UNDERSTANDING THE ORIGINS OF THE STARS AND GALAXIES IN OUR UNIVERSE

Allocation: NSF PRAC/4,940 Knh
PI: Philip F. Hopkins[1]
Collaborators: Claude–André Faucher–Giguère[2], Dušan Kereš[3], Eliot Quataert[4], Norman Murray[5], Mike Boylan–Kolchin[6], James Bullock[7], Andrew Wetzel[3], Robyn Sanderson[8], Chris Hayward[9], Robert Feldman[10], Christine Corbett–Moran[11]

[1]California Institute of Technology
[2]Northwestern University
[3]University of California, San Diego
[4]University of California, Berkeley
[5]Canadian Institute for Theoretical Astrophysics
[6]University of Texas at Austin
[7]University of California, Irvine
[8]University of Pennsylvania
[9]Flatiron Institute
[10]ETH Zurich
[11]NASA JPL

EXECUTIVE SUMMARY

This research 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, 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 timescales is tremendous (from one to ten billion years). As such, massive numerical simulations that can follow all of these processes are required. By using numerical simulations, the researchers have gained fundamental insights into why galaxies today look as they do and, in the process, have strongly constrained the allowed nature of the dark matter.

RESEARCH CHALLENGE

The 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. The 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, simply, “How did we get from the Big Bang to the Milky Way?” as well as, “Why did the Universe form so few stars (compared to what it could have done)?” Further questions include, “Why did stars form where and when they did?” and “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 supernova explosions. This energy can blow material out of the galaxy entirely and completely alter the evolutionary history of galaxies.

But these stellar and galactic processes remain poorly understood, in large part because they: (1) couple very small and very large scales in the Universe and require 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 run on Blue Waters incorporated all of these processes into the highest-resolution simulations yet completed, allowing the research team 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; these simulations are critical tools to make detailed predictions and leverage these transformative observations.

METHODS & CODES

The researchers 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-hydrodynamics code (unique in numerical methods employed and physics supported).

RESULTS & IMPACT

These cosmological simulations target galaxies from the faintest dwarfs through to the Milky Way and run at the ultrahigh resolution and realism required to interpret the next generation of observations. The petascale resources of Blue Waters allow the researchers to resolve each galaxy with approximately one billion particles and follow them self-consistently over their entire history in realistic 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. The 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, cosmic rays) but also magnetic fields, physical (anisotropic) Braginskii conduction and viscosity, passive scalar (metal) diffusion, and explicit, multiwavelength radiation hydrodynamics.

This work represents the culmination of several years of research supported by the National Science Foundation, and has been critical in enabling 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 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, and undergraduate students, as well as a large science team using these simulations. The simulations have already been utilized to make predictions specifically for next-generation telescopes including (but not limited to) JWST, LSST, Gaia, and HST, in order to constrain the origin of the heavy elements in the Universe, and test theories of galaxy and star formation, 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 was critical for this research because the enormous computational challenges detailed in this report required more than 100 million CPU-hours on tens of thousands of processors with tens of terabytes of active memory to store and evolve the immensely complex physical systems, which produced petabytes of data products. No other facility could have enabled this research.

PUBLICATIONS & DATA SETS

E.–R. Moseley, J. Squire, and P. F. Hopkins, “Non-linear evolution of instabilities between dust and sound waves,” *Mon. Notices Royal Astron. Soc.*, vol. 489, p. 325, 2019.

T. K. Chan, D. Kereš, P. F. Hopkins, E. Quataert, K.-Y. Su, C. C. Hayward, C.–A. Faucher-Giguère, “Cosmic ray feedback in the FIRE simulations: constraining cosmic ray propagation with GeV γ-ray emission,” *Mon. Notices Royal Astron. Soc.*, vol. 488, p. 3716, 2019.

M. Y. Grudić and P. F. Hopkins, “The elephant in the room: the importance of the details of massive star formation in molecular clouds,” *Mon. Notices Royal Astron. Soc.*, vol. 488, p. 2970, 2019.

