. HST surveys of high-redshift, star-forming galaxies cover a volume comparable to a cube 25 Mpc. This volume not only allowed us to make direct comparisons with HST surveys but also to enhance their value by providing a better understanding as to how these galaxies evolve to the present.

Proper treatment of black hole dynamics also requires high dark matter mass resolution. This treatment is needed so that the sinking of black holes to the centers of galaxies is not interrupted by two-body scattering on the dark matter. Combining these two resolution requirements with the complete simulation requires an order of magnitude more computationally intensive than what we could previously use. Therefore, a sustained petascale facility like Blue Waters was necessary.

NEXT GENERATION WORK

Nevertheless, this simulation was still a compromise. For example, if we wish to understand how high-redshift galaxies influence surrounding intergalactic gas, a much larger volume of gas will be needed in our simulations. Intergalactic gas is studied from absorption observations of background quasars using the HST Cosmic Origins Spectrograph. Statistical samples of this gas require a volume of order 60 Mpc; over an order of magnitude larger than our current simulation. Simulations made with samples of this magnitude is the only way we will be able to understand the extent to which star formation, supernovae, and active galactic nuclei in individual galaxies influence the surrounding gas, and to conduct a proper census of the majority of the baryonic matter in the universe. The next generation of Track-1 computational resources will be required to run simulations using higher volumes of intergalactic gas.

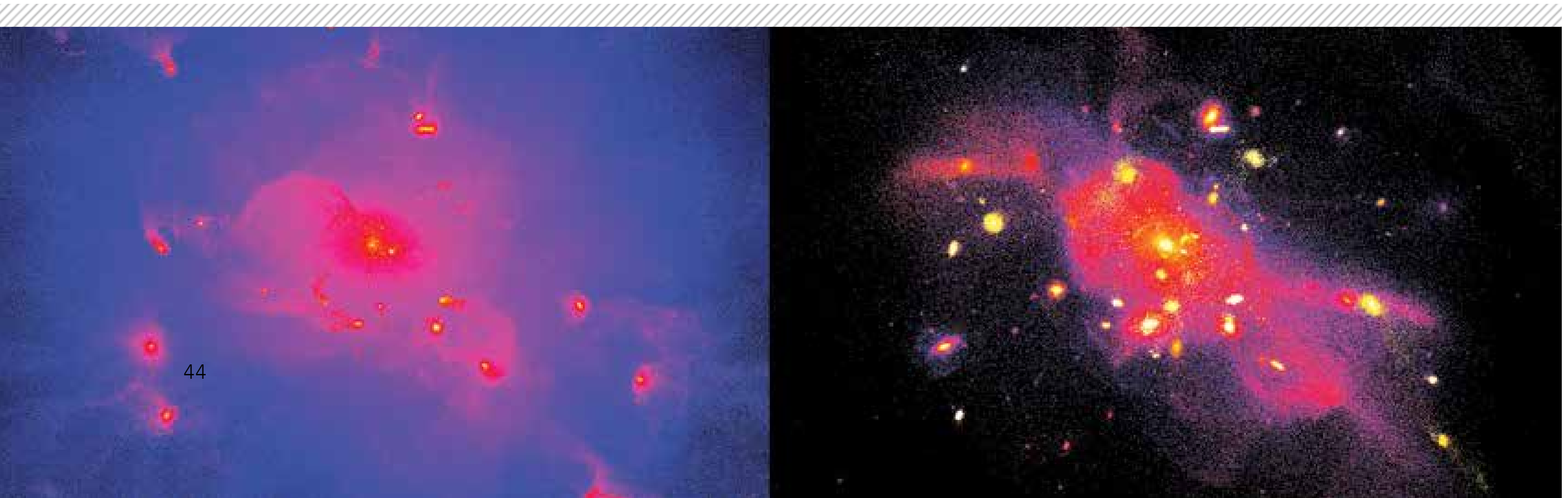
PUBLICATIONS AND DATA SETS

Menon, H., et al., Adaptive techniques for clustered N-body cosmological simulations. *CompAC*, 2 (2015), 1.

Tremmel, M., Governato, F., Volonteri, M., Quinn, T. Off the beaten path: A new approach to realistically model the orbital decay of supermassive black holes in galaxy formation simulations. Mon. Not. R. Astron. Soc., 451:2 (2015), pp. 1868-1874.

Loebman, S., et al., Big-data management use-case: A cloud service for creating and analyzing galactic merger trees. *DanaC: Workshop on Data analytics in the Cloud*. Snowbird, UT. June 22 - 27, 2014.

FIGURE 2: Distribution of gas (left) and stars (right) in a group of galaxies at z = 0.25. Stars are colored by their formation time such that young stars are white. Comparing left and right images, one can find a number of gas-free galaxies with older stellar populations.



BINARY NEUTRON STARS MERGERS: A JET ENGINE FOR SHORT GAMMA-RAY BURSTS

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EXECUTIVE SUMMARY

The LIGO-Virgo Collaborations recently reported the first direct detection of a gravitational-wave (GW) signal produced by the inspiral and coalescence of a binary black hole (BHBH) system. This breakthrough marks the beginning of the era of gravitational-wave astrophysics. GWs are expected to be generated not only by BHBH binaries but also by neutron star-neutron star (NSNS) and black hole-neutron star (BHNS) binaries. Merging NSNSs and BHNSs are not only important sources of GWs but also the two most popular candidates to produce relativistic jets and serve as the engines which power short-hard gamma-ray bursts (sGRBs). Simultaneous observation of GWs and gamma rays from these systems is the holy grail of multimessenger astronomy. We have performed ideal magnetohydrodynamic simulations of NSNS systems in full general relativity and have shown unambiguously that they can indeed launch incipient jets even when the initial B field is confined to the interior of the stars.

INTRODUCTION

A century after the General Relativity (GR) was published, the LIGO-VIRGO collaboration reported, for the first time, the direct detection of the GWs (event GW150914) [1]. This detection provided a spectacular confirmation of GR theory as the fundamental theory of gravitation and confirmed the existence of BHs and BHBHs. Most importantly, this breakthrough opens a new window to our universe, as GWs can provide us with information that cannot be obtained from the typical electromagnetic spectrum. This includes the observation of BHBH and measurement of their properties, the study of the early universe before the recombination era, as well as the nature of matter above nuclear density. Also, GW signals are expected to be generated not only by BH binaries but also from NSNSs and BHNSs, among other compact objects. Many of these sources are likely to also generate electromagnetic (EM) radiation counterparts to the GWs. Detecting both GW and EM radiation from the same cosmic source will constitute a major advance in multimessenger astronomy.

GRBs were first discovered in 1967, and theorists have been working to explain them ever since. The mergers of a NS with a companion NS or BH are the two most popular candidate progenitors of short gamma ray bursts, those with a duration less than two seconds. These systems are thus excellent candidates for multimessenger detection. To verify the binary-short gamma ray bursts association and properly interpret the GW and EM signals we will receive, we need to model these systems and simulate their evolution in full general relativity with magnetohydrodynamics (GRMHD). Our work to date has focused on studying the merger of magnetized BHNS and NSNS systems.

METHODS & RESULTS

GRMHD numerical simulations require the solution of the GR equations to determine the gravitational field, the relativistic MHD equations to determine the flow of matter, and Maxwell's equations to determine the electromagnetic fields. Together the equations constitute a large system of highly nonlinear, multidimensional, partial differential equations in space and time.

Recently, we demonstrated that mergers of magnetized BHNS systems can launch jets and be the engines that power short gamma ray bursts [2]. The key ingredient for generating a jet was found