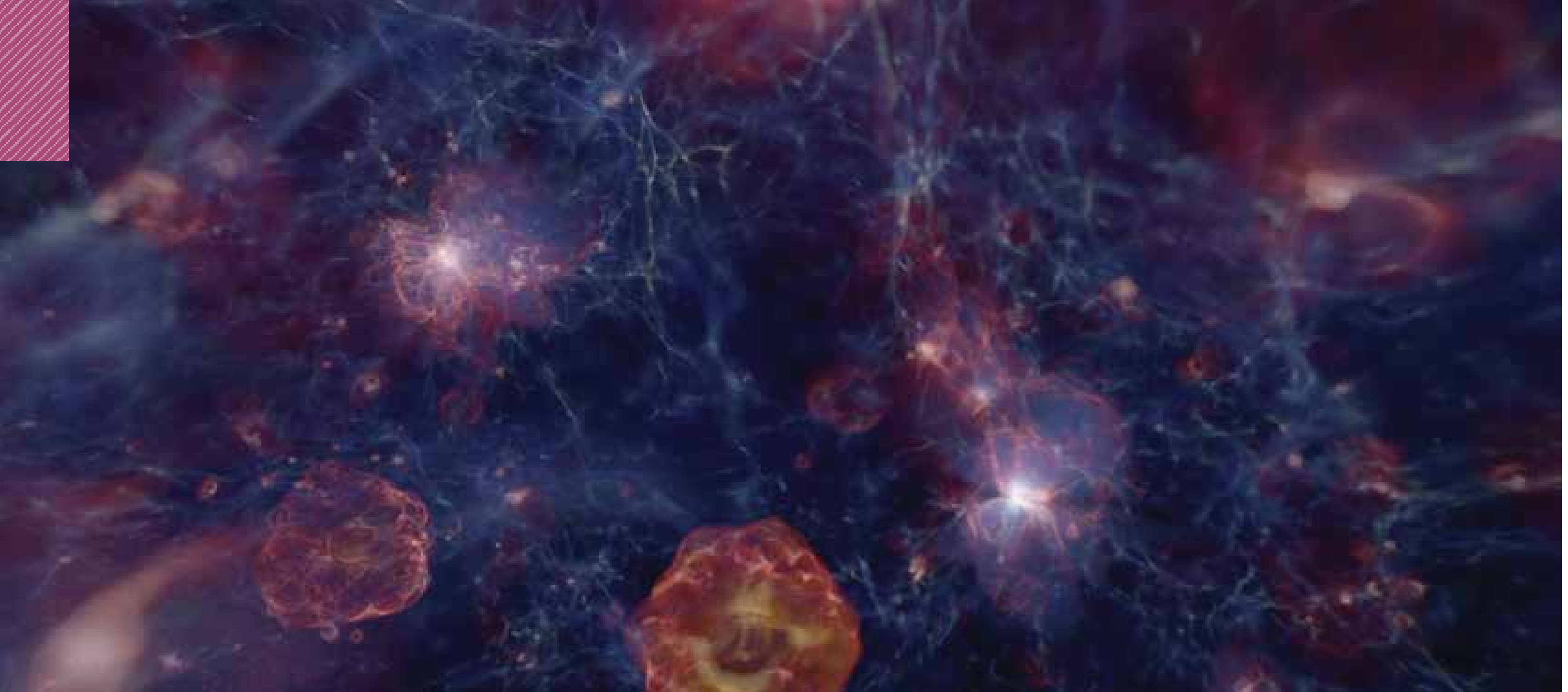

CONNECTING GALAXIES IN THE EARLY UNIVERSE TO THE MILKY WAY

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EXECUTIVE SUMMARY

In this project, we are investigating the growth and evolution of galaxies like the Milky Way and its satellites over the entire age of the Universe, and we are addressing observational questions raised by a variety of astronomical observations. In particular, we are examining the life cycle of gas in galaxies, the evolution of the Milky Way's earliest progenitor galaxies, and the ways in which ionizing radiation and magnetic fields are created and escape from galaxies. All of these problems require simulations with an extremely high dynamic range in space and time, complex physics (including radiation transport, magnetohydrodynamics, and complex gas chemistry), and large simulation volumes. We use the Enzo code, which has been modified to scale to large core counts on Blue Waters, the only machine available where the heavy data and communication needs can be satisfied.

