THE EPOCH OF THE FIRST LUMINOUS BLACK HOLES: EVOLVING THE BLUETIDES SIMULATION INTO THE FIRST BILLION YEARS OF COSMIC HISTORY

Allocation: NSF PRAC/4,400 Knh
PI: Tiziana Di Matteo[1]
Co-PIs: Yu Feng[2], Rupert Croft[1]
Collaborators: Aklant Bhowmick[1], Yueying Ni[1], Ananth Tenneti[3], Steve Wilkins[4], Madeleine Marshall[5], Stuart Wyithe[5]

[1]Carnegie Mellon University
[2]University of California, Berkeley
[3]University College, London
[4]University of Sussex
[5]University of Melbourne

EXECUTIVE SUMMARY

Quasars, powered by supermassive black holes, are the most luminous objects known. As a result, they enable unparalleled studies of the Universe at the earliest cosmic epochs. The absolute record holder, a black hole with a mass of 800 million times that of our sun, has recently been discovered from when the Universe was only 690 million years old—just five percent of its current age, and at the very dawn of galaxy formation.

With their large simulation volume, the researchers have made many predictions on what the James Webb Space Telescope (JWST) will see when pointed at such early quasars after its launch in 2021. By comparison, the BlueTides simulation box is ten thousand times larger in angular area than the field of view of JWST's Near Infrared Camera, allowing the rare regions where quasars form to be translated into mock JWST observations. JWST should reveal an assortment of black hole galaxies, including compact spheroids, and isolated galaxies.

RESEARCH CHALLENGE

The previous phase of the BlueTides (BT) simulation made direct contact with the observations of the giant record holding black hole, making predictions for its host galaxy. Remarkably, the sample of early Universe quasars has grown tremendously over the last year, with 30 more quasars having been found from the first billion years of the universe. The researchers would like to study these types of objects directly with BlueTides, if they are able to form, to look at the conditions that induce the rapid black hole growth necessary to reach these giant masses and make predictions for upcoming telescopes. In order to make contact with this much larger sample, it was necessary to evolve BlueTides forward in time, reaching into a new regime where hundreds of thousands of galaxies in the simulation volume are forming stars, and the Universe is at a new level of complexity.

METHODS & CODES

BlueTides is run on the entire set of compute nodes on Blue Waters using the latest version of the research team's MP-Gadget code. The general characteristics of the GADGET family of codes are those of a flexible TreePM-SPH solver for cosmological fluids of dark matter, gas, and stars. In addition to the basic physics of gravity and hydrodynamics, the code also contains numerous further physics modules covering aspects of star formation and black hole growth. The MP-Gadget code variant was developed to be lean, efficient, and scalable. As the simulation progresses, the computation starts to become dominated by the hydrodynamics solver as more galaxies form. This part of the code has traditionally been the hardest to scale, with timesteps getting very small in highly clustered regions of very high density. These regions, however, are the most interesting ones, where the observable massive galaxies and quasars form. The MP-Gadget hydrosolver is MPI/thread hybridized, and the team has recently further improved the threading efficiency. More threads mean fewer MPI ranks, and thus easier over-decomposition.

RESULTS & IMPACT

As the cosmic web of gas and dark matter was evolving in BlueTides at an ever-increasing pace, a large sample of massive black holes had formed in the simulation volume over the course of the current run. With such a set of objects, the researchers can now carry out statistical tests on the whole population, and test cosmological models quantitatively. The host galaxies of these black holes have detailed stellar properties available: They all tend to be highly star-forming but have a wide range of kinematic characteristics (disks, bulges), and lie in a variety of large-scale environments. The assembly of each galaxy happens at the same time that the central black holes grow, and for approximately 30 objects the black hole outshines the galaxy significantly and the object would be observed as a quasar.

