USING BLUE WATERS TO UNDERSTAND THE ORIGINS OF GALAXIES AND THE NATURE OF DARK MATTER

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EXECUTIVE SUMMARY

Our research program uses Blue Waters to explore the origins of galaxies and stars and the nature of dark matter. At a fundamental level, the study of galaxies and stars seeks to answer the question: "How did we get from the Big Bang to the Milky Way?" This is an immensely challenging question involving the interplay among gravity, fluid dynamics, radiation and matter, and stars exploding as supernovae, giving rise to explosive outflows of material from galaxies that can reach across the observable universe. The physics is chaotic and wildly nonlinear, and the range of scales is tremendous (from one to 10 billion years). As such, our work requires massive numerical simulations that can follow all of these processes. By using these simulations, we have gained fundamental insights into why galaxies today look as they do and, in the process, strongly constrained the allowed nature of the dark matter.

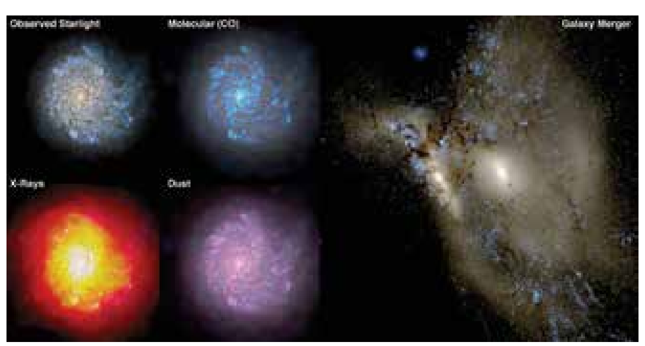

Figure 1: Simulations of a Milky Way-like galaxy. Observed starlight (mock images) is presented with overlaid intensity maps showing mock carbon monoxide (molecular gas), X-rays, and dust emission. At the right is a mock Hubble image during a galaxy collision, where violent bursts of star formation are triggered.

RESEARCH CHALLENGE

Our program seeks to understand the origin and nature of galaxies, using massively parallel simulations that follow the birth and evolution of galaxies and stars from the very early universe to the present day. Our simulations model the origins, evolution, internal structure, and observable properties of galaxies ranging in size from the smallest observed "dwarf" galaxies with just a few thousand stars to the Milky Way and Andromeda (the "Local Group").

Deep and fundamental questions remain unsolved in this area, including: "How did we get from the Big Bang to the Milky Way? Why did the universe form so few stars compared to its total mass? Why did stars form where and when they did? How can we use galaxies to probe the fundamental nature of dark matter?" At the heart of these issues lies the fact that stars, once they form, are not passive actors within a galaxy. They shine and emit tremendous amounts of energy in the form of light (radiation), stellar winds, and (sometimes) supernovae explosions. This energy can blow material out of the galaxy entirely and completely alter the evolutionary history of galaxies. But these processes remain poorly understood, in large part because they: (1) couple very small and very large scales in the universe, thus requiring simulations with enormous dynamic range to model them; and (2) involve a diverse range of physics including (but not limited to) gravity, fluid dynamics, magnetic fields, conduction and viscosity, radiation–matter interactions, interstellar chemistry, and stellar evolution. The simulations we have conducted incorporated all of these processes into the highest-resolution simulations yet run to address these questions for the first time at the level of detail needed to make observable predictions. Billions of dollars are being invested in new telescopes and instruments to explore these questions experimentally. Simulations will be critical tools to make detailed predictions and leverage these transformative observations.

METHODS & CODES

We have run a large suite of cosmological, high-resolution simulations including detailed treatments of the physics of the interstellar medium, star formation, feedback in radiation and supernovae, magnetic fields, and cosmic rays. The simulations use the Feedback In Realistic Environments (FIRE) physics methods in the GIZMO code, a new massively parallel multimethod, hybrid Lagrangian–Eulerian finite-element, high-order, radiation-magnetohydrodynamics code (unique in numerical methods and physics-supported).

RESULTS & IMPACT

Our cosmological simulations target galaxies from the faintest dwarfs through the Milky Way at the ultra-high-resolution and realism required to leverage the next generation of observations. The petascale resources of Blue Waters allow us to resolve each galaxy with ~1 billion particles and follow them self-consistently over their entire history in live cosmological settings. When the interstellar medium is resolved into dense molecular clouds, massive stars naturally form and then inject large quantities of energy and momentum into the surrounding medium via "stellar feedback." This feedback is critical to produce realistic galaxies and generate the powerful galactic winds observed, radically altering the baryon cycle between galaxies and the circumgalactic medium.

These simulations model the physics of galaxy formation with unprecedented realism, uniquely incorporating not only all of the important stellar feedback mechanisms, (radiation pressure, photo-heating, stellar winds, supernovae, and cosmic rays) but also magnetic fields, physical (anisotropic) Braginskii conduction and viscosity, passive scalar (metal) diffusion, and explicit, multiwavelength radiation hydrodynamics. This represents the culmination of several years of work supported by NSF, and has been critical to enable the science of the FIRE project, a collaboration of theorists across 13 different major institutions. The program has revealed fundamental new insights into how stars alter their galactic environments and has changed our observational inferences about the nature of dark matter in those galaxies. The simulations are also being used to support an outreach component involving high school students and teachers, undergraduate students, and a large science team. In addition, this work has been used to make predictions specifically for next-generation observatories including (but not limited to): the James Web Space Telescope, the Large Synoptic Survey Telescope, Gaia, and the Hubble Space Telescope, in order to test theories of galaxy and star formation, the origin of the heavy elements in the universe, the reionization history of the early universe, the effects of fundamental plasma physics in the circum- and intergalactic medium, and the nature of cold dark matter.

WHY BLUE WATERS

Blue Waters is critical for this research because the enormous computational challenges enumerated above require >100 million CPU-hours on tens of thousands of processors and requiring tens of terabytes of active memory to store and evolve the immensely complex physical systems, and the simulations produce petabytes of data products. No other current facility enables this research.

PUBLICATIONS & DATA SETS

Lamberts, A., Predicting the binary black hole population of the Milky Way with cosmological simulations. *Monthly Notices of the Royal Astronomical Society*, in press (2018), arXiv:1801.03099.

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Sanderson, R., et al., Reconciling Observed and Simulated Stellar Halo Masses. *Monthly Notices of the Royal Astronomical Society*, in press (2018), arXiv:1712.05808

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Hopkins, P., A New Public Release of the GIZMO Code. *arXiv:1712.01294* (2017).

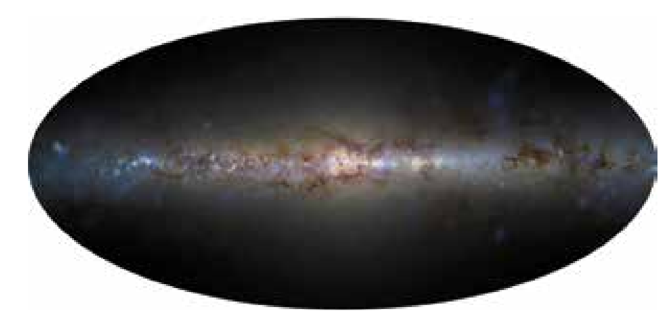

Figure 2: Mock Hubble map of a simulated galaxy, as seen from a Sun-like star. Filamentary molecular cloud complexes and young star clusters are visible within the "Milky Way" (galactic disk). Our combination of physics and resolution allow us to model galactic structure with unprecedented realism.