M. Y. Grudić, P. F. Hopkins, E. J. Lee, N. Murray, C.–A. Faucher-Giguère, and L. C. Johnson, “On the nature of variations in the measured star formation efficiency of molecular clouds,” *Mon. Notices Royal Astron. Soc.*, vol. 488, p. 1501, 2019.

Z. Hafen *et al.*, “The origins of the circumgalactic medium in the FIRE simulations,” *Mon. Notices Royal Astron. Soc.*, vol. 488, p. 1248, 2019.

K.–Y. Su *et al.*, “The failure of stellar feedback, magnetic fields, conduction, and morphological quenching in maintaining red galaxies,” *Mon. Notices Royal Astron. Soc.*, vol. 487, p. 4393, 2019.

S. Garrison–Kimmel *et al.*, “The Local Group on FIRE: Dwarf galaxy populations across a suite of hydrodynamic simulations,” *Mon. Notices Royal Astron. Soc.*, vol. 487, p. 1380, 2019.

V. P. Debattista *et al.*, “Formation, vertex deviation, and age of the Milky Way’s bulge: Input from a cosmological simulation with a late-forming bar,” *Mon. Notices Royal Astron. Soc.*, vol. 485, p. 5073, 2019.

D. Guszejnov, P. F. Hopkins, and A. S. Graus, “Is it possible to reconcile extragalactic IMF variations with a universal Milky Way IMF?” *Mon. Notices Royal Astron. Soc.*, vol. 485, p. 4852, 2019.

D. Seligman , P. F. Hopkins, and J. Squire, “Non-linear evolution of the resonant drag instability in magnetized gas,” *Mon. Notices Royal Astron. Soc.*, vol. 485, p. 3991, 2019.

C.–L. Hung *et al.*, “What drives the evolution of gas kinematics in star-forming galaxies?” *Mon. Notices Royal Astron. Soc.*, vol. 482, p. 5125, 2019.

P. F. Hopkins and M. Y. Grudić,, “Numerical problems in coupling photon momentum (radiation pressure) to gas,” *Mon. Notices Royal Astron. Soc.*, vol. 483, no. 3, pp. 4187–4196, 2019.

A. Lamberts et al.,, “Predicting the binary black hole population of the Milky Way with cosmological simulations,” *Mon. Notices Royal Astron. Soc.*, vol. 480, no. 2, pp. 2704–2718, 2018.

C. Corbett–Moran, M. Y. Grudić, and P. F. Hopkins, “The effects of metallicity and cooling physics on fragmentation: Implications on direct-collapse black hole formation,” *Mon. Notices Royal Astron. Soc.*, submitted for publication, 2018, arXiv:1803.06430.

R. Sanderson *et al.*, “Reconciling observed and simulated stellar halo masses,” *The Astrophysical Journal*, vol. 869, no. 1, p. 12, 2018.

S. Garrison–Kimmel *et al.*, “The origin of the diverse morphologies and kinematics of Milky Way-mass galaxies in the FIRE-2 simulations,” *Mon. Notices Royal Astron. Soc.*, vol. 481, no. 3, pp. 4133–4157, 2018.

P. F. Hopkins, “A new public release of the GIZMO code,” arXiv preprint, 2017, arXiv:1712.01294.

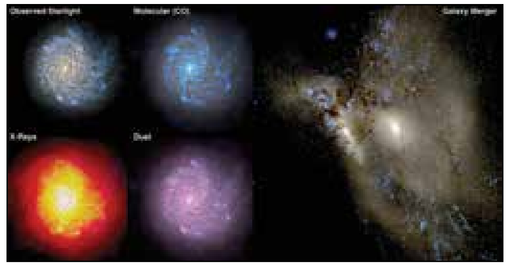

Figure 1: Simulations of a Milky Way-like galaxy. Observed starlight (mock images) is shown with overlaid intensity maps showing mock carbon monoxide (molecular gas), X-rays, and dust emission. The “Galaxy Merger” portion shows a mock Hubble image during a galaxy collision, where violent “bursts” of star formation are triggered.

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). The research team’s combination of physics and resolution allows them to model galactic structure with unprecedented realism.