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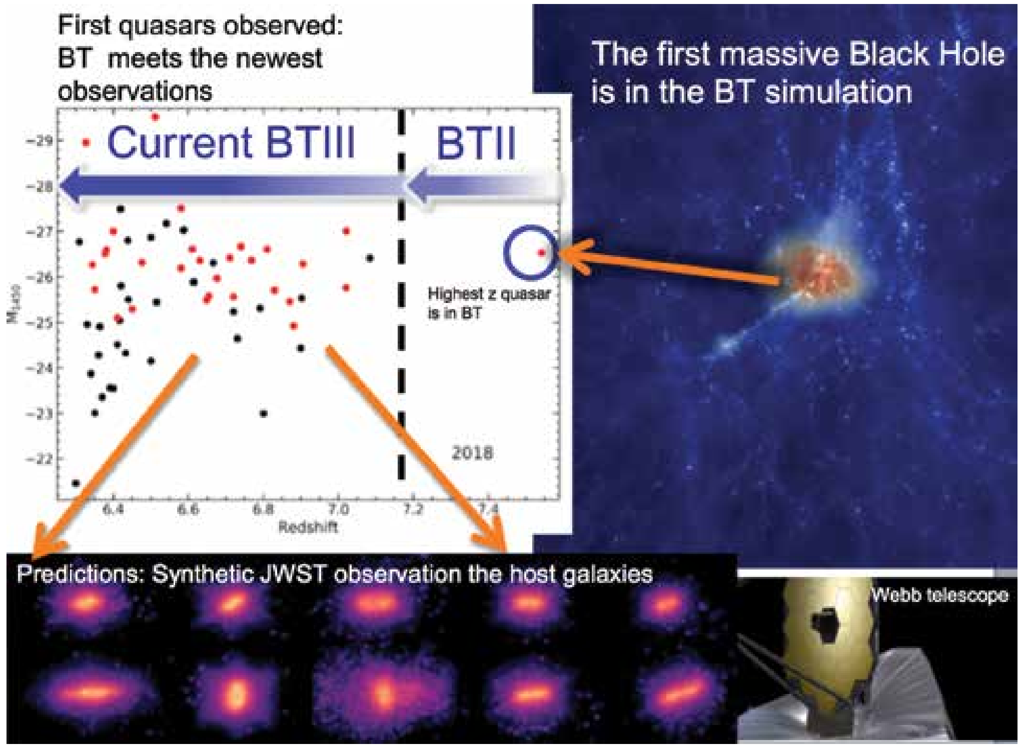

Figure 1: Left—The current (as of 2019) quasar sample in the early Universe. Thirty new quasars at z > 6 (the first billion years) were discovered recently. Right: The large-scale environment surrounding the first massive black hole to form in BlueTides. Bottom: BlueTides galaxies as they would be seen by the Webb telescope.

WHY BLUE WATERS

A complete simulation of the Universe at the epochs the researchers are studying requires a small enough particle mass to model the dwarf galaxies, which significantly contribute to the summed ionizing photon output of all sources. It also requires an enormous volume (on the order of 1 cubic gigaparsec or Gpc, where 1 Gpc is 3×10^{10} cubic light years) in order to capture the rarest and brightest objects: the first quasars. The first requirement is therefore equivalent to a high particle density, and the second to a large volume.

Previous calculations on smaller high-performance computing systems have either fulfilled the first requirement in a small volume, or the second with large particle masses, thus only resolved for large galaxies. With Blue Waters, however, the research team has reached the point where the required number of particles (about one trillion) could be contained in memory, and the petaflop computing power was available to evolve them forward in time. Blue Waters, therefore, has made possible this qualitative advance, allowing arguably the first complete simulation (at least in terms of the hydrodynamics and gravitational physics) of the creation of the first galaxies and large-scale structures in the Universe.

The application runs required essentially the full system: The researchers used 20,250 nodes (648,000 core equivalents—the new version of the code can scale higher, but the team left a safety margin) using 57 GB/node (89%). This application thus uses 1.15 PB of memory—something Blue Waters can provide, as it is 90% of the available memory. Running such large jobs on a regular basis in a very timely fashion obviously requires advanced resource management, and the way the Blue Waters project has been set up made this possible.

PUBLICATIONS & DATA SETS

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