INTRODUCTION

Despite the wealth of astronomical observations examining the properties of galaxies, a detailed and self-consistent theoretical model of galaxy formation does not yet exist. The evolution of galaxies has been examined in great detail and in many wavelength bands from approximately 600 million years after the Big Bang to the present day. These observations show that the galaxies that we can see have undergone radical changes in size, appearance, and content over the last 13 billion years and that the properties of galaxies are intimately tied to their environment and formation history [1].

Complementary observations of our own Milky Way have provided a rich dataset of the kinematics and elemental abundances of local stellar populations, including large numbers of metal-poor stars in the halo of our galaxy and local dwarf galaxies [2]. In principle, this "galactic fossil record" can probe the entire merger and star formation history of the Milky Way and its satellites, and is an extremely useful counterpoint to direct observations of distant galaxies. Similarly, observations of diffuse clouds of gas in the halo of the Milky Way provide important constraints on how gas reaches the disks of galaxies, thus feeding star formation [3]. This complements observations of the same process in distant galaxies from surveys like the Hubble Space Telescope's COS-Halos project [4].

The volume of observational data on galaxy formation, which is already staggering, will increase exponentially over the next decade as observatories such as the Large Synoptic Survey Telescope and James Webb Space Telescope come online. At present, however, we lack the theoretical models necessary to interpret such observational datasets adequately. This lack of theoretical models is a result of the inherent challenges in the modeling of galaxies, which includes the necessity for both high dynamic range and complex, interconnected physics. As such, it is necessary to resort to large-scale numerical simulations to accurately model these physical phenomena.

METHODS & RESULTS

This project was carried out using the Enzo code [5], which is used for the simulation of cosmological and astrophysical phenomena. Enzo uses an adaptive mesh refinement scheme to achieve high spatial and temporal resolution and provides a huge range of physics modules including dark matter, hydrodynamics, magnetohydrodynamics, radiation transport, non-equilibrium many-species gas chemistry, and prescriptions for star and black hole formation and feedback. Enzo is publicly available and used to model many types of astrophysical phenomena.

Thus far, we have primarily focused on the analysis of the results of our previous Blue Waters-related project and have run large simulations of the formation of Milky Way-type galaxies. Our most interesting results have been the characterization of the properties of galaxies in the early universe – namely, the galaxies that form the seeds that will one day become the Milky Way and its satellites. We have found that these galaxies have very intermittent star formation, form stars very inefficiently at lower masses (as compared to higher-mass galaxies), and that the properties of individual galaxies' stellar and gas content, including metallicity and formation history, vary significantly from galaxy to galaxy.

WHY BLUE WATERS

The simulations required to properly model galaxies over the age of the universe require extremely high spatial and temporal dynamic range, and also require complex physics – most importantly for our problem –radiation transport, magnetohydrodynamics, and non-equilibrium gas chemistry. Furthermore, large simulation volumes (and thus many resolution elements) are needed to model enough galaxies to be able to adequately compare theory to observations in a statistically meaningful way. Taken together, this requires the use of a supercomputer with large memory and disk space (to accommodate the tremendous dataset 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 system available to the academic community that fits all of these requirements.

NEXT GENERATION WORK

A future-generation system will allow us to include even more physics – simultaneously including much more sophisticated models for radiation transport that resolve line transport as well as continuum transport, for example – and increased spatial and temporal dynamical range. The goal for Milky Way-type galaxies is to be able to simulate the entire system from the "virial radius" (the scale defining the "edge" of the Milky Way's neighborhood – approximately one million light years from the center of the galaxy) down to the size of individual star-forming clouds (a few light years), all within a cosmological context. This capability would allow us to perform incredibly realistic simulations of cosmological structure including all possible important physical phenomena.

FIGURE 1 (LEFT): This image shows several galaxies in a small region of the universe approximately 500 million years after the Big Bang. These galaxies will eventually become part of a galaxy like our own Milky Way. The blue filamentary structure shows neutral hydrogen (i.e., the "cosmic web"), which feeds cold gas into galaxies to form stars. The red and yellow clouds show gas that has been ionized by massive stars in the individual galaxies, and the white glowing regions show radiation from populations of massive stars that are currently ionizing the universe. Image credit: Bob Patterson (NCSA Advanced Visualization Laboratory).