TINY GALAXIES HOST THE FIRST GIANT BLACK HOLES: BLUETIDES SIMULATION MAKES CONTACT WITH THE FIRST 700 MILLION YEARS OF COSMIC HISTORY

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EXECUTIVE SUMMARY

Quasars, powered by supermassive black holes, are the most luminous objects known. As a result, they enable studies of the universe at the earliest cosmic epochs. A record-holding black hole with a mass 800 million times that of the Sun has recently been discovered. It formed when the universe was only 690 million years old—just 5% of its current age. The BlueTides (BT) simulation is the largest state-of-the-art hydrodynamical cosmological simulation that incorporates the processes of structure formation at cosmological scales with all the physics at much smaller galactical scales. Thus, it captures our most realistic understanding of black holes and their connection to galaxy formation in the early universe. These rare black holes grow at a super high rate, emitting enough energy to blow out gas that would eventually make stars in the galaxies. By growing so fast, the black hole stunts the growth of its host galaxy. We predict that the JWST (James Webb Space Telescope, the successor of the Hubble) should be able to peek at the primordial environment of these extreme objects.

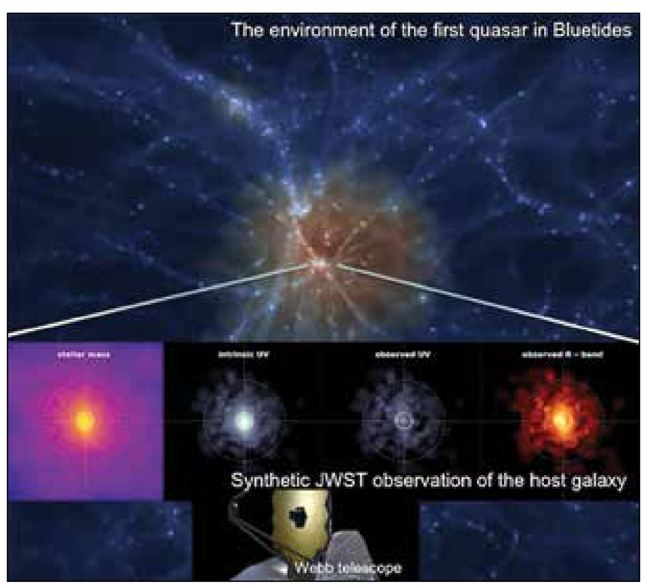

Figure 1: Images showing the distribution of gas in the region centered on the most massive black hole of a size corresponding to the JWST field of view. The background image shows the distribution of gas (density color coded by temperature). The insets show the host galaxy of the brightest quasar as JWST should see it.

RESEARCH CHALLENGE

The first billion years is a pivotal time for cosmic structure formation. This epoch is also known as the cosmic dawn: the galaxies and black holes that formed then shaped and influenced all future generations of stars and black holes. Understanding and detecting the first galaxies and black holes is therefore one of the main observational and theoretical challenges in galaxy formation. The fundamental challenge to understanding this epoch of the Universe is that extremely large volumes need to be simulated as the first objects are rare, while at the same time extremely high resolution is required as the first galaxies and quasars are expected to be small and compact. With our BT simulation on Blue Waters (BW), this has now become possible, and it is the first and only cosmological simulation of structure formation that has run on the full BW machine.

A complete simulation of the universe at the epochs we are studying requires a small enough particle mass to model the first galaxies. It also requires an enormous volume, of the order of 1 cubic gigaparsec (1 Gpc^3 is 3×10^{28} cubic light years) to capture the rarest and brightest objects. The first requirement is therefore equivalent to a high particle density, and the second to a large volume.

In the last year, we have extended the BT-I simulation to cover the evolution of the first billion years of cosmic history (second phase: BT-II). The goal is to significantly increase the scientific impact of this calculation to the community. The effort has paid off: BT is the only simulation that makes contact with the recently discovered supermassive black hole and can now make predictions regarding its formation, history, and future observations by next-generation telescopes.

METHODS & CODES

The run was made possible through our new code, Massively Parallel (MP)–Gadget. MP–Gadget is a cosmological hydrodynamic simulation code. Recent radical updates to the code efficiency and the Smooth Particle Hydrodynamics formulation and star formation modeling mean that we have met the challenge of simulating the next-generation space telescope fields and are effectively using the full BW machine. We have extended the BT run, which has an unprecedented volume and resolution, to cover the evolution of the first billion years of cosmic history.

RESULTS & IMPACT

The most distant known quasar (from 690 million years after the Big Bang) was recently discovered by [1]. We explore the host galaxy of this quasar in the large-volume cosmological hydrodynamic simulation BT, which in Phase II has reached these redshifts. The brightest quasar in BT has a luminosity of 10^{13} times that of the Sun and a black hole mass of 700 million solar masses, comparable to the observed quasar (Fig. 1).

The quasar resides in a rare halo of 10^{12} solar masses, and has a host galaxy comparable to the Milky Way's mass. We derive quasar and galaxy spectral energy distributions in the mid- and near-infrared range and make predictions in JWST bands. We predict a significant amount of dust is present in the galaxy. We present mock JWST images of the galaxy: The host galaxy is detectable in NIRCam filters, but it is extremely compact (10 times smaller than our Milky Way). JWST's exquisite sensitivity, resolution, and wide wavelength coverage will be essential (and, we hope, sufficient) to constrain the stellar mass of these tiny host galaxies that are currently undetectable with the Hubble Space Telescope.

Many theoretical models predict that quasar-driven outflows account for the observed quenching of star formation in massive galaxies. There is growing observational evidence for quasar-launched massive outflows even in the very early universe. This is referred to as "quasar feedback." We have studied the feedback around the highest redshift quasar in the BT simulation and predict that there are significant outflows around this quasar. The gas is blown out from the galaxy; the quasar stops growing and so does its host galaxy.

The outflow gas contains a cold, dense molecular component that originates from the inner region of the halo, within a few kiloparsecs of the central black hole. This would be observable in CO emission at radio wavelengths. The velocities of the outflow gas reach thousands of km/s, within which the molecular component has mass averaged outward radial velocity of 1,300 km/s, consistent with observations. The averaged outflow rate has an enormous value, about 200–300 solar masses per year, or one hundred times greater than the current outflow from our own Milky Way galaxy.

We predict that the outflows we have seen in the simulated galaxy halo are likely to be present in the observed quasar. In addition, the presence of such significant quasar-driven outflows may help explain the low star formation rate in the host galaxy.

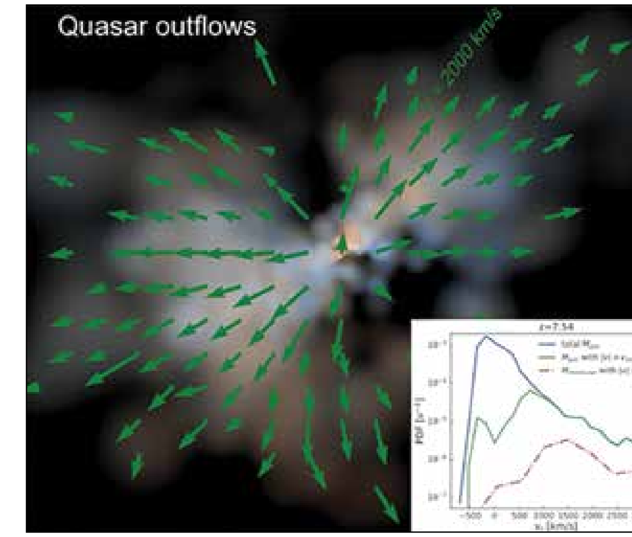

Figure 2: Conical gas outflows around the most massive black hole are powered by the quasar, which energizes and blows gas out from the host galaxy and also quenches star formation. The insert shows a histogram of the gas velocities around the black hole. The simulations predict this outflow should be observable around the first massive black holes.

WHY BLUE WATERS

In broad terms, the size of our problem meant that BW was the only system that could solve it, both in terms of memory and compute cores (we use essentially all system memory and cores). There were many essential aspects for this success. For example, scheduling allowed the system to be drained efficiently so our run could begin and make regular progress. Project staff retuned aspects of the file system and scheduling. In addition, they identified obscure issues with the system, working with Cray in a fashion that we could never have accomplished. Thus, we achieved some of the highest I/O speeds seen on BW, which was essential to our research. The PAID program, linking computer scientists and domain scientists, was forward-thinking, progressive, and immensely useful.

PUBLICATIONS & DATA SETS

Tenneti, A., et al., A tiny host galaxy for the first giant black hole: z = 7.5 quasar in BlueTides. *MNRAS*, submitted (2018).

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Huang, K.-W., et al., BLUETIDES simulation: establishing black hole-galaxy relations at high-redshift. *MNRAS*, (2018), DOI:10.1093/mnras/sty1329.

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Wilkins, S., et al., Dust-obscured star-forming galaxies in the early universe. *MNRAS*, 473:4 (2018), pp. 5363–5369